Evaluation of the CERES models in different production regions of the Czech Republic

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ABSTRACT

The main goal of this work was to calibrate and evaluate the CERES-Barley and CERES-Wheat crop models. The experimental fields used for the model evaluation are situated in three different production regions (maize, sugar beet and potato main growing regions, respectively) with altitudes of 179, 204 and 560 meters above the sea level. Grain yield and date of anthesis together with maturity dates served as reference for the model evaluation. Two evaluation approaches were tested in this study. The first one uses historical data series and it is based on long-term field experiments with capability to reflect interannual weather variability. The second approach uses results of one-year multiple treatment experiment. The model evaluation is then based on a set of treatments differing e.g. in sowing date or an amount of used nitrogen fertilizer. Grain yields simulated by both models are acceptable when compared with experimental results: the coefficient of determination for historical series varied from 0.69 to 0.86 for evaluation of CERES-Barley at the three examined sites and reached values of 0.60 and 0.86 for the CERES-Wheat model at two experimental sites. The lower coefficient of determination of the wheat model was recorded at the locality with the highest altitude and coldest winter conditions. There, also the worst reliability of simulated phenological development was noted. At the second locality where the CERES-Wheat model was tested and at all three localities where CERES-Barley was applied, the simulated duration of vegetation period and anthesis dates were relatively accurate and yielded strong statistical correlation. The one-year multiple treatment experiment proved to be useful to determine the models sensitivity to differences in crop management. The combination of both approaches seems to be the best solution for evaluation of similar crop models if the detail long term experimental data are not available.

Keywords: spring barley; winter wheat; crop model; model evaluation

The development of dynamic crop growth models, which started more than thirty years ago, considerably improved analytic solution of problems in crop sciences but new scientific problems were created in the same time. One of the main advantages of crop model application is the possibility to use them under various weather and soil conditions and under different environment in different regions of the world, which is not usually possible when models based on the statistical analysis are used. One of the important preconditions of the application of dynamic models is the evaluation of the model reliability in reproducing the real conditions at the given place and time (Penning de Vries 1977, Addiscot et al. 1995). The processes of evaluation of any crop model are relatively long and difficult because they require the collection of large data sets including weather, soil, crop and crop management data over extensive time periods. Most of the field experiments that are normally used in order to evaluate crop models were designed for other purposes, so they often do not contain the complete data set necessary for crop model inputs. These gaps have to be filled either by calculations (e.g. using Angström formula in order to calculate daily global radiation sums from sunshine or calculating initial available soil water content at planting time from available data) or approximation (as in case of crop residues of the previous crop or initial nitrogen content in the deeper soil layers). Some useful data as e.g. maximum LAI or total aboveground measurements are not often available and cannot be exactly calculated or estimated. The evaluation of the models normally includes their evaluation on independent data sets i.e. defining the usefulness and relevance of a model for a pre-defined purpose. This contribution represents experiences and results with evaluation of two crop models under different weather and soil conditions gathered by the authors over more than seven years of work.

MATERIAL AND METHODS

The objectives of the study included the calibration and evaluation of the CERES-Barley and CERES-Wheat models for three sites in the southeastern part of the Czech Republic. The calibration and evaluation process consists of the following steps:

1) collection (observation or measurement) of the experimental data (anthesis, maturity dates and grain yields),
2) calibration of crop models using experimental data,
3) evaluation of crop models by comparison of the observed and simulated data.

Table 1. Characteristics of the experimental sites for the three crop production regions of the Czech Republic. Meteorological data were collected from 1961 through 1990

Characteristic	Region 1	Region 2	Region 3
Site	Žabčice	Kroměříž	Domanínek
Latitude	49°01' N	49°18' N	49°32' N
Longitude	16°37' E	17°23' E	16°15' E
Elevation (m)	179	234	560
Primary crop	maize	sugar beet	potato
Soil type	Fluvisol	Chernozem	Cambisol
Mean annual temperature (°C)	9.2	8.6	6.5
Mean air temperature (April–September)	15.7	15.1	12.8
Mean annual precipitation (mm)	480	599	651
Mean precipitation (April–September)	312	389	396
Range of annual accumulated global radiation ($MJ.m^{-2}$)	3584–4312	3601–4228	3213–3843

4) assessment of the possibilities and limitations of the two evaluation techniques used

Each of the experimental sites is situated in a different production region, which differ significantly in climatic as well as soil conditions. However, the crop management procedures of the trial management are almost identical. Meteorological, pedological, crop, and management data were collected from experimental sites (Table 1). As the experiments which were used for models evaluation had been carried out between years 1974–2000, five cultivars of spring barley and two cultivars of winter wheat had to be included into simulations (Table 2).

