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Evaluating SHOOTGRO 4.0 as a potential winter wheat management tool in the Czech Republic

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Abstract

Improving current cultural practices often involves more precise timing of the management activity based on crop development. Using crop simulation models to predict crop development and phenology has several problems. First, most existing models do not simulate sufficient developmental and phenological detail required to optimize selected management practices. Second, crop models normally emphasize the cultivars and conditions for the region in which they were developed, and may not generate satisfactory results when applied in new regions. Lastly, when users apply these models to new regions they often lack the specific data and knowledge of the model to adequately determine the crop parameters. Our objective was to assess whether the simulation model SHOOTGRO 4.0, which had the necessary level of developmental and phenological detail required for use as a management decision aid, could be easily and adequately parameterized to simulate winter wheat phenology and grain yield in the Czech Republic. We found that only a few parameters from the generic winter wheat cultivar used for the Central Great Plains in the USA needed to be changed, and the information needed to determine these few parameters were readily obtainable. The result was that the dates of anthesis and physiological maturity and final grain yield were predicted well at sites within the three major crop production regions of the Czech Republic. Sensitivity analysis also showed that the most sensitive management practices and initial conditions in SHOOTGRO are relatively easy to determine (e.g. sowing date, N fertilizer rate and timing, daily temperature), while it is not overly sensitive to those variables more difficult to determine (e.g. initial soil water in the profile). Based on this study, farmers and scientists needing wheat development information to increase the efficacy of their management practices can use SHOOTGRO 4.0 as a tool.
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Keywords: Winter wheat; Crop model; Validation; Phenology; Yield

1. Introduction

The development of precision agriculture coupled with the recognition that many management practices need to be supported by real-time crop development and phenological information is

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resulting in increased interest in using crop simulation models as, or as part of, decision aids. Efforts to optimize planting dates and rates, select cultivars, forecast harvest dates, and increase the efficacy of management practices involving herbicides, fertilizers (especially split application practices), and irrigation have underscored the need for accurate predictions of crop development to aid in these decisions. The approach is to maximize the desired plant response by optimizing the timing of the management practice at the critical growth stage(s) for determining yield. As our understanding of wheat (*Triticum aestivum* L.) development has increased, many developmental events occurring at the shoot apical meristem such as single and double ridges, terminal spikelet, beginning of internode elongation, and appearance of the flag leaf have been identified as critical in determining yield potential (McMaster, 1997).

Over 70 models predicting wheat yield were identified in 1993 (McMaster, 1993), and the number has grown substantially since. Many of these models have been used to examine the impact of certain management practices (e.g. N fertilizer rates, planting dates, harvest date) on yield with current or changed climate conditions (e.g. Iglesias, 1995; Moot et al., 1996; McMaster and Wilhelm, 1997a; Wolf, 1993; Žalud, 1999; Dubrovský et al., 2000). Most of these models would be characterized as carbon- or energy-driven models, and developmental and phenological detail has not been emphasized. As a result, with management practices increasingly focused on finer resolution of developmental and phenological detail, these models are of limited use for these applications.

A few mechanistic models, such as SHOOTGRO (McMaster et al., 1991, 1992a,b; Wilhelm et al., 1993), MODWht (Rickman et al., 1996), AFRCWHEAT (Weir et al., 1984), and SIRIUS (Jamieson et al., 1998), incorporate considerable developmental and phenological detail. These models address the need for greater resolution in simulating development to aid optimizing management practices. SHOOTGRO and MODWht predict development and growth of the canopy and subsequent yield by using temperature, the primary factor controlling wheat development (McMaster, 1997), to simulate developmental events occurring at or near the shoot apical meristem (e.g. leaf, tiller, spikelet, and floret primordium initiation and growth). This approach provides a complete picture of all sources and sinks present in the canopy at any time and a thorough (realistic) representation of the distribution of developmental stages of all shoot apices comprising the entire canopy.

An older version of the SHOOTGRO model (version 2.0) showed promise in simulating phenology of all growth stages for a range of conditions and cultivars in the Central Great Plains of the United States (McMaster et al., 1992b). The current unpublished version (4.0) has incorporated the effects of water and N stress on phenology, which should allow SHOOTGRO to better predict wheat phenological responses to management practices and, therefore, aid in optimizing these practices.

Developmentally-driven models, such as SHOOTGRO, MODWht, AFRCWHEAT, and SIRIUS, expand the suite of existing models available to users for different purposes, but two problems in adapting these models, and all models, still must be addressed: parameterizing and evaluating them for conditions and cultivars outside of their region of development. Almost all simulation models were developed within a few countries or regions (US, Western Europe, Australia, and New Zealand) for their conditions and cultivars. Users from other countries where conditions and cultivars differ must first determine what is needed to adequately parameterize the model for their situation, and then evaluate the model predictions under the new conditions. Occasionally, partial sensitivity analysis is performed to evaluate the importance of selected inputs and parameters on output, but rarely do these analyses explore the mechanisms for the model response.

