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CALIBRATION AND VALIDATION OF THE CROP GROWTH MODEL DAISY FOR SPRING BARLEY IN THE CZECH REPUBLIC

Eva Pohanková[1,2], Petr Hlavinka[1,2], Jozef Takáč[3], Zdeněk Žalud[1,2], Miroslav Trnka[1,2]

[1] Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic

[2] Global Change Research Centre, Academy of Sciences of the Czech Republic, v.v.i., Bělidla 986/4a, 603 00 Brno, Czech Republic

[3] Soil Science and Conservation Research Institute, Gagarinova 10, 827 13 Bratislava, Slovak Republic

Abstract

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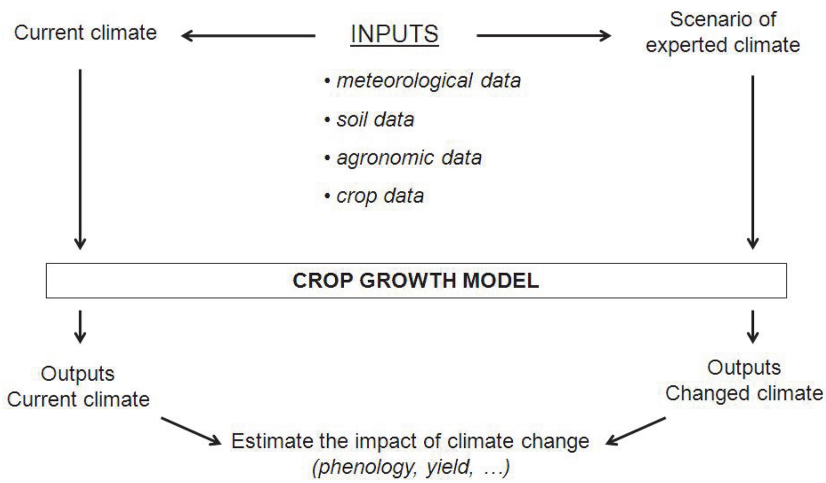
In this paper, the crop growth model DAISY for spring barley (cultivar "Tolar") was calibrated and subsequently validated in three different soil-climate locations in the Czech Republic – Lednice (48°48′51″ N, 16°48′46″ E, altitude 180 m), Věrovany (49°27′39″ N, 17°17′42″ E, altitude 210 m) and Domanínek (49°31′42″ N, 16°14′13″ E, altitude 560 m). The calibration and validation were based on data from a multi-year field experiment from the Central Institute for Supervising and Testing in Agriculture and from a two-year field experiment in Domanínek (2011 and 2012) that was conducted by the Institute of Agrosystems and Bioclimatology in cooperation with the Global Change Research Centre AS CR. The calibration for Lednice, Věrovany and Domanínek was performed using 4 growth seasons from each station, the subsequent validation for Lednice and Věrovany was performed based on 3 growth seasons from each station, and that for Domanínek was based on 6 growth seasons. The value of the RMSE (root mean square error) statistic for flowering was 2 days for calibration and 4 days for validation on average; for maturity, the RMSE was 11 days for both calibration and validation. The average RMSE for the yields was 0.9 $t \cdot ha^{-1}$ for calibration and 1.6 $t \cdot ha^{-1}$ for validation. According to the statistical index MBE (mean bias error) for the flowering phenological phase, the crop growth model DAISY showed a delay of 2 days in both calibration and validation. There was also delay of 6 days in calibration and of 8 days in validation for maturity. According to the MBE, the crop growth model DAISY underestimates the yield by 0.2 $t \cdot ha^{-1}$ for calibration and underestimates the yield by 0.4 $t \cdot ha^{-1}$ for validation.

Keywords: spring barley, crop growth model, DAISY, "Tolar", field experiments, phenology, growth dynamics

INTRODUCTION

The main cause of the ongoing changes in the environment are, according to the IPCC scientists (Intergovernmental Panel on Climate Change), anthropogenic influences. The temperature and the concentration of greenhouse gases (CO_2) are increasing (e.g., IPCC, 2013). The atmospheric CO_2 is a key source of carbon for plants (Amthor, 2001), and its increased concentration in the atmosphere accelerates photosynthesis and increases yield and biomass. However, the plant growth and development are also affected by meteorological elements (temperature, precipitation and global radiation) and the increase in temperature in general shortens the plant growth period and the duration of phenological phases (e.g., Batts, 1997; Brown and Rosenberg, 1997; Hay and Porter, 2006), which results in an accelerated development



1: *A simplified chart of the possible use of the growth model to estimate the impact of possible climate changes*

and in a decreased yield. One of the possible ways to estimate the effects of the expected climate conditions on the growth, development and yield of crops is the use of the crop growth models (Fig. 1), (e.g., Eitzinger *et al.*, 2013; Rosenzweigh *et al.*, 2013; Thaler *et al.*, 2012).

