IS CROP GROWTH MODEL ABLE TO REPRODUCE DROUGHT STRESS CAUSED BY RAIN-OUT SHELTERS ABOVE WINTER WHEAT?

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Abstract

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This study evaluates drought stress effect on winter wheat. Simultaneously, the ability of the HERMES crop growth model to reproduce the process correctly was tested. The field experiment was conducted at Domanín station in 2014 and 2015, where mobile rain-out shelters were installed on plots of winter wheat (May 2015). Precipitation was reduced in three replications and the findings were compared with results from control plots with ambient precipitation. A precipitation reduction of 93 mm led to reduced growth and decrease in grain yields. The results of this study showed that the model was able to reproduce soil moisture content well and reproduce the drought stress for crop yields of winter wheat to a certain extent. When rain-out shelters were used, real winter wheat yields were reduced by 1.7 t/ha. The model underestimated the yields for the sheltered variant by 0.67 t/ha on average against observed yields and overestimated development of leaf area for both unsheltered and sheltered variants. This overestimation was partly explained by the effect of excluded UV radiation. The outcome of this paper may help to reduce uncertainty within simulated yields of winter wheat under extreme weather conditions through a better understanding of model behavior.

Keywords: leaf area index, rain-out shelters, soil water content, water balance, yields

INTRODUCTION

Drought in the Czech Republic is becoming a major problem. The summer drought in 2015 belongs to the most serious of historical drought episodes (Daňhelka *et al.*, 2015). Major crops in temperate regions are expected to experience adverse climate change, which will have a negative impact on production (increased variability in annual yields in many areas) if the temperature rises by 2 degrees or more above late 20th century levels (IPCC 2014). Current research is trying to imitate some of the conditions posed by climate change

to understand what we can expect in the near future (e.g. Graß *et al.*, 2015, Hlaváčová 2015, Hlavinka *et al.*, 2009, Hlavinka *et al.*, 2015a, Hlavinka *et al.*, 2015b or Zeiter *et al.*, 2015).

Several modelers are engaged in assessing the impact of future climatic conditions. For their work, they use crop growth models that differ in their complexity, parameters and focus (Palosuo *et al.*, 2011). The HERMES crop growth model belongs among the widely used crop growth simulation models (e.g. Kersebaum *et al.*, 2011, Palosuo *et al.*, 2011, Rötter *et al.*, 2015).

Wheat is the most widely grown cereal in the Czech Republic (Mikulášová, 2015). Although winter wheat is highly dependent on soil conditions, its yields variability is affected much more by the weather (Zimolka *et al.*, 2005). From 2014 to 2015, wheat exceeded the area of 830 000 ha (5 274 000 tons). Grain production is used both to cover domestic demand and as an export commodity (ČSÚ, 2016, Mikulášová, 2015).

The aim of this study was to evaluate the ability of the HERMES crop growth model to simulate the effect of changes in weather (ambient precipitation and reduced soil moisture using rain-out shelters) that may occur in the near future. The model was tested on winter wheat, specifically the variety "Bohemia", from 2014 to 2015. The winter wheat variety was chosen in terms of the traditional and most important crops that are grown in Czech Republic. Modeled parameters such as phenological phases, leaf area index (LAI), soil moisture and yields were compared with observed data. We hypothesized that the model would be able to simulate drought effects induced by rain-out shelters. We also expected that the model would not be able to provide completely realistic data due to additional effects of rain-out shelters such as the effect of UV exclusion, microclimate deviations including, e.g. wind reduction, or the inability to exclude horizontal water movement in deeper soil layers. In the best case the model should be able to approximate actual measured values after a calibration process. Otherwise, it will be necessary to adapt modeled parameters using experiments in the upcoming years.

MATERIALS AND METHODS

Site description

The field experiment was conducted at the Domanín experimental station (49° 31' 42" N, 16° 14' 13" E, altitude 560 m) from 2014 to 2015. Climate conditions were represented as cool and wet. The average annual precipitation was 609.3 mm and the average annual temperature was 7.2 °C from 1981 to 2010. The soil type was classified as dystic cambisol. This area was characterized by low soil quality and the potential risk of late frosts. A more detailed description of soil properties is shown in Tab. I.