Our objective was to assess whether the simulation model SHOOTGRO 4.0, which had the necessary level of developmental and phenological detail required for use as a management decision aid, could be easily and adequately parameterized to simulate winter wheat phenology and grain yield in the Czech Republic. To achieve this objective, we validated the previously untested

modifications to the phenology submodel of version 2.0 and yield prediction. We also conducted sensitivity analyses to assess the value of more accurate parameter estimation or inputs than was done for our limited parameterization and examine model sensitivity and response to certain management practices (e.g. planting date and amount, N fertilizer amount and timing) and environmental conditions (e.g. temperature, initial soil water) in predicting winter wheat phenology and yield.

2. Materials and methods

2.1. SHOOTGRO 4.0 overview

SHOOTGRO 4.0 is a phenologically driven model that simulates development and growth of the shoot apex of wheat and barley (*Hordeum vulgare* L.) for up to six cohorts (or age classes) of plants based on the time of seedling emergence. The appearance, growth (both size and weight), and abortion/senescence of each leaf blade and sheath, node, internode and spike component (spikelet, floret, kernel, rachis, and floral bracts) on each morphologically identified leaf, culm, and spike component (Klepper et al., 1983; Wilhelm and McMaster, 1996) are simulated for each age class. Model output includes the date each culm of each age class reaches each growth stage or shoot apex developmental event and summaries of developmental and physiological processes such as organ size (length, width, biomass), yield, yield components, tiller and spike number, LAI, and N concentration in each plant component or culm. The CERES-Wheat (Ritchie and Otter, 1985) soil water and N submodels are used and require initial soil conditions for each layer such as bulk density, pH, organic C, initial soil water content, NO_3, and NH_4 concentrations. Daily meteorological variables required are maximum and minimum temperature, precipitation, and solar radiation.

For wheat and barley, temperature is the primary factor controlling development (McMaster, 1997). Thermal time is used to determine developmental rates. Growing degree-days (GDD) are used to estimate thermal time using Method 1 of McMaster and Wilhelm (1997b) and the base temperature is set to 0 °C (McMaster, 1997; McMaster and Smika, 1988). Rather than using static estimates of GDD for thermal time requirements for developmental and growth processes, SHOOTGRO bases many processes on the phyllochron, or rate of leaf appearance. The phyllochron is calculated at the time of seedling emergence of each cohort from the change in day length using the equation of Baker et al. (1980), which was the most accurate of nine equations available for calculating the phyllochron for winter wheat (McMaster and Wilhelm, 1995).

SHOOTGRO 4.0 has been changed from SHOOTGRO/SPIKEGRO 2.0 (McMaster et al., 1991, 1992a,b; Wilhelm et al., 1993) in several ways. Simulating spring wheat and spring barley has been added as well as an algorithm for simulating rooting depth based on GDD accumulation. Most importantly for this manuscript, the effects of water and N stress on phenology were incorporated. Version 2.0 used only thermal time for estimating growth stages. However, for wheat and barley, phenological growth stages are reached earlier under water and N stress once a threshold level of the stress is achieved (e.g. McMaster, 1997; McMaster and Smika, 1988; McMaster et al., 2002). Therefore, the phenology submodel was modified so that once the water and N resource 0-1 index factors (multiplied together) were less than 0.8, the required phyllochrons (or GDD) were linearly reduced until a maximum of 20% reduction was achieved.

2.2. Crop production regions of Czech Republic

Wheat is grown in three crop production regions within the Czech Republic. These regions are characterized by different climates, topographies, and primary crops (Table 1). Maize (*Zea mays* L.) is the primary crop grown in Region 1 (Žabčice, southern part of the Moravia region) with Oxyaquic Cryofluvent soils with topsoils of clay loam and silty clay textures. Sugar beet (*Beta vulgare* L.) is the primary crop grown on loam soils (Luvi Haplic Chernozem) of Region 2 (Kroměříž, the Upper-Moravian region). Region 3 (Domanínek, Bohemian-Moravian Uplands) is the potato (*So-*

Table 1
Characteristics of the experimental fields located in the three crop production regions of the Czech Republic

Characteristic	Site 1	Site 2	Site 3
Location	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	Qxyaqic Cryofluvents	Luvi Haplic Chernozem	Cambisol with sandy-loam
Mean annual temperature (°C)	9.2	8.6	6.5
Mean temperature (April–September, °C)	15.7	15.1	12.8
Mean annual precipitation (mm)	480	599	651
Mean precipitation (April–September, mm)	312	389	396
Range of annual accumulated global radiation (MJ m^{-2})	3584–4312	3601–4228	3213–3843

Meteorological data were collected from 1961 through 1990.

lanum tuberosum L.) production region with Cambisol sandy loam soils that have three diagnostic horizons. Elevation and precipitation increase and temperature decreases from Region 1 to 3. SHOOTGRO 4.0 was evaluated for one site in each region.