To use a growth crop model for such a purpose, calibration and subsequent validation must be performed. To calibrate the crop growth models, high quality datasets are required. These datasets consist of the following 4 basic dataset groups:

1. meteorological data (i.e., daily precipitation (mm), average daily air temperature (°C), global radiation ($MJ \cdot m^{-2}$), wind speed ($m \cdot s^{-1}$), vapor pressure and relative humidity (%)),
2. cultivation technology (e.g., term and method of tillage, term of seeding, and term and dose of fertilizing, irrigation, harvesting),
3. soil conditions (e.g., soil bulk density, humus content, C:N ratio, hydraulic conductivity of soil and soil retention curve parameters), and
4. crop species and cultivar characteristics.

The crop growth model DAISY is the Danish Soil-Plant-Atmosphere System Model. This model is designed to simulate the daily step water balance, heat balance, solute balance and crop production in agro-ecosystems that are subjected to various management strategies (Abrahamsen and Hansen, 2000). To calculate the water balance, the model uses the Richards equation (Richards, 1931; Pachepsky, 2003), which requires a retention curve and a hydraulic conductivity function for each soil horizon. When there are no retention curves, the model calculates the water balance using HYPRES (HYdraulic Properties of European Soils), (Wösten *et al.*, 1999). The aim of this paper is to calibrate and validate the crop growth model DAISY for spring barley, specifically the malting mid-late variety "Tolar" (VÚPS, 2009). The calibration of the crop growth model DAISY should help make the results of the growth model simulation as close as possible to the measured and observed values. The subsequent validation should then verify the calibration reliability and robustness, i.e., whether the model is able to correctly estimate the key growth parameters and their dynamics in different seasons and/or at sites that were not included in the calibration dataset. The calibration and validation of any crop model are challenging and long-lasting processes but are necessary before use (e.g., Rötter *et al.*, 2012). In this paper, a 4.01 version of the model DAISY was used. A detailed description of the model is available in the "Daisy Program Reference Manual" (Abrahamsen, 1999) or in "Daisy – a flexible Soil-Plant-Atmosphere System Model" (Hansen, 2000).

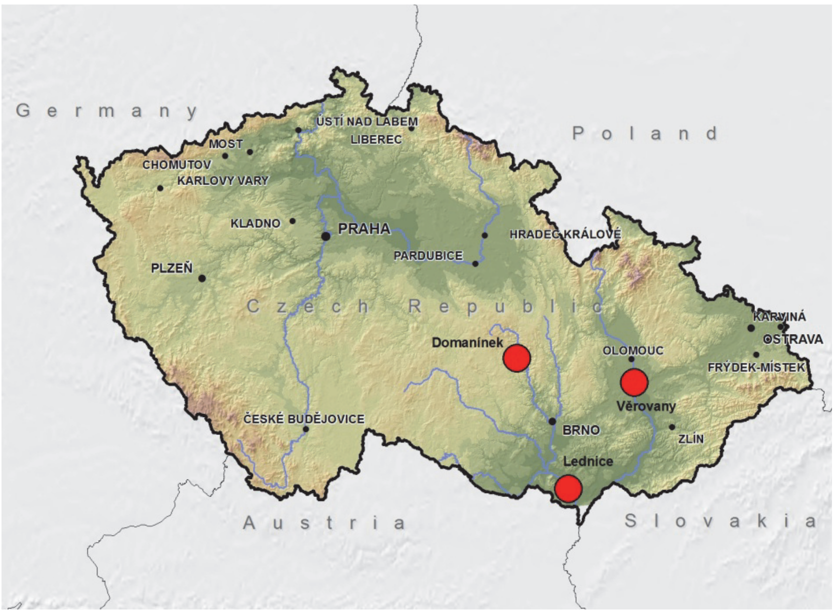
MATERIALS AND METHODS

The crop growth model DAISY was applied to three different soil-climate conditions in the Czech Republic: in Lednice, Věrovany and Domanínek (Fig. 2).