Brief description of the CERES-Barley and CERES-Wheat models

The explanatory and dynamic crop models of the CERES group are composed from several modules, which serve for data input, mathematical calculations of the growth and development processes and finally for presentation of the simulation outputs.

The model takes into account several processes simultaneously to provide a realistic description of the crop-soil-atmosphere system. Each simulation consists of the following steps:

– calculations of the phenological development,
– formation of leaf, stem and root biomass and its partitioning,
– available soil water and its utilization by the crop,
– the nitrogen balance and its distribution to crop organs.

Output data files provide a detailed description of the above ground biomass formation and the biomass nitrogen content as well as information about soil reserves of available water and nitrogen. A lot of additional and useful information is provided through the utilities of DSSAT (Decision Support System for Agrotechnology Transfer, Hoogenboom et al., 1994).

Calibration of input data

There are four groups of input data necessary in order to prepare and run model simulation. The minimum data set of the weather data includes daily values of maximum and minimum air temperature, global radiation and precipitation. The meteorological stations (automatic or climatological) were used as a source of these needed values. Genetic coefficients were derived partly from literature sources (e.g. Thornton et al. 1991) and partly from experimental data from test sites by using measured grain

Table 2. Cultivars of spring barley and winter wheat used at the three experimental sites for the study

Variety name	Evaluated in years	Evaluated on localities	Notes
Spring barley			
Akcent	1994–1998 and 2000	Domanínek, Kroměříž, Žabčice	middle late ripening cultivar
Bonus	1985–1988	Žabčice	middle late ripening cultivar
KM 1992	1974–1976	Žabčice	middle late ripening cultivar
Orbit	1985–1994	Domanínek	middle early ripening cultivar
Spartan	1977–1984	Žabčice	middle late ripening cultivar
Winter wheat			
Hana	1984–2000	Kroměříž, Domanínek	early ripening cultivar
Samanta	1997	Kroměříž	middle early ripening cultivar

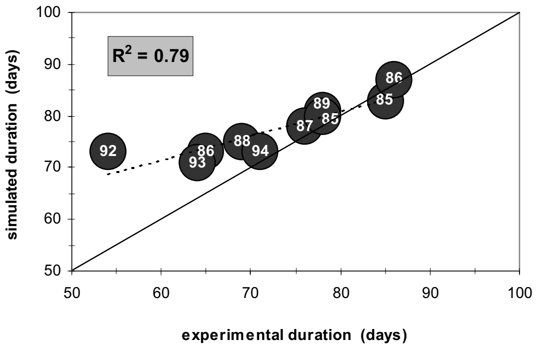

Figure 1. Evaluation of the duration of vegetation period from sowing to anthesis of spring barley (cultivar Orbit) at Domanínek; the straight dashed line represents the linear regression function relating the observed and simulated anthesis date; diagonal line represents 1:1 ratio; the years are marked by numbers inside the circles

yield and length of vegetation period of the tested spring barley and winter wheat cultivars. Soil input data were derived from soil pits that were situated directly at the experimental sites. Crop management data included information about sowing, emergence and harvest dates as well as about used amount of nitrogen, potassium and phosphorus fertilizers and finally, data about tillage practices and previous crop.

The model is designed to be used for simulation of two production levels. Only temperature, solar radiation, and the specific physiological plant characteristics limit the potential yield production level. This level was not considered in our study. At the water and nutrients-limited production level, the soil and plant water balance together with available nutrients are included in the simulation of crop growth.

CERES models are based on black box approach and therefore cannot be easily adapted or modified by the user for local conditions, as their source codes are not normally available. On the contrary some models enable such adaptation e.g. WOFOST (Supit et al. 1994).