2.3. Setting up SHOOTGRO 4.0 for simulation runs

Setting up SHOOTGRO 4.0 for simulation runs requires that appropriate crop parameters are selected for the cultivar, the initial conditions at the beginning of the simulation are set, and the required driving variables and inputs are provided. Methods for data collection related to initial conditions and driving variables are provided in Section 2.4.1 (Model validation). Four soil layers were used in the simulation 0–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.8 m.

To assist in setting crop parameters, generic meteorological and pedologic data files were created to aid in crop parameterization and for sensitivity analysis. Temperature and precipitation data were measured from 1961 through 1990 at each field site. Global radiation was partly obtained by measurements using a CM 6B pyranometer (WMO first class standard, produced by Kipp and Zonen company, Delft Holland[3]) and partly computed for Site 1 (Rožnovský and Svoboda, 1995), Site 2 (Střalková et al., 1998), and Site 3 (Trnka, 1999). To create the generic meteorological data sets for each region, long-term temperature, precipitation, and global radiation means were used from the above data.

Little information was available for the cultivar Hana, so parameters for a generic winter wheat plant (derived for US cultivars) were used for most crop parameters. To modify the phenological parameters, the typical planting date and day of jointing, anthesis, and physiological maturity for each site was estimated by agronomists from the Czech Republic Agricultural Office. Then using the generic weather files, thermal time between growth stages was calculated using Method 1 of McMaster and Wilhelm (1997b) and base temperature was set to 0 °C (McMaster, 1997; McMaster and Smika, 1988). Other growth stages (e.g. tiller initiation, single and double ridge, terminal spikelet, beginning of internode elongation, booting, heading) were based on the typical relationships found for wheat cultivars (McMaster, 1997). The only other parameters modified

[3] Product names are mentioned for information purposes and do not represent endorsement by the authors or USDA.

were the rates of spikelet and floret primordium initiation so that the maximum final number of simulated spikelets per spike and florets per central spikelet equated the observed values based on the opinion of agronomists from the Czech Republic Agricultural Office.

2.4. Model evaluation

Model evaluation consisted of two components: validation and sensitivity analysis.

2.4.1. Model validation

Wheat is grown in all three crop production regions of the Czech Republic. To validate SHOOTGRO 4.0 for the diverse production regions, meteorological, pedological, crop, and management data were collected from an experimental field in each crop production region (Table 1). Experimental methods followed the official methodology for the field trials outlined by the Czech Central Institute for Supervision and Testing and were under its constant supervision.

One field trial for each region was conducted in 1998–1999, using the semi-dwarf, hard-red winter wheat cultivar Hana at each of the three sites. The experimental design was a randomized complete block, with four replications. Treatments at each location consisted of previous crop (barley or alfalfa, *Medicago sativa* L.), planting date (two dates at each site; Site 1: 258 and 281 day of year (DOY); Site 2: 259 and 274 DOY, Site 3: 277 and 282 DOY), planting rate (250 or 400 seeds per m^2), and nitrogen fertilizer rate and timing (40 kg N ha^{-1} applied in autumn or 40 kg N ha^{-1} applied in autumn and 80 kg N ha^{-1} applied in the spring).

An automated meteorological station was used to collect daily weather data at the field trial at Site 1. Meteorological data for the field trials at Sites 2 and 3 were collected by a World Meteorological Organization (WMO) standard meteorological station. Pedological parameters such as bulk density, organic carbon, lower limit of plant extractable water, drained upper limit, saturated water content, and bare soil albedo were obtained from soil cores at planting or direct measurements at each experimental site. Soil cores used for these assays were collected to 1.8 m and divided into 0.1 m sections for analysis. Other soil parameters such as pH, NO_3, and NH_4 were based on long-term means for each site. The date when 2/3 of the culms reached anthesis (Zadoks growth stage 61; Zadoks et al., 1974) and physiological maturity were based on daily observations of 0.5 m^2 in each plot (about 325 spikes per plot). Physiological maturity was determined as the complete loss of green color in all spike components. Yield measurements were obtained by plot combine.

Four statistics were used to evaluate simulation results: (1) paired t-test to determine if differences existed between observed and simulated values; (2) simple linear regressions were computed to determine the r^2-value between observed and simulated data; (3) percentage of predicted dates plus or minus 7 days of the observed growth stage date or percentage of simulated yields plus or minus 20% of the observed yield; and (4) root mean square error (RMSE), with associated sum of the residuals (SRES) and sum of the absolute residuals (SARES) as described by McMaster et al. (1992b). The RMSE, SRES, and SARES measures give an indication of the variability around the mean and tendency for prediction bias.

2.4.2. Sensitivity analysis

Sensitivity analysis evaluated model grain yield and phenological responses to selected management practices and environmental conditions. A unique weather file based on long-term temperature, precipitation, and solar radiation for each site was created. Parameters or model inputs were increased and decreased by specified increments over a broad range and corresponding model phenological responses (emergence, first tiller, initiation of stem elongation, jointing, booting, heading, anthesis, and physiological maturity) and crop growth characteristics (grain yield, above ground biomass, harvest index, number of culms and spikes, and LAI) noted.