The sites were selected to represent different climate conditions with Lednice representing a warm and relatively dry spring barley growing region and Věrovany being within the most fertile area of the country with warm with mostly sufficient rainfall conditions while Domanínek is the coolest and wettest of all three sites. The major characteristics of each location are summarized in Tab. I.

For the crop growth model DAISY calibration and validation purposes, experimental data from a SIAST's (Central Institute for Supervising and Testing in Agriculture) multi-year field experiments in the mentioned locations, were used as well as measured and observed data from two-year field experiments with "Tolar" 2011 and 2012 in Domanínek (Tab. II).

For each calibrated and validated year, SIAST provided the following crop management data: the date and depth of the tillage, dates and doses

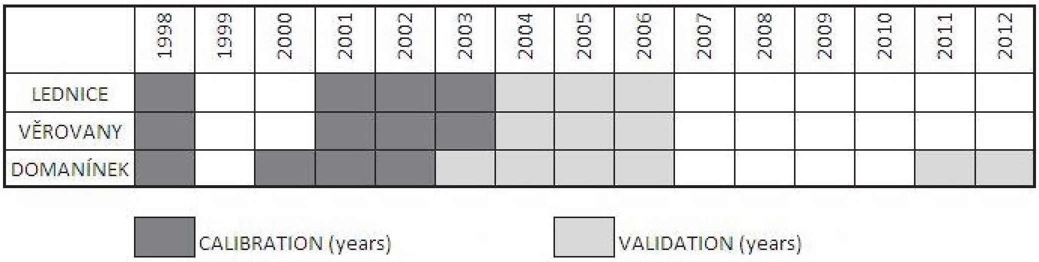


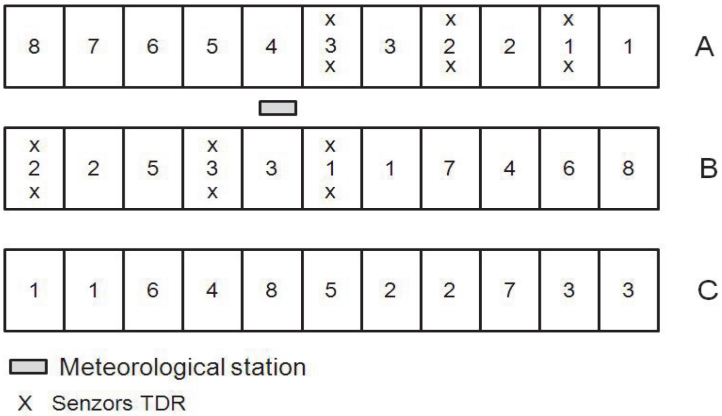
2: *Map of the Czech Republic with marked interest stations (Lednice, Věrovany, and Domanínek)*

I: *Basic characteristics of the locations of Lednice, Věrovany, and Domanínek (Tomiška et al., 2003). The climate data were evaluated from 1971–2000*

Locality	Lednice		Věrovany		Domanínek	
Production area	Maize		Sugar beet		Potato	
Ø annual precipitation (mm)	461		502		575	
Ø annual temperature (°C)	9.6		8.7		6.8	
Soil types	Chernozem		Chernozem		Dystric cambisol	
Soil fractions	Loamy clay		Loamy		Loamy	
The depth profile (m)	1.50		1.50		1.50	
	(m)	(%)	(m)	(%)	(m)	(%)
Clay	0–0.30	0.223	0–0.28	0.169	0–0.24	0.158
	0.30–0.82	0.251	0.28–0.64	0.219	0.24–0.66	0.263
	0.82–1.02	0.198	0.64–0.94	0.247	0.66–0.94	0.186
	1.02–1.50	0.151	0.94–1.22	0.184	0.94–1.30	0.133
			1.22–1.50	0.180	1.30–1.50	0.129
Silt	0–0.30	0.606	0–0.28	0.664	0–0.24	0.500
	0.30–0.82	0.575	0.28–0.64	0.637	0.24–0.66	0.461
	0.82–1.02	0.628	0.64–0.94	0.617	0.66–0.94	0.387
	1.02–1.50	0.645	0.94–1.22	0.658	0.94–1.30	0.196
			1.22–1.50	0.632	1.30–1.50	0.262
Sand	0–0.30	0.171	0–0.28	0.167	0–0.24	0.342
	0.30–0.82	0.174	0.28–0.64	0.144	0.24–0.66	0.276
	0.82–1.02	0.174	0.64–0.94	0.136	0.66–0.94	0.493
	1.02–1.50	0.204	0.94–1.22	0.158	0.94–1.30	0.382
			1.22–1.50	0.187	1.30–1.50	0.452
Ø bulk density ($g \cdot cm^{-3}$)	1.54		1.53		1.62	
Ø wilting point (%)	14		14.6		13.5	
Ø maximum capillary capacity (%)	38.6		37		36.9	
Ø growing season (simulated DAISY)						
Evapotranspiration (mm)	297.4		286.9		392.0	
Reference evapotranspiration (mm)	386.2		354.0		394.1	
Potential evapotranspiration (mm)	444.5		406.9		445.8	