Two approaches of crop model evaluation

The models were calibrated for the three experimental sites by adapting soil, weather, management and crop model parameters into input files. Where available, the anthesis date was also used as evaluation parameter besides the two main characteristics i.e. duration of vegetation period (from sowing to maturity) and grain yield. The first approach of crop model evaluation was based on historical series with length from 7 to 24 years depending on data availability at individual sites. The evaluation of any model through an extensive time period enables to include the annual weather variability, which should be well reflected by the model (e.g. Colson et al. 1995). The second approach for model evaluation was based on one-year multiple treatment series. This possibility was used in our study in order to obtain a more complete picture of the model accuracy. Multiple treatment series over one or two years consist of trials which included one or more cultivars of a crop grown under different regimes of fertilization, crop rotation, sowing date or number of seeds per sq. meter etc. The purpose of this approach is to test whether the model can realistically reflect such modifications of the production technique during the same weather conditions (partly with exception of sowing date testing) and to gain perspectives on the model accuracy and sensitivity.

RESULTS AND DISCUSSION

CERES-Barley evaluation

The model evaluation results are based on observed data from three sites, i.e. in Domanínek 1985–1994, Kroměříž 1993–2000 and Žabčice 1974–1998. At the first locality data originate from trials of the State Institute for Supervision and Testing and Zemservis Test Station in Domanínek Ltd., data from locality Kroměříž were provided by the Agricultural Research Institute Kroměříž Ltd.

Table 3. Comparison of experimental (exp) and simulated (sim) length of vegetation period and grain yield (dry matter) of spring barley at Domanínek, Kroměříž and Žabčice

Locality		Domanínek		Kroměříž		Žabčice	
Experimental years		1985–1994		1993–2000		1974–1998	
Cultivars		Orbit		Akcent		KM 1992, Spartan, Bonus, Akcent	
		exp	sim	exp	sim	exp	sim
Vegetation period (days)	maximum	126	126	139	134	133	132
	mean	117	118	124	118	117	113
	minimum	103	110	113	108	102	103
	standard deviation	8.69	5.39	8.20	7.86	8.02	7.25
Yield ($kg.ha^{-1}$)	maximum	7530	7137	7165	7121	5736	6078
	mean	5387	5729	6096	6493	4606	5006
	minimum	4021	3848	5211	5350	3247	3796
	standard deviation	1084.63	998.13	663.26	683.96	679.22	635.62

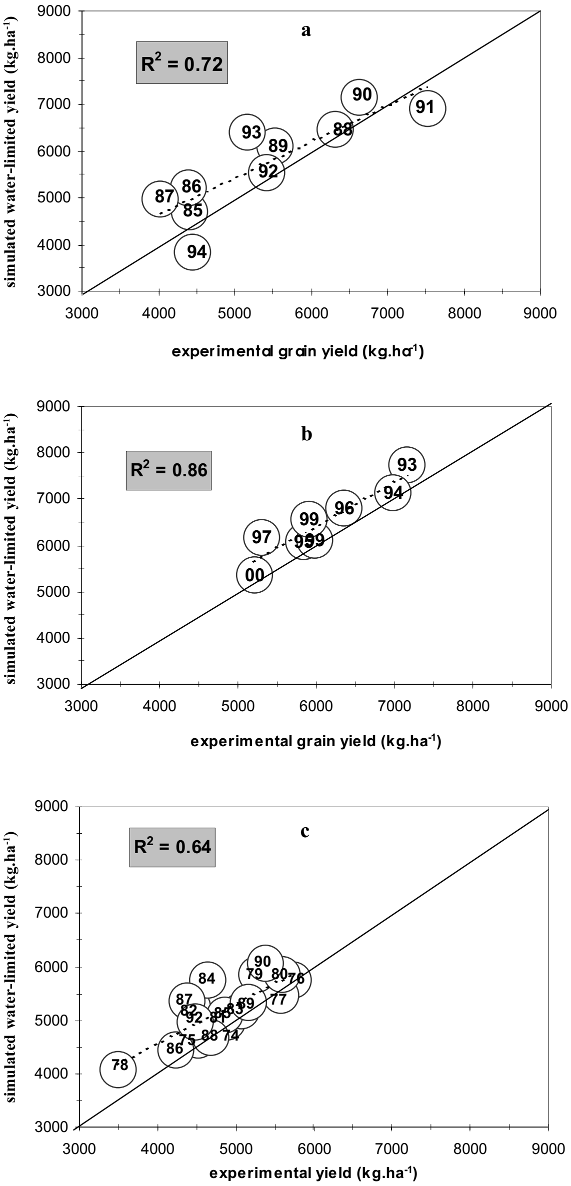

Figure 2. Evaluation of spring barley grain yield (dry matter) at a) Domanínek (cultivar Orbit), b) Kroměříž (cultivar Akcent), and c) Žabčice (cultivars: KM 1992, Spartan, Bonus, Perun and Akcent); the straight dashed lines in the figures represent the linear regression functions relating the observed and simulated grain yields; diagonal lines represent 1:1 ratio; the years are marked by numbers inside the circles