Trial description

The trial was conducted with the winter wheat cultivar Bohemia, which was sown on 30th September 2014. A field trial was set up in 2 variants. The first variant was conducted under natural climatic conditions (abbreviated as CONT, plot size 1.5 × 8.0 m). In the second variant, drought stress was induced using the rain-out shelters (abbreviated as DRY, plot size 3.1 × 8.0 m). Mobile rain-out shelters of size 3.1 × 8.0 m were installed on plots of winter wheat on 19th May 2015. To manufacture the shelters a corrugated material (Suntuf CS – clear polycarbonate with two-sided UV filter; trapezium 76/16, thickness 0.8 mm) was used. A strip of width 1.5 m in the middle of each plot was harvested to eliminate the edge effect. The sheltered area was large enough to perform sampling for determination of growth parameters. Access paths were placed between each plot. Each variant was repeated three times (Fig. 1). The sampling parts of each plot were placed in proximity to the harvested strips of both sheltered (DRY) and control parcels (CONT).

The experimental plots were fertilized uniformly with a total dose of 140 kg N/ha split into 4 doses (20 kg of N/ha in autumn as basal fertilization, 35 kg of N/ha as the first regenerative fertilization, 25 kg of N/ha as the second regenerative fertilization and 60 kg of N/ha as production fertilization).

To analyze the effect of UV exclusion by the rain-out shelters on wheat yield, an additional experiment in open top chambers (OTCs) was conducted at the same location from 2014 to 2015. The OTCs had a hexagonal ground plan with a diameter of 4 m and a basic height of 2 m (Fig. 2). Above this construction was placed a roof with rotating lamellas enabled to control chamber ventilation. The ventilation was provided automatically using a radial fan with feedback regulation based on data from temperature sensors outside and inside the chamber with the aim of maintaining a temperature difference no higher than 0.5 °C compared with the ambient temperature. Two winter wheat (variety Bohemia) subplots, each with an area 1.8 m², were grown in 6 chambers randomized within the experimental field. One subplot was grown without nitrogen fertilization and another one was fertilized with 200 kg N/ha (calcium nitrate) at the growth stage DC 24–25. Three chambers were made from UV

I: Basic soil characteristic of the Domanín location

Soil layers [m]	Wilting point [% vol.]	Field water capacity [% vol.]	Soil porosity [% vol.]	Corg [%]	Ø soil texture		
					clay [%]	silt [%]	sand [%]
0.0–0.3	8	24	44	1.03	12.5	45.0	42.5
0.3–0.4	6	23	39	0.25	4.0	32.0	63.5
0.4–0.5	6	23	39	0.20	10.0	25.0	65.0
0.5–2.0	2	6	17	-	10.0	25.0	65.0

Corg–organic carbon

transmitting acrylic (UVT Solar, Quinn Plastic) and three from acrylic filtering UV-B and a majority of UV-A radiation (XT, Quinn Plastic), both of a 4 mm thickness.

The leaf area index (LAI) was measured by SunScan (Delta-T Devices, Cambridge, UK) at intervals of 6–21 days from June to August. In parcels destined for harvest (Fig. 1) the TDR sensors (time domain reflectometry, CS 616, Campbell Scientific Inc., Shepshed, UK) were installed to measure the soil water content from a depth of 0.3 m (see Fig. 1). Two TDR sensors were always present under each roof and another sensor was always present outside of each roof (control).

Using the crop growth simulation model

Evaluation of drought stress was also based on the HERMES model (e.g. Kersebaum, 2008). This model belongs among the widely used, easily accessible and well-documented crop growth simulation models (e.g. Palosuo *et al.*, 2011). It is a process-oriented model for estimating development and growth of the field crops, soil water balance and the dynamics of nitrogen for arable land. The benefit of using HERMES is

the ability to work with a relatively small amount of input data sets that are ordinarily available at the farm level and that take into consideration plant growth, N-uptake, the process of net mineralization, the denitrification and transport of water and nitrate (Kersebaum *et al.*, 2011). The sub-model for crop growth was developed on the basis of the SUCROS model (van Keulen *et al.*, 1982). The daily net dry matter production by photosynthesis, respiration, global radiation and temperature was simulated (Kersebaum *et al.*, 2011). Crop growth was capped by water and nitrogen stress. Drought stress was indicated by the ratio of actual and potential transpiration. For this study the Penman-Monteith approach for estimating reference evapotranspiration was selected (Allen *et al.*, 1998, Monteith, 1965). The dynamics of soil water were derived from a simple capacity approach. According to Kersebaum (2011), field capacity, wilting point and porosity may either be provided directly or applied from the stone content, texture and bulk density classes by German soil taxonomy.