II: *Table of the years that were used for the calibration and validation of the Lednice, Věrovany and Domanínek locations*





3: *A scheme of field experiments in Domanínek in 2011 and 2012. The "Tolar" cultivar was placed in the plots with numbers 1–4*

III: *The dates of sowing and the doses of nitrogen fertilizer in the field experiments with the spring barley "Tolar" cultivar in Domanínek in 2011 and 2012*

Variants of "Tolar"	Term of sowing 2011	Dose of fertilizer 2011 (kg N/ha)	Term of sowing 2012	Dose of fertilizer 2012 (kg N/ha)
1	12. 04.	60	18. 04.	70
2	12. 04.	69 + 20	18. 04.	81+20
3	27. 04.	60	03. 05.	70
4	27. 04.	69 + 20	03. 05.	81+20

of the nitrogen fertilizer, dates of sowing and harvesting, information on the previous crop, nitrogen content and yield quality. The "Tolar" field experiments in Domanínek took place in 2011 and 2012. Unlike the SIAST' experiments, additional variables were observed within these experiments. The designs of the experiments were identical for both years. The experiments were established on standardized 12 m^2 plots. The "Tolar" field experiment itself consisted of four variants (marked 1–4) in three replicates (A, B, and C).

Variants (1–4) differed from each other as follows:

1. date of sowing (variants 1 and 2 with normal agrotechnical date of sowing vs. variants 3 and 4 with 14 days delayed agrotechnical date of sowing) and
2. fertilizer dose (variants 1 and 3 with normal level of fertilization vs. variants 2 and 4 with a 1/3 increased fertilizer dose).

A description of these variants is provided in Tab. III.

For three variants (1, 2, and 3), the plots were duplicated. One plot was a sampling plot, while the others were harvesting plots. In the harvesting plots, two sensors TDR (time domain reflectometry, CS 616, Campbell Scientific Inc., Shepshed, UK) to measure the soil water content were placed vertically to monitor the soil water content from the surface to a depth of 30 cm. In the weekly step, the leaf area index was measured with SunScan (Delta-T Devices, Cambridge, UK). From the sampling plots, the samples of the aboveground biomass and soil samples during the growing season were collected in weekly or bi-weekly intervals. From the aboveground biomass, the dry matter content per 1 m^2 and the content of nitrogen in the plant were always determined. Moreover, for gravimetric estimation of soil moisture, mixed soil samples up to 30 cm depth were also collected. These observations were used to calibrate the TDR sensors that were placed in the harvesting plots and that provided continuous information on the soil water content in hourly time- steps. The first soil sampling was carried out before sowing and served to determine the content of mineral nitrogen and the soil water content in the individual soil layers. The initial conditions in the experimental plots were determined based on these soil samplings. Other soil samples (to a 30 cm depth) were always collected right after collecting a sample of the aboveground biomass and after harvesting. We carefully observed the beginning and the course of the phenological phases (emergence, tillering, shooting, heading, flowering, yellow maturity and harvest), crop health, main yield parameters (number of grains per spike, productive tiller number, thousand grain weight, number of emerged plants, and number of ears per m^2) and yield. The field experiment was monitored by a meteorological station that was placed in the middle of the experiment that, in addition to the soil water content (TDRs), measured the air temperature and humidity at 2 and 0.2 m above the ground, soil temperature and soil water. Additional information, i.e., global radiation, precipitation and wind speed, were collected at the base station in close proximity (less than 500 m). The results of the calibration and validation for phenological phases of flowering and maturity and for yield were evaluated using the following statistical parameters: the root mean square error (RMSE), which describes the average absolute deviation between the observed and modeled values, and the mean bias error (MBE) as an indicator of the average systematic error (Davies and McKay, 1988).