and at the third locality experimental data are based on final reports from long-term spring barley experiments, which were conducted by several Institutes of the Mendel University of Agriculture and Forestry in Brno. The simulated anthesis date could be validated for Domanínek and Žabčice only because the experimental data at Kroměříž were not available. The modeled results in Domanínek (Figure 1) well resemble the real data. The coefficient of determination calculated for Žabčice is lower and reaches 0.59 (not shown).

The duration of vegetation period (i.e. from sowing to maturity) could be used for model evaluation at all three sites. The coefficients of determination at the experimental sites in Domanínek and Kroměříž equalled to 0.86 and 0.83, respectively. The results in Žabčice were much worse showing the coefficient of determination of 0.34. There are three possible explanations for the unsatisfactory results of the phenological simulations:

1) Determination of the phenological development of the crop is greatly influenced by the individual experience of each researcher and even a relatively small error in the stage description can greatly influence the overall statistical results.
2) As the main driving force, apart from the phenological development, is the temperature, the error might be partly due to the distance between the trial and the meteorological station, which was originally about 2 km (the station was later re-installed directly on the experimental field).
3) The genetic coefficients could not be precisely estimated, as some cultivars were grown for short period of time. However, as one can see in Table 3, the absolute differences between the simulated and experimental values are only small. The simulated data show that the model mostly underestimates the length of vegetation period in Kroměříž and Žabčice.

The evaluation of the model using grain yield was successful in all three sites with the coefficients of determination ranging from 0.64 in Žabčice to 0.86 in Kroměříž, which is in an acceptable range as proposed by Básci and Hunkár (1994). The grain yield evaluations for three test sites are presented in Figure 2. As may be seen from Table 3, the variability of the experimental and simulated yields is very similar. It should be noted that the overall maximum experimental grain yield (during considered period) was recorded in 1991 in Domanínek but the model did not respond correctly in this year and the simulated yield underestimated the experimental one. The overall minimum grain yield was recorded in Žabčice in 1978 and also the model did not satisfactorily assess this extreme. Our conclusion is that the model is not sufficiently precise for simulations in years with extremely

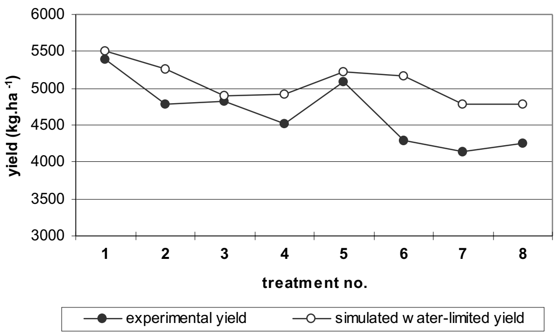

Figure 3. Evaluation of spring barley (cultivars Akcent and Orbit) grain yield (dry matter) at Domanínek in 2000; treatments are defined in Table 4

Table 4. Field experiment of spring barley (Akcent and Orbit cultivars), previous crop field pea, sowing density 400 seeds.m^{-2}, overview of the treatments

Treatment	Cultivar	Sowing date	N-fertilizer basic	N-fertilizer additional
			(kg.ha^{-1})	
1	Orbit	10. 4. 2000	70	
2	Orbit	10. 4. 2000	70	20
3	Orbit	21. 4. 2000	70	
4	Orbit	21. 4. 2000	70	20
5	Akcent	10. 4. 2000	70	
6	Akcent	10. 4. 2000	70	20
7	Akcent	21. 4. 2000	70	
8	Akcent	21. 4. 2000	70	20

high or low yields or some yield limiting factors were not well considered by the model that might limit reliability of the model in some cases.