Phenological parameters for the thermal time between growth stages were varied by 50 GDD (for grain filling duration) or 0.1 phyllochrons (for all other growth stage intervals). Planting date was varied by 5 days, sowing rate by 50 seeds per m^2, daily maximum and minimum air temperature

decreased and increased by 1 °C increments until altered by −4 and +4 °C, and fall N fertilizer by 5 kg N ha^{-1} increments beginning with no fertilizer and ending at 85 kg N ha^{-1}. The timing of N fertilizer application was based on three possible application times with each application time applying 40 kg N ha^{-1} for Sites 1 and 2 and 45 kg N ha^{-1} for Site 3. The first application time was pre-sowing in the fall [DOY 271, 273, and 282 for Sites 1–3, respectively] and two application times in the spring. The early spring application time was DOY 55, 64, and 104, respectively, and the late application time was DOY 110, 125, and 139 for Sites 1–3, respectively. Initial soil water content for the profile was simulated for three levels designated 'low' (decreasing the 'medium' levels by 10%), 'medium' (determined by 'normal' levels typically observed at the time of planting, and 'high' (equal to field capacity water content).

From the variety of sensitivity indices available we chose the following sensitivity index based on Deer-Ascough (1995):

$$S = \left(\frac{O_{\text{base}} - O_{\text{i}}}{O_{\text{base}}}\right) \Big/ \left(\frac{I_{\text{base}} - I_{\text{i}}}{I_{\text{base}}}\right)$$

where S is the sensitivity index for the specific variable, I_{base} is the default or initial value for the specific input variable about which it is changed, I_{i}, is the specific value of the input variable that is incremented from I_{base}, O_{base} is the output variable value for the I_{base} input, and O_{i} is the output variable value for the I_{i} input.

The sensitivity index was calculated for each incremental change in the input variable tested ($= I_{\text{i}}$), and the associated O_{i} used in the equation listed above. We chose grain yield and date of emergence, jointing, anthesis, and physiological maturity as the output variables.

3. Results and discussion

3.1. Validation

Regardless of the measure used to assess the simulation accuracy of SHOOTGRO in predicting anthesis and physiological maturity (RMSE, r^2, paired t-test, or percentage of points within some error estimate), SHOOTGRO was able to simulate the date of anthesis and physiological maturity well for each site in all three regions, with equal prediction accuracy for all sites. The SRES and SARES indicated no model bias towards predicting anthesis and physiological maturity earlier or later. Maturity was predicted slightly better than anthesis regardless of measure used for this analysis (number of points within 7 days, RMSE, r^2, or paired t-test).

The phenological simulation results are encouraging that SHOOTGRO can be useful in predicting growth stages in the Czech Republic with little effort needed to parameterize the model. In our evaluation work, parameterization of phenological parameters of SHOOTGRO consisted of using only the general dates of jointing, anthesis, and maturity of generic wheat cultivars in each production region obtained from agronomists familiar with the region. The successful results of this are denoted by open diamond symbols falling on the 1:1 line in Figs. 1 and 2. This suggests that SHOOTGRO can be used to predict phenological growth stages for specific cultivars with readily available information, and therefore, assist in optimizing management decisions.

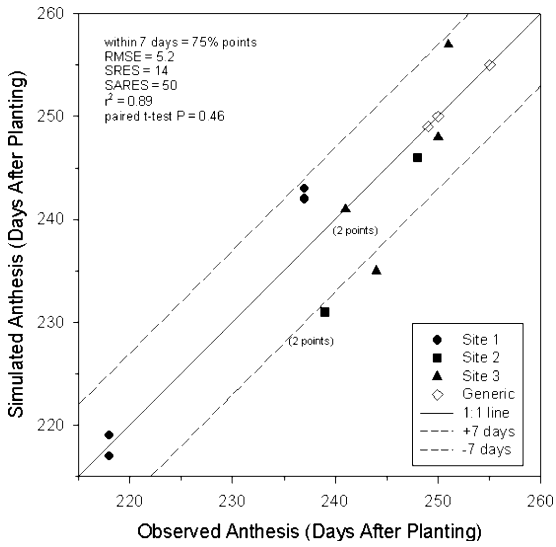

Fig. 1. Observed vs. simulated day of anthesis.

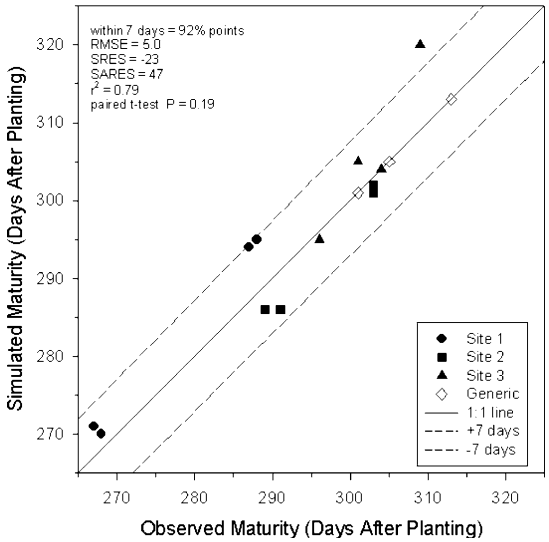

Fig. 2. Observed vs. simulated day of physiological maturity.