MBE as the mean bias error and RMSE as the root mean square error can be calculated as follows:

$$MBE = \frac{\sum_{i=1}^{n}(S_i - O_i)}{n},$$

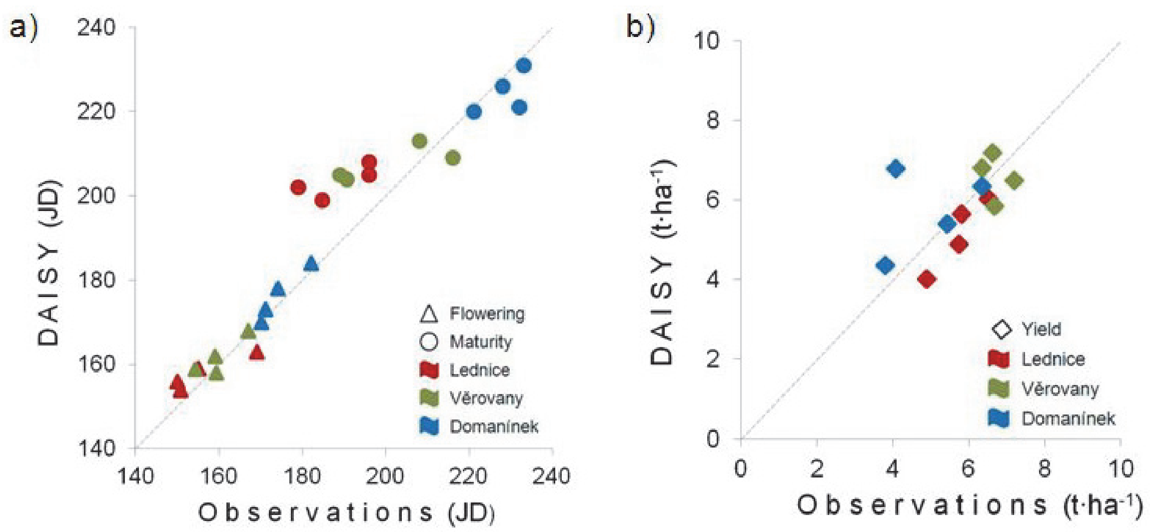
$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}},$$

where
S_i.... the estimated value of the variable,
O_i... the observed value of the variable and
n.... the number of pairs of observed and estimated values.

RESULTS AND DISCUSSION

The crop growth model DAISY was calibrated in several steps. The first step was to approximate the conditions of the observed phenological phases (flowering and maturity) to the modeled phenological phases (Fig. 4a). The parameters for the length of the vegetative and reproductive development stages were modified in the DAISY basic settings. The crop growth model DAISY simulated the gradual phenological development in different soil-climate locations very well. At lower altitudes (Lednice and Věrovany), the onset of barley's phenological phases of flowering and maturity was earlier, thanks to the early onset of suitable conditions for sowing (Fig. 4a). The second step of calibration was to compare the observed yields with the yields that were simulated by DAISY. In this case, the sensitivity of the model to water stress had to be adjusted. Graphical representations of the modeled and simulated yields can be found in Fig. 4b. The obtained values of the RMSE and MBE can be found in Tab. IV.

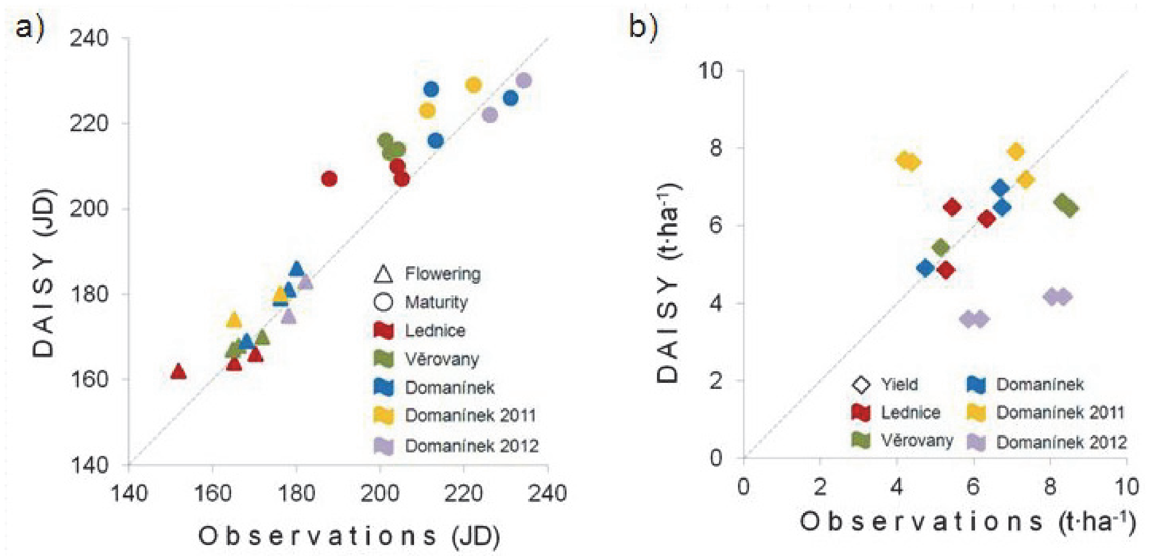
The major deviation between the observed and modeled yields as depicted in Fig. 4b (4.7 t·ha observed vs. 6.8 t·ha estimated) is apparent for 2002 in Domanínek. The experimental logbook, which states that even though the vegetation conditions