To provide an example of one-year multiple treatment evaluation, the results of an experiment carried out during 2000 in Domanínek using two different cultivars (Akcent and Orbit), two sowing dates (difference of 11 days) and two levels of nitrogen fertilization (70 and 90 kg.ha^{-1}) are presented in Figure 3 and Table 4. As one can see, the model response to various treatments is limited, especially for different levels of nitrogen fertilizing. The insignificant difference between treatments with various levels of nitrogen input might be related both to the extreme weather conditions (unusually dry weather in April and May) and to the high level of available soil nitrogen on the experimental site. However, the model well reflected different sowing dates and the simulated number of grains per ear and also number of grains per sq. m. were simulated reasonably. As the simulated differences between individual treatments were relatively small and only irrelevant statistical relationship between simulated and experimental yields could be established, different kind of chart (compared to the previous ones) was used to visualize the trends in multiple treatment experiments (Figures 3 and 6). The model simulates yields with lower variability and thereby responds only to a certain extent to the different cultivars and date of sowing. On the other hand, the additional dose of nitrogen (20 kg.ha^{-1}) caused no change in the simulated yields, which could be explained by high level of soil nitrogen content at this locality.

CERES-Wheat evaluation

The model evaluation of CERES-Wheat was carried out also on the three experimental sites. The results from Žabčice were published by Žalud et al. (1999) and two of the new evaluations at Domanínek (1984–1997) and Kroměříž (1993–1999) are presented in this study (experimental data originated from the same sources as in case of spring barley for both localities). The evaluation of the phenological data was restricted only to duration of vegetation period as the anthesis dates were not available at neither of the two localities. As one may see in Table 5, the simulated duration of vegetation period was underestimated in both localities by 3 or 4 days on average. The values of standard deviation for experimental and simulated duration of vegetation period were very similar for both sites. However, virtually, no statistically significant relationship is revealed in Domanínek (coefficient of determination equals 0.14). This unsatisfactory outcome was caused partially by missing data of winter wheat anthesis dates, which made the process of the model evaluation more difficult. The second possible cause is that the CERES-Wheat model was not able to simulate correctly the effect of harsh and relatively long winters on wheat growth and development, which are typical for that site. This conclusion might be supported also by the fact that in the other two localities the statistical relationship between experimental and simulated duration of vegetation period was much better (coefficients of determination in Kroměříž equals 0.61 as may

Table 5. Comparison of experimental (exp) and simulated (sim) length of vegetation period and grain yield (dry matter) of winter wheat at Domanínek and Kroměříž

Locality		Domanínek		Kroměříž	
Experimental years		1984–1997		1993–1999	
Cultivar		Hana		Hana	
		exp	sim	exp	sim
Vegetation period (days)	maximum	315	316	300	303
	mean	306	303	293	289
	minimum	296	291	277	278
	standard deviation	6.87	6.31	7.16	8.33
Yield (kg.ha^{-1})	maximum	7370	7370	6426	6041
	mean	5677	6052	5444	5618
	minimum	4709	4751	4395	4998
	standard deviation	793.28	752.41	676.87	469.08

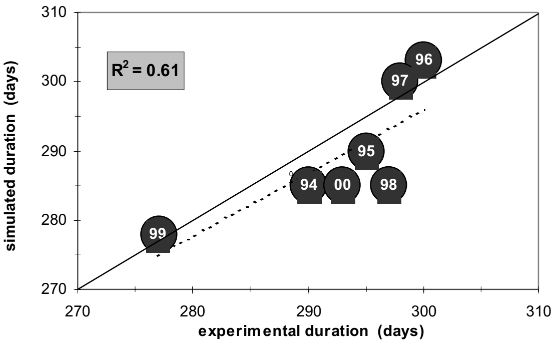

Figure 4. Evaluation of winter wheat (cultivar Hana), duration of vegetation period at Kroměříž; the straight dashed line represents the linear regression function relating the observed and simulated maturity date; diagonal line represents 1:1 ratio; the years are marked by numbers inside the circles

be seen at Figure 4). The differences between simulated and experimental yields are about the same as in similar studies made with cereals (Nonhebel 1994, Chipansky et al. 1997, Alexandrov et al. 2000, Eitzinger et al. 2000).

The evaluation of the model using grain yield was successful both in Kroměříž and Domanínek with coefficients of determination being 0.60 for Domanínek and 0.86 for Kroměříž. The grain yield evaluations for the two test sites are presented in Figure 5. The worse results of the grain yield evaluation and performance of the model in the potato growing production region (Domanínek) is closely connected with ability of the model to simulate correctly the influence of winter conditions on the overall performance of the crop. One may see in Table 5 that the variability of the experimental yields is higher than the variability of the simulated yields, which well corresponds with literature (e.g. Wolf 1993, Dubrovský et al. 2000).