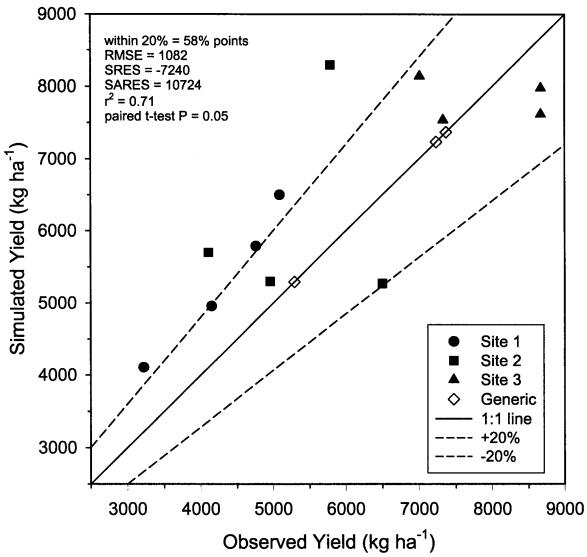

Fig. 3. Observed vs. simulated yield.

Grain yield predictions were not as good as growth stage predictions, although the r^2 was 0.71 (Fig. 3). Model bias was towards over-predicting yield at sites of Sites 1 and 2. The over-prediction of yield might be reduced if more effort is put into parameterization and increasing the accuracy of the initial conditions and driving variables. No other parameterization was done of SHOOTGRO aside from the phenological parameters and setting parameters for the maximum number of spikelets and florets per spikelet expected by agronomists from the region. The validation data set also was missing information for some initial inputs (soil and water parameters). Given the considerable difference between cultivars and growing conditions between the Central Great Plains of the US and Czech Republic, the yield simulations results are quite good.

3.2. Sensitivity analysis

3.2.1. Phenological parameters

Changing the thermal estimates between various growth stages resulted in low mean sensitivity indexes for almost all output variables (including those not shown in Table 2 such as above ground biomass, number of culms and spikes produced, harvest index, and maximum LAI), regardless of site. For all phenological parameters changed (including those not shown in Table 2 such as the thermal time between jointing and booting, booting and heading, and heading and anthesis), the only output variable showing any significant model sensitivity was the date of physiological maturity to changing the thermal time for grain filling (MATPA).

Analysis of individual sensitivity index calculations for each incremental change in the thermal estimates did not identify any unusual patterns (data not shown). Using MATPA (number of GDD from anthesis to physiological maturity) to illustrate the most unusual pattern, the individual sensitivity index for all three sites usually was within 0.2–0.3, with most values close to 0.25 (Fig. 4). The model was more sensitive at higher thermal estimates, although no pattern was discernable, especially when viewed across sites.

Changing phenological parameters did change the mean date that specific growth stages were reached for all stages occurring after the interval changed, as would be expected. Again using MATPA to illustrate this, the date of physiological maturity was linearly and positively related to thermal time for grain filling (Fig. 4).

Given that SHOOTGRO is not overly sensitive to changing thermal time estimates, and that we

Table 2
Means of sensitivity index calculations for the three sites. Last three columns are qualitative assessments because index could not be calculated

Output variable	Variable changed										
	SRPA[a]	DRPA[a]	TSPA[a]	JTPA[a]	MATPA[b]	Sowing date	Sowing rate	N fertilizer amount	Maximum/ Minimum air temperature	Initial soil water	N fertilizer timing
Site 1											
Yield (T ha^{-1})	−0.1	−0.01	0.02	−0.1	0.04	2.58	0.05	0.12	High	Low	High
Emergence (DOY)	0	0	0	0	0	1.35	0	0	High	None	None
Jointing (DOY)	0.1	0.06	0.07	0.06	0	−0.2	0	0	High	None	None
Anthesis (DOY)	0.07	0.03	0.04	0.03	0	0	0	0	High	None	Low
Maturity (DOY)	0.03	0.02	0.03	0.02	0.29	−0.1	0	0	High	None	Low
Site 2											
Yield (T ha^{-1})	−0.14	−0.03	−0.07	−0.11	0.05	1.96	0.18	0.07	High	Low	High
Emergence (DOY)	0	0	0	0	0	1.55	0	0	High	None	None
Jointing (DOY)	0.11	0.06	0.09	0.06	0	−0.13	−0	0	High	None	None
Anthesis (DOY)	0.05	0.03	0.05	0.03	0.02	−0.09	−0.02	0	High	None	Low
Maturity (DOY)	0.04	0.02	0.03	0.02	0.23	−0.07	−0.01	0	High	None	Low
Site 3											
Yield (T ha^{-1})	−0.23	0.03	0.07	0	0.04	0.94	0.22	0.40	Medium	Low	High
Emergence (DOY)	0	0	0	0	0	5.55	0	0	High	None	None
Jointing (DOY)	0.08	0.05	0.07	0.05	0	−0.58	−0.01	0.01	High	None	Low
Anthesis (DOY)	0.05	0.03	0.05	0.03	0	−0.96	−0.02	0.02	High	None	Low
Maturity (DOY)	0.03	0.02	0.03	0.02	0.24	−0.58	0	0.01	High	None	Low