4: *a) Calibration – the comparison of the observed and modeled onset of the phenological phases of flowering and maturity for the cultivar "Tolar" at Lednice, Věrovany and Domanínek using the growth model DAISY. JD – the number of day from the beginning of the year; b) Calibration – comparison of the observed and estimated yields for the cultivar "Tolar" at Lednice, Věrovany and Domanínek using the growth model DAISY*

IV: *The evaluation of calibrations according to the statistical parameters MBE (Mean Bias Error) and RMSE (Root Mean Square Error)*

		MBE		
	Flowering (days)	**Maturity (days)**	**Yields ($t \cdot ha^{-1}$) (with year 2002)**	**Yields ($t \cdot ha^{-1}$) (without year 2002)**
Lednice	2	15	–0.6	–0.6
Věrovany	2	7	–0.1	–0.1
Domanínek	2	–4	0.8	0.2
Ø	2	6	0.0	–0.2
		RMSE		
	Flowering (days)	**Maturity (days)**	**Yields ($t \cdot ha^{-1}$) (with year 2002)**	**Yields ($t \cdot ha^{-1}$) (without year 2002)**
Lednice	5	15	0.6	0.7
Věrovany	3	11	0.7	0.7
Domanínek	2	6	1.4	0.3
Ø	2	11	0.9	0.5



5: *a) Validation – the comparison of the observed and modeled onset of the phenological phases of flowering and maturity for the cultivar "Tolar" at Věrovany, Lednice and Domanínek using the growth model DAISY. JD – the number of day from the beginning of the year; b) Validation – comparison of the observed and estimated yields for the cultivar "Tolar" at Věrovany, Lednice and Domanínek using the growth model DAISY*

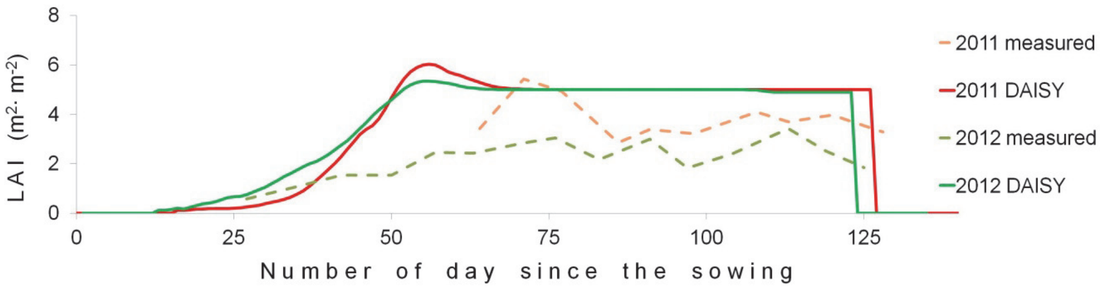
during the year were favorable, with respect to the sparse vegetation (even on working areas), the yields could not reach the previous year's quality. The experimental logbook does not explain why the vegetation was sparse when the vegetation conditions were favorable in 2002. Therefore, we can only suppose, that something could have negatively affected the real barley canopy experiment, possibly an agrotechnical error, bad conditions during sowing or damage to the crop in a way that is not measurable by a model. Therefore, two statistical evaluations were performed for the calibration yields in Domanínek. The first evaluation includes the year 2002 while the second does not.