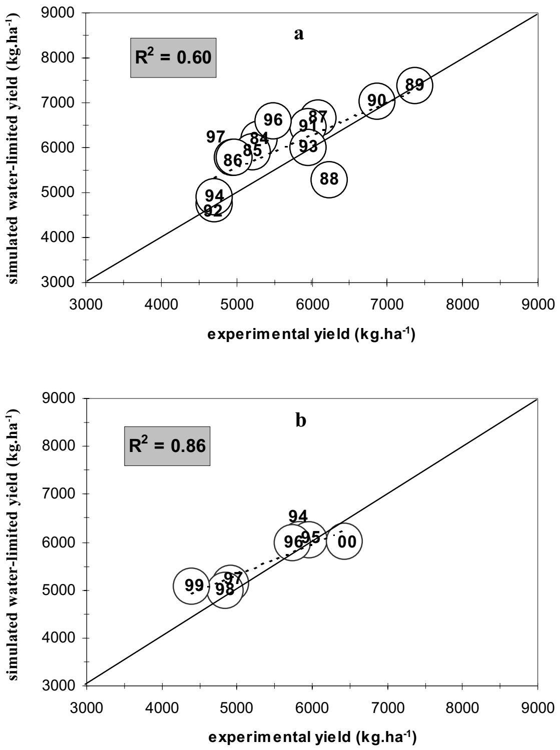

Figure 5. Evaluation of winter wheat (cultivar Hana) grain yield (dry matter) at a) Domanínek and b) Kroměříž; the straight dashed lines represent the linear regression functions relating the observed and simulated grain yields; diagonal lines represent 1:1 ratio; the years are marked by numbers inside the circles

The presented one-year multiple treatment experiment with winter wheat (cultivar Samanta), which was used for evaluation, was carried out during 1997/1998 in Kroměříž (Figure 6). The trial consisted of 10 treatments in total, including three sowing dates (differing by 15 and 35 days, respectively), previous crop (alfalfa, spring barley and maize), sowing density (250 and 350 seed.m^{-2}) and also in different levels of nitrogen fertilization (40 and 120 kg ha^{-1}). However, not all-possible combinations were tested (Table 6). The model correctly simulated the treatments 1, 2, 5, 7, 9 and 10. The simulations of the remaining treatments (3, 4, 6 and 8) were not successful because they were infested by *Psammotettix alienus*, which infected the winter wheat with semi persistent virus of winter wheat dwarfness. The pest survived in the crop residues of spring barley, which was the previous crop for these treatments. This disease significantly reduced yield of these treatments. These results clearly demonstrate the necessity of including pest and disease sub-models into crop models.

CONCLUSIONS

The results of this study confirm the possibility of the application of the CERES-Barley and CERES-Wheat models in the Czech Republic. Both models were successfully evaluated as far as the simulation of grain yield is concerned. The models tend to overestimate the grain yield under unsuitable growing conditions (i.e. when experimental yields are low) and to underestimate in years with unusually high yields. The simulation of the phenological development yielded mixed results. Reliability of the CERES-Barley model was high at all three localities.

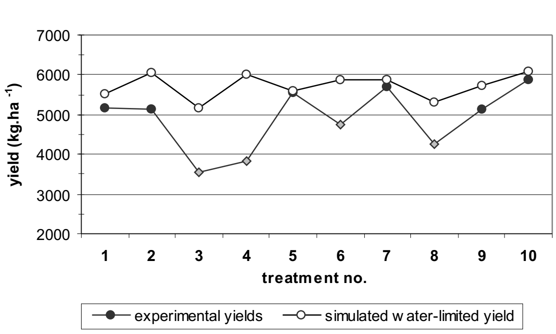

Figure 6. Evaluation of winter wheat (cultivar Samanta) grain yield (dry matter) at Kroměříž in season 1997/1998; treatments are defined in Table 6; treatments damaged by *Psammotettix alienus* are marked by gray rhombs

Table 6. Field experiment of winter wheat (Samanta cultivar), overview of the treatments (I. = basic N-fertilizing, II. = regeneration N-fertilizing, III. = production N-fertilizing)