The input data were divided into the following three parts: weather data, soil information and management data. Individual parameters

a)

b)

1: (a) Illustrative photo. (b) Field trial map with the position of the rain-out shelters (DRY) and the TDR sensors for soil moisture measurements (figures are in meters).

entered into the model were obtained from soil and meteorological measurements including data about global solar radiation, air temperature (average, minimum and maximum), air humidity, wind speed, precipitation and tillage. Further, data of harvest, pre-crop and initial conditions were used to launch the model. These data were acquired from the Domaníněk experimental station for the period 2013–2015. The average monthly air temperature and rainfall from sowing to harvesting are shown in Tab. II. The rainfall difference between the DRY and CONT plots was 93 mm (period from May to August).

Subsequently, the output data sets (phenological phases, leaf area index–LAI, soil moisture and yields) were compared with observations.

RESULTS AND DISCUSSION

The first step to evaluate the results correctly was to calibrate for crop phenology (emergence, tillering, heading, flowering and maturity) by approximating the conditions according to observed phenological phases (Fig. 3). The model was calibrated on the basis of measured and observed data from field experiments. Successive alteration temperature sums led to corresponding phenological phases.

2: Open top chambers (OTCs) used for an additional experiment on the effect of exclusion of UV radiation. The OTCs were placed at the same location as the rain-out shelter experiment in distance cca. 150 m.

II: Mean monthly air temperature (°C) and rainfall (mm) in CONT and DRY variations from sowing to harvesting

Month	°C	CONT [mm]	DRY [mm]	Difference [mm]
September 2014	13.2	0.2	0.2	0.0
October	8.9	29.2	29.2	0.0
November	5.6	32.6	32.6	0.0
December	0.5	37.2	37.2	0.0
January 2015	−0.5	42.4	42.4	0.0
February	−0.7	7.0	7.0	0.0
March	3.5	46.0	46.0	0.0
April	7.3	14.6	14.6	0.0
May	11.5	38.2	22.0	16.2
June	16.0	17.7	0.0	17.7
July	19.9	56.4	0.0	56.4
August (harvest date)	20.9	2.7	0.0	2.7

Therefore, observed values in each phenological phase for the CONT and DRY variants did not change. Fig. 3 shows both variants at the same level. The phenological phase of emergence occurred 13 days after sowing. Winter wheat began to form tiller after 62 days. The other phenological phases of heading, flowering and maturity occurred at 153, 164 and 218 days, respectively, in 2015. After calibration, the model showed almost the same results as measured values. Under the phenological phase of maturity, the model underestimated the DRY variant by 11 days.

Regarding leaf area development, the crop growth model overestimated that development (Fig. 4). Considering that 2015 was arid, the wheat was low and had sparse participation. Furthermore, it is necessary to take into account the fact that the HERMES model simulates only the leaf area, while measuring with SunScan covers a total above-ground area of plants. Therefore, the measurement points should be above simulated curves. It is necessary to recalibrate the model from

ongoing measurements to obtain more precise results from the HERMES model. The results from further seasons will be used for this recalibration. In Palosuo *et al.* (2011), which compared models for winter wheat, the HERMES model led the average. In the current study, the HERMES crop growth model was able to evaluate the CONT option a little bit better than the DRY variant. However, the differences between the CONT and DRY variants were almost similar within the simulated and measured leaf area index. Conversely, the model captured the growth dynamics of the leaf area at similar levels as in Pohanková *et al.* (2013).

Evaluation of soil moisture using the TDR sensors was very satisfactory. Within the DRY variant, modeled results were evaluated as a nearly flat curve, confirming the roofs were waterproof (Fig. 5b). The CONT variant depicted changes in soil moisture under the influence of precipitation with good precision when compared with the curves of controls (Fig. 5a). Figs. 5a, 5b show the entire period from sowing to the end of August. The simulated curve

3: Phenological phases observed and modeled. (a) From emergence to tillering and (b) from heading to maturity in days of the year (DOY).