The MBE was estimated as 2 days for all on the stations. The RMSE results were best for Domanínek (2 days) and worst for Lednice (5 days). The onset of phenophase maturity was, according to the statistical evaluation, worse than the onset of the flowering phenophase, ranging from –4 to 15 days. When we exclude the year 2002, the MBE in the yield of Domanínek deteriorated by 0.2 $t \cdot ha^{-1}$, in contrast, the RMSE increased by 0.4 $t \cdot ha^{-1}$

In addition, the study Rötter *et al.* (2012) presented the calibration results of the spring barley's phenology and shows some discrepancies with the observations. The mentioned study, which compared 9 crop growth models, including DAISY, with spring barley's growth and development, includes the observation results from experiments that were carried out in several European countries. Flowering did not correspond to reality by ±11 days or to maturity by ±12 days. Not even the simulated yield was satisfactorly by any of the models. In DAISY, the yield was systematically underestimated. Despite these facts, the crop growth model DAISY

V: *The evaluation of validation according to the statistical parameters MBE (Mean Bias Error) and RMSE (Root Mean Square Error)*

	MBE		
	Flowering (days)	**Maturity (days)**	**Yields (t·ha⁻¹)**
Lednice	2	9	0.2
Věrovany	1	12	−1.1
Domanínek	3	4	−0.2
Ø	2	8	−0.4
	RMSE		
	Flowering (days)	**Maturity (days)**	**Yields (t·ha⁻¹)**
Lednice	6	12	0.7
Věrovany	2	12	1.5
Domanínek	5	9	2.5
Ø	4	11	1.6



6: *Comparison of the estimated LAI with the observed values for variants in 2011 and 2012*

was one of the three best models as far as the yield estimation is concerned. The model DAISY was also calibrated in Slovakia where the differences in the respective simulations between the simulated and real spring barley's yield ranged from 0.1 t·ha⁻¹ to 2.2 t·ha⁻¹ (Takáč and Šiška, 2011).

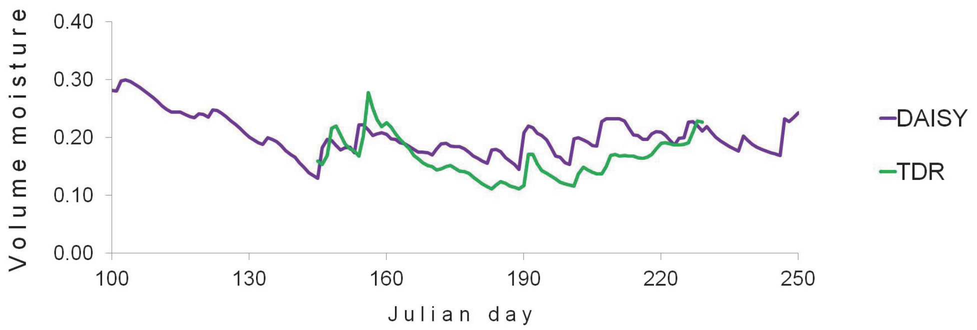
Based on the satisfactory results of the crop growth model DAISY calibration, the verification of this model followed in the form of the model validation. For the calibrated crop growth model, similar experimental data from Lednice, Věrovany and Domanínek from other experimental years served as the input. The validation results are presented Fig. 5a and Fig. 5b and Tab. V.

The best results were obtained for Věrovany, where the MBE was only 1 day. The RMSE was an average of 4 days, which is 2 days worse than in the calibration. The onset of the phenological phase maturity for validation was, according to the statistical evaluation, the same as for calibration and again was worse than the onset of the flowering phenological phase. The deviations range fluctuated from 4 to 12 days. The best results were for Domanínek, and the worst results were for Věrovany. The closest simulated yield to that of the experiments was in Lednice.