[a] Number of phyllochrons from 1st January to single ridge (SRPA), single ridge to double ridge (DRPA), double ridge to terminal spikelet (TSPA) and start of internode elongation to jointing (JTPA).
[b] Number of GDD from anthesis to physiological maturity (MATPA).

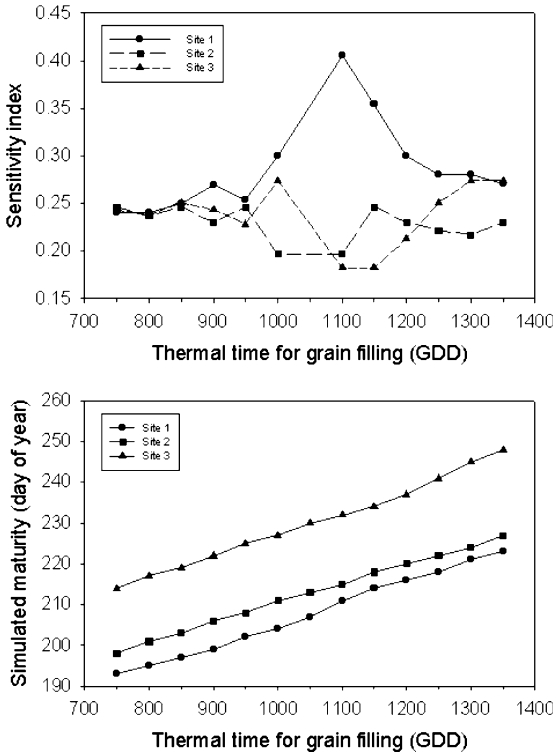

Fig. 4. Sensitivity analysis results and simulated maturity date for changing the thermal time required for grain filling (MATPA). Thermal time is the cumulative GDD using 0 °C base temperature from the start of anthesis to physiological maturity.

were able to validate the growth stages of anthesis and physiological maturity well with a few readily available parameterization data, we believe that SHOOTGRO can be readily used in the Czech Republic to predict growth stages as an aid in management decision-making.

3.2.2. Management practices and initial conditions

For all three sites, SHOOTGRO was most sensitive to changes in sowing date and daily temperature and insensitive to soil water in the profile at planting (Tables 2–5). Model sensitivity to sowing rate and N fertilizer amount and timing tended to be moderate, but was somewhat variable dependent on the site. If the model showed sensitivity to a management practice or initial conditions, predicted yield always reflected this sensitivity and was generally the variable showing the greatest response. The only exception to this generality was at Site 3, when varying sowing date or daily temperature, in which case, predicted emergence showed a greater response than yield. (The other output variables examined were above ground biomass, number of culms or spikes, harvest index, and LAI; data not shown).

Simulated yield response to different levels of management practices and initial conditions generally followed the expected pattern. For sowing date, if planting occured much before our default date, then yield was reduced (Fig. 5). At both Sites 2 and 3 yield plateaued with late planting dates, and the default date was at or near the maximum plateau. Model results indicate that planting date should be delayed a little if maximum yield is the goal for Site 1. Changing the daily temperature gave similar grain yield responses in each site: as temperature increased yield decreased (Table 3). Sowing rate had relatively little effect on grain yield at Sites 1 and 2, although the trend for all sites was a positive correlation between sowing rate and yield, with the correlation most positive for Sites 2 and 3 (Fig. 6). The results support that sowing rates are near optimum for Sites 2 and 3, and could be decreased at Site 1. Grain yield responses to N fertilizer amount were positively correlated, with Site 3 showing the greatest response. Our default fertilizer amount of 40 kg N ha^{-1} seems to be near optimal for Sites 1 and 2, and a little low for Site 3. The timing of N fertilizer on grain yield (Table 5) depended primarily on the total amount applied for Sites 1 and 2, with little response to timing. Although probably not a significant difference, simulated yield for all three sites was slightly greater for the split applications when the latest spring application time was used. This result suggests that delaying the second application will not negatively impact yield, but allows the producer additional time to better estimate the N needed based on current conditions of the crop. This will improve the likelihood of not over-applying N, and thereby save the cost of unnecessary fertilizer and potential environmental degradation of excess N. Soil water in the profile at planting had little, if any, impact on final grain yield (Table 4). There was a tendency for final grain yield to be slightly positively correlated with

