Dynamic phenological model for winter rye and winter barley

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Abstract

A detailed dynamic crop stand phenological model is presented for winter barley and winter rye. The modelled phenological stages are described in different scale units (FEEKES [1–20], BBCH [1–100] and DC [1–100]) and a differentiation in mathematical approaches and in parameterisation is made between the germination, the vegetative and the generative phases. The following driving forces are taken into account: temperature, day length, drought stress and nitrogen availability. Drought stress is described using the ratio of actual to potential evapotranspiration and nitrogen availability is described using the nitrogen content in the above-ground biomass. Vernalisation is considered as a process influencing phenology and is described normalised between 0 and 1. In the paper the model parameters are listed separately for winter barley and winter rye. Model parameterisation and validation results are presented for three different German locations (Müncheberg, Hohenfinow, Halle). The comparison of calculated and observed phenological phases (emergence, shooting, flowering, maturity) gives an $R^2$ between 0.87 and 0.99 for winter rye and between 0.92 and 0.99 for winter barley. For these phenological stages the maximum mean deviation between calculations and observations is 5 days. For tillering an insufficient agreement was occurred only. Investigations regarding the geographical extrapolation of the model are carried out for two different German locations (Dedelow and Mariensee). The model-experiment-comparison results for all phenological phases show a sufficient accuracy ($R^2 = 0.98, N = 82$), followed by the presentation and discussion of their results. Model simulation runs with drought stress and not enough nitrogen availability show the dominance of drought stress induced phenology acceleration.

Keywords: Phenology; Dynamic model; Vernalisation; Winter rye; Winter barley; Model transfer

1. Introduction

For all crops, phenology plays an essential role by acting as a specific biological time scale. Phenology directly or indirectly controls processes relevant to crop like senescence, grain filling, photosynthesis, nutrition uptake and others. Dependent on phenology, crop pro-
cesses are switched on or switched off, accelerated or slowed down. This is the reason why the phenological development is one of the main processes within crop growth and agro-ecosystem models. Within operative decision support systems phenology also is a guideline for the realisation of agricultural management activities, i.e. from sowing to harvest. Moreover, phenology is one of the great forthcoming modifications of the future cropping systems because of climate change with a possible temperature increase.

Phenology mainly depends on the temperature and length of the photo-period, i.e. values not controlled by man (Travis et al., 1988; Mirschel and Kretschmer, 1990a). However, it also significantly depends on water and nitrogen supply, i.e. values controlled by man because of irrigation or nitrogen fertilisation (Mirschel et al., 1990b). Drought stress and not enough nitrogen availability can significantly accelerate phenology. Drought stress leads to a lower plant turgor, to lower actual evapotranspiration rates and therefore to a lower cooling effect by transpiration which induces higher crop stand temperatures and finally an accelerated phenology. In irrigation experiments with winter cereals on sandy soils at the location of Müncheberg, drought stress related phenology accelerations up to 7 days were obtained (Künkel et al., 1985) in normal years. In this experiments the highest phenology acceleration rates by drought stress could obtain in the grain filling phase after flowering.

For a better understanding and a better comparability of crop phenology a numerical division