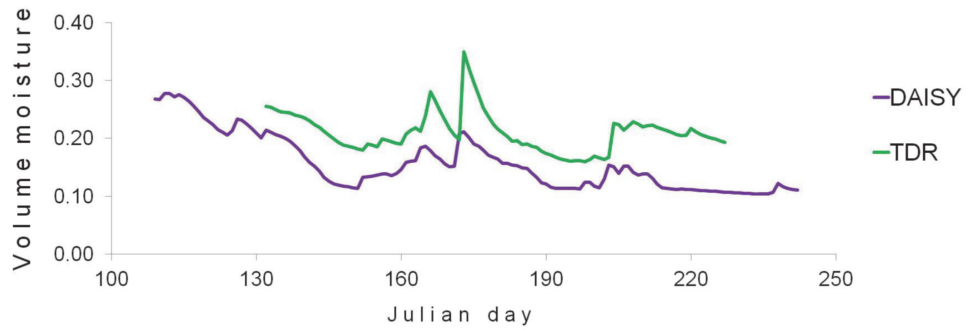
For the Domanínek' field experiments in 2011 and 2012, further information and data are available to compare the real situation and the simulation, i.e., the size and development of the leaf area (Fig. 6) and soil water content (Figs. 7 and 8).

In the graph in Fig. 6 with LAI values, the growth model DAISY overestimated the development of the leaf area in both years and compared to other crop growth models (Rötter *et al.*, 2012).

Moreover, the model here simulates the much earlier and largest increase in the leaf area than the maximum that was measured with SunScan. This result could partly explain the underestimation of the yield model in these years. As the Fig. 6 indicates DAISY provides more biomass to stems and leaves much earlier than we observed in the experiments. This might lead to considerable higher water depletion as it is indicated at Fig. 8 which in turn causes earlier onset of water stress according to the model and reduces growth and thus yield. However the harvest index is not particularly affected with observed values in 2012 being 1.08 and 0.81 for variants 1 and 3 with modelled values 0.83 and 0.81. It is apparent that the real LAI values are lower than those estimated by the model which has significant impact on the models ability to estimate water withdrawal correctly as well as growth dynamics. These results demonstrate need for multiple physiologically based observations to be used in calibrating the models for the local conditions. However such data are only rarely available and the described spring barley experiment is to our knowledge only of its kind in the Central Europe. The data of year 2011 and 2012 were unfortunately not suitable for model calibration, as in 2011 the barley canopy lodged



7: *Comparisons between the simulated and measured soil water content for spring barley from 0–30 cm in 2011 (variant 1)*



8: *Comparisons between the simulated and measured soil water content for spring barley from 0–30 cm in 2012 (variant 1)*

fairly early during the growing period due to strong wind with intense precipitation. The measured data of leaf area are therefore burdened with considerable error. The season of 2012 was affected by considerable drought event and was also not deemed suitable for calibration. While at the present time another batch of 2 experimental years (2013–2014) are available for improved DAISY calibration, these experiments needed to swap "Tolar" variety for a more contemporary one i.e. "Bojos". Unfortunately "Tolar" has been completely phased in 2010 and the good quality seed was not available after 2012 even from the original breeder. This only illustrates difficulty faced by the crop model calibration study in acquiring sufficient data for the calibration and verification.

The crop growth model DAISY relatively satisfactorily simulates the main feature soil water content dynamics as measured by TRD sensors in 2011 and 2012. In this case, the crop growth model DAISY simulated the movement of soil water based on the numerical solution of Richards' equation. However, in 2012 the soil water content and yield were underestimated by the model, which can be partly explained by the fact that the model overestimated the leaf area and required more water to create it.

In the comparative study by Kröbel *et al.* (2010), which focused on modeling the water dynamics with DNDC (DeNitrification DeComposition Model) and DAISY in a soil of the North China Plain, DAISY underestimated the soil water quantities against TDR sensors. The crop growth model DAISY is very sensitive to the water content in the soil. However, this model is not so sensitive to different doses of nitrogen fertilizer. The yields of the more fertilized variants differ only slightly compared to those of the less fertilized variants (Tab. III and Fig. 5b).

CONCLUSION

When calibrating and validating the crop growth model DAISY for spring barley, in particular the "Tolar" cultivar, satisfactory results both in phenology and yield were achieved compared to those of similar foreign studies or of different data samples. The gained experience from the calibration and validation of the crop growth model DAISY and the obtained results are a good starting point for the further use of this model (e.g., searching for optimal farming methods under current conditions or estimating the possible impact of future climate conditions). When the calibration and validation of the crop growth model DAISY are also available for other crops, it will be possible to simulate whole crop rotations including their long-term effects.

Acknowledgement

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Contact information

Eva Pohanková: eva.pohankova@mendelu.cz
Petr Hlavinka: petr.hlavinka@mendelu.cz
Jozef Takáč: takac@vupop.sk
Zdeněk Žalud: zalud@mendelu.cz
Miroslav Trnka: mirek_trnka@yahoo.com