Table 3
Sensitivity analysis of changing the daily maximum and minimum air temperature from −4 to 4 °C

Simulated variable	Daily maximum and minimum temperature change (°C)								
	−4	−3	−2	−1	0	−1	+2	+3	+4
Site I									
Yield (T ha^{-1})	6.10	5.87	5.79	5.18	4.68	4.63	4.82	4.97	4.66
Emergence (DOY)	289	287	285	283	282	281	280	280	279
Jointing (DOY)	145	139	133	127	120	113	105	96	88
Anthesis (DOY)	185	177	169	162	155	148	140	133	126
Maturity (DOY)	244	236	226	216	207	198	190	182	173
Site 2									
Yield (T ha^{-1})	7.20	7.45	6.67	6.98	6.40	6.18	6.18	6.30	6.10
Emergence (DOY)	295	290	288	286	285	284	283	282	282
Jointing (DOY)	149	142	136	130	123	115	107	97	89
Anthesis (DOY)	191	183	174	166	158	151	143	135	128
Maturity (DOY)	275	265	250	239	213	209	204	198	189
Site 3									
Yield (T ha^{-1})	6.78	6.71	6.53	7.13	6.51	6.61	6.36	6.09	5.59
Emergence (DOY)	122	111	96	32	309	303	299	297	295
Jointing (DOY)	159	149	137	134	134	129	123	117	109
Anthesis (DOY)	194	183	179	172	172	165	159	152	142
Maturity (DOY)	251	242	237	230	230	221	213	204	194

soil water at planting. Similar results were estimated by Šťastná and Žalud (1999) with the help of the MACROS and CERES models for grain maize.

The only instances where phenological output variables showed sensitivity to management practices and initial conditions were for sowing date and changing the daily temperature. These results would be expected from field studies. Since temperature is the primary factor controlling development (McMaster, 1997), and changing the daily temperature alters the rate of thermal accumulation, phenological output variables should be affected. Delaying the sowing date has the same impact on thermal accumulation as sowing in a season with cooler temperatures in the fall so that heat units accumulate more slowly. We should note that delayed sowing, and sowing at normal dates but during a season with abnormally cool temperatures, will not have the same impact on wheat development as may be implied by the previous statement. The impact of shorter daylengths with delayed sowing on the phyllochron (shorter phyllochron) interacts with the slower rate of accumulation of thermal time, in general, to result in the interaction having less impact on wheat development than on thermal time accumulation. The reduced effect on post-winter growth stages reflects the secondary influence of fall development on post-winter phenology, especially anthesis and physiological maturity.

These results are encouraging as the management practices and initial conditions that SHOOTGRO is most sensitive to are relatively easy to determine (e.g. sowing date, N fertilizer rate and timing, daily temperature), while SHOOTGRO is not overly sensitive to variables that are more difficult to determine, such as initial soil water in the profile. One caveat to this generalization is that if the specific cultivar grown differs significantly from the generic cultivar used, then adjusting the

Table 4
Sensitivity analysis of changing the initial amount of soil water in the profile at planting (0–1.8 m). The 'medium' values were based on several years of observed data, the 'low' values were decreasing the observed data by 10%, and the 'high' values were for saturated water content

Simulated variable	Site 1			Site 2			Site 3		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Emergence (DOY)	282	282	282	285	285	285	309	309	309
First tiller (DOY)	306	306	306	315	315	315	104	104	104
Begin stem elongation (DOY)	113	113	113	115	115	115	127	127	127
Jointing (DOY)	120	120	120	123	123	123	134	134	134
Booting (DOY)	142	142	142	145	145	145	158	158	158
Heading (DOY)	150	150	150	154	154	154	167	167	167
Anthesis (DOY)	185	185	185	158	158	158	172	172	172
Physiological maturity (DOY)	207	207	207	213	213	213	230	230	230
Yield (T ha^{-1})	4.62	4.66	4.68	6.35	6.38	6.38	6.52	6.67	6.51
Total culms produced per m^2	1847	1841	1843	1841	1857	1849	1285	1293	1286
Final number of spikes per m^2	553	556	559	549	553	552	501	501	501
Harvest index	0.42	0.42	0.42	0.49	0.45	0.45	0.61	0.61	0.61

Table 5
Sensitivity analysis of changing the timing and amount of N fertilizer (kg K ha^{-1}). Nitrogen application was at one of three times, with the first position denoting a pre-sowine application (DOY 271, 273 and 282 for Sites 1–3, respectively), and the second (DOY 55, 64 and 104 for Sites 1–3, respectively), and third positions (DOY 110, 125 and 139 for Site 1–3, respectively) denoting spring applications