SunScan vs. HERMES LAI 2014-2015

4: SunScan measurements compared with simulated LAI. The average measured values are indicated with circles. The whiskers extend to the most extreme (minimum/maximum) measured values. A black box depict sheltered period (from 19th May to 6th August 2015).

also corresponded relatively and sufficiently to the shape of curve values measured by the TDR sensors. Overall, the HERMES model estimated soil moisture with satisfactory accuracy, e.g. comparable to Pohanková *et al.* (2013), which compared the results of two models (HERMES, DAISY) at the experimental station in Domaníněk. Model credibility was validated based on crop model inter-comparison by Palosuo *et al.* (2011) and Rötter *et al.* (2012), where the HERMES crop growth model estimated soil water content with pinpoint accuracy.

Real and simulated yields were compared in the next step (CONT vs. DRY). The effect of the soil moisture shortage was reflected. For the CONT and DRY variants 2.65 and 0.94 t/ha grain yields, respectively, were measured. Using the rain-out shelters reduced real winter wheat yields by 1.7 t/ha. The model overestimated the yields in the uncovered variant (CONT) by an average of 0.15 t/ha and underestimated the yields in the rain-out shelters variant (DRY) by an average of 0.67 t/ha (Fig. 7). This result could be explained by the fact that the model was not able to simulate all types of stress (like the effect

of pests or diseases). One likely influence was different levels of UV radiation between sheltered (reduced UV level) and unsheltered plots (ambient UV level). For example Feng *et al.* (2007), Kataria and Guruprasad (2012) and Lizana *et al.* (2009) showed that UV radiation has a significant effect on wheat yield. Kataria and Guruprasad (2012) demonstrated increased yields when the UV-B and UV-A radiation are reduced. Lizana *et al.* (2009) reexamined the effect of increased UV-B radiation (by 30%), leading to a yield reduction of 12–20%. Within our additional experiment in OTCs we tested the effect of UV exclusion under two levels of nitrogen nutrition. Although it was evident that higher doses of nitrogen increased the effect of UV radiation, in both doses the effect was statistically non-significant in both nitrogen nutrition levels. Additionally, the yield reduction caused by UV radiation was only 4.5 and 7.5% in 0 and 200 kg N/ha, respectively (Fig. 6). Consequently, although UV radiation is one important cause of the deviation between the modeled (lower stress due to UV filtration by shelters is not considered by the HERMES) and experimental yields for DRY variant, other causes may also exist, such as

5: Comparisons between the simulated and measured (under the rain-out shelters and outside) soil water content from 0.0 to 0.3 m. (a) Control (CONT) represents measurement outside the rain-out shelters for three repetitions. (b) DRY_a_TDR and DRY_b_TDR depict repetitions of the TDR sensors that were placed under one roof. Gray columns represent precipitation. The period depicted is from sowing to the end of August.

horizontal water flow in deeper soil layers, affected microclimate including, e.g. wind reduction, or effects on disease development.

The current study recorded a 71% difference between measured and simulated average values

of the DRY variant, which may be caused by UV filter. For the CONT variant, especially in first and second parcels, the HERMES model assessed winter wheat yields excellently. Real and modeled yields are shown in Fig. 7.

6: The effect of UV exclusion (UV-) compared with ambient UV radiation (UV+) on grain yield of winter wheat under two levels of nitrogen nutrition (N0–0 kg N/ha and N200–200 kg N/ha). The means (vertical bars) and standard deviations (error bars) are presented ($n = 3$). Different letters denote statistically significant differences ($P > 0.05$) among UV and nitrogen nutrition treatments using Tukey's ANOVA post-hoc test.

7: Comparison between observed (columns) and modeled (lines) winter wheat yields for roof versions (DRY) and rainfed parcels (CONT) and for repetitions 1 to 3.

CONCLUSION

In summary, within a calibration process, the phenological phases that affected the values of other modeled parameters were modified. Further, selected parameters were compared with each other. The leaf area development was compared, and although the modeled values were higher than the measured values, they were still within a reasonable range. Estimated soil moisture results were very similar to data measured using the TDR sensors. The HERMES model also overestimated mean yields by approximately 0.15 t/ha for ambient climate conditions. In case of drought stress, the HERMES model underestimated mean yield by approximately 0.67 t/ha (71%). This underestimation may be result of UV exclusion by rain-out shelter since the model does not take into consideration filtration of UV radiation, but other causes may also exist. The impact of UV exclusion caused by rain-out shelter on grain yield will be investigated in a future experiment. It was proven that the used rain-out shelters may be an experimental technique with important potential for the evaluation and quantification of the drought stress effects.

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