Treatment	Previous crop	Sowing date	No. of seeds per m^2	N-fertilizer ($kg.ha^{-1}$)		
				I.	II.	III.
1	alfalfa	16. 9. 1997	250	40		
2	alfalfa	16. 9. 1997	250	40	40	40
3	spring barley	16. 9. 1997	250	40		
4	spring barley	16. 9. 1997	250	40	40	40
5	alfalfa	1. 10. 1997	350	40		
6	spring barley	1. 10. 1997	350	40	40	40
7	alfalfa	1. 10. 1997	350	40	40	40
8	spring barley	1. 10. 1997	350	40		
9	maize	21. 10. 1997	500	40		
10	maize	21. 10. 1997	500	40	40	40

The simulated values of the duration of vegetation period were slightly overestimated by the model in most years. On the other hand for CERES-Wheat the results were not satisfactory in Domanínek. The main reason could be found in the inability of the model to simulate correctly the effect of cold winter weather, especially at Domanínek, on wheat growth. Further research in this area is therefore needed in order to improve model calibration for better simulation of phenological development. Longer and more detailed historical data should be examined and further field trials should be carried out including e.g. continuous measurements of soil water and soil temperatures or LAI development.

Two methods for model evaluation were examined in this study. As it is apparent from the presented figures, the historical series approach enables to examine in detail the influence of interannual weather variability on crop yields and duration of phenological stages. The use of this method is necessary in order to evaluate properly all model-input data, especially those relating soil and plant physiology. However, experiments that were used for model evaluation were designed for other purposes than the model evaluation. This is the reason why some of the data, which are important in order to evaluate or improve the model, are not available (e.g. soil water and soil nitrogen content in the beginning of the vegetation period or anthesis date observations). Field experiments, which would be designed for the purpose of model evaluation, are expensive because of the time they require and the number of measurements that are necessary. In this sense the multiple treatment experiments (the second method) might be a suitable alternative. If such experiments are designed and executed properly, it can yield good database that could be used in the process of model evaluation. The differences between treatments might serve for testing the model sensitivity and for setting limits in which the use of the model is reasonable. Before there will be a sufficient amount of observational data from long-period trials with multiple treatments available in the Czech Republic, the combination of historical series and multiple treatment approach can be highly recommended for model evaluation. This evaluation procedure can minimize the disadvantages of each method and improve our ability to test a model in more details. Only carefully calibrated and evaluated models can be used for purposes of dynamic grain yield and harvest predictions, climate change impact studies, adaptation and sensitivity analyses, optimization of management performances (e.g. irrigation and fertilizing practices) and for other practical applications.

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ABSTRAKT

Evaluace modelů řady CERES v různých výrobních oblastech ČR

Byla provedena kalibrace a evaluace růstových simulačních modelů CERES-Barley a CERES-Wheat. Experimentální plochy, na kterých byly modely ověřovány, představují zástupce tří různých výrobních oblastí (kukuřičné, řepařské a bramborářské) s nadmořskou výškou 179, 204 a 560 m n. m. Byly využity dva různé přístupy pro evaluaci hodnot výnosu zrna, termínů kvetení a plné zralosti. U prvního se pracuje s časovou řadou údajů získaných z dlouhodobých pokusů, a je tak schopen zachytit vliv meziroční variability počasí na vývoj a výnos modelované plodiny, druhý využívá výsledků jednoletých experimentů s více opakováními, kde je evaluace prováděna u různých variant, odlišujících se datem setí, množstvím aplikovaného dusíkatého hnojiva či jiným agrotechnickým opatřením. U obou modelů bylo dosaženo evaluace u výnosu, jak ukazují hodnoty koeficientu determinace pro dlouhou časovou řadu, které se pohybují v rozmezí hodnot 0,69 a 0,86 u modelu CERES-Barley pro všechny tři experimentální oblasti a hodnot 0,60 a 0,86 na dvou experimentálních místech u modelu CERES-Wheat. Nižší koeficient determinace u modelu CERES-Wheat byl zaznamenán na lokalitě s nejvyšší nadmořskou výškou a nejnižšími teplotami v zimním období. Zde bylo také dosaženo nejhorších výsledků při simulaci fenologického vývoje. Na druhé lokalitě testované modelem CERES-Wheat a na třech lokalitách, u nichž byl použit model CERES-Barley, vykazovaly simulovaná doba trvání doby vegetace a data kvetení vysokou statistickou průkaznost. Jednoleté experimenty s více opakováními prokázaly svůj význam při posuzování citlivosti modelů k agrotechnickým zásahům. Kombinace obou přístupů se zdá nejlepším řešením při evaluaci podobných růstových modelů.

Klíčová slova: jarní ječmen; ozimá pšenice; růstový model; evaluace

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