Simulated variable	Site 1				Site 2				Site 3			
	40 - -	40 40 -	40 40 40	40 - 40	40 - -	40 40 -	40 40 40	40 - 40	45 - -	45 45 -	45 45 45	45 - 45
Emergence (DOY)	282	282	282	282	285	285	285	285	309	309	309	309
First tiller (DOY)	306	306	306	306	315	315	315	315	108	108	105	105
Begin stem elongation (DOY)	113	113	113	113	115	115	115	115	127	127	128	128
Jointing (DOY)	120	120	120	120	123	123	123	123	134	134	136	136
Booting (DOY)	142	142	143	143	145	145	146	146	157	157	159	159
Heading (DOY)	150	150	151	152	154	154	155	155	167	168	168	168
Anthesis (DOY)	155	155	156	156	158	358	160	160	171	172	173	173
Physiological maturity (DOY)	207	207	208	208	213	213	214	214	229	233	230	230
Yield (T ha^{-1})	4.44	5.36	5.43	6.05	6.4	7.1	8.27	7.31	5.17	6.51	7.89	6.68
Total culms produced per m^2	1771	2051	2051	1843	1852	2033	2033	1852	1286	1286	1334	1334
Final number of spikes per m^2	544	592	612	583	552	585	616	571	501	501	501	501
Harvest index	0.43	0.40	0.39	0.41	0.45	0.44	0.45	0.45	0.60	0.61	0.58	0.57

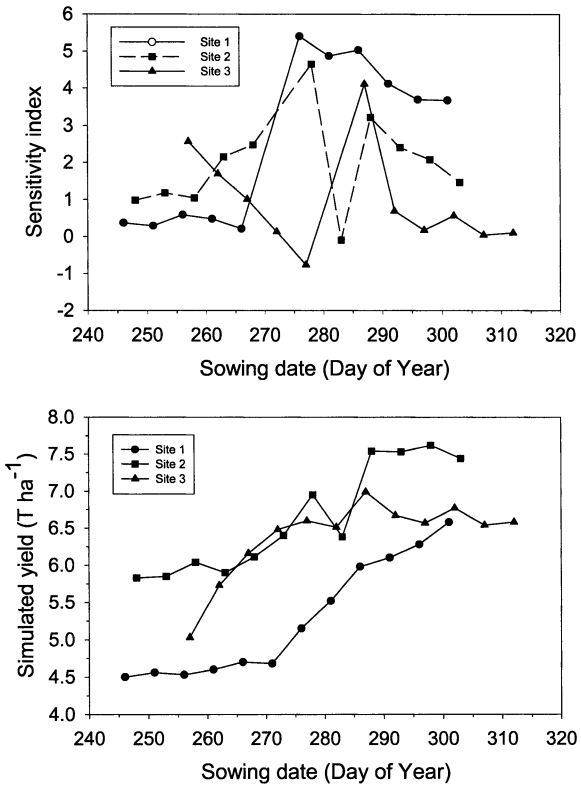

Fig. 5. Sensitivity analysis results for changing the sowing date on grain yield. The mean of the sensitivity index is given in Table 2.

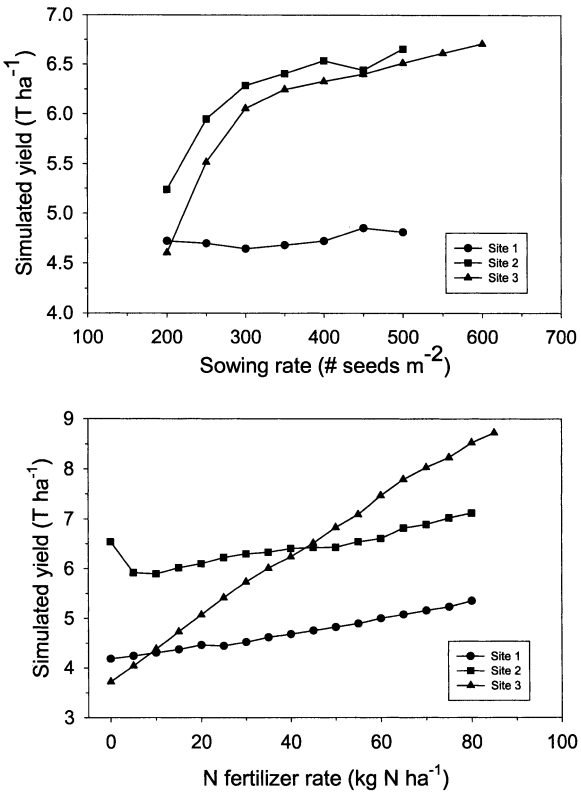

Fig. 6. Sensitivity analysis results for changing the sowing rate and N fertilizer amount at planting on grain yield. The means of the sensitivity index are given in Table 2.

default parameters becomes more important for accurate simulation. This is more important for yield prediction than phenology because the developmental sequence is remarkably similar for most widely used cultivars (McMaster, 1997).

4. Conclusions

Based on this study, we believe that the developmentally-based model SHOOTGRO 4.0 can be easily parameterized and can accurately simulate phenological growth stages and grain yield in the different crop production regions of the Czech Republic. Therefore, farmers and scientists needing wheat development information to increase the efficacy of their management practices can use SHOOTGRO 4.0 as a tool to assist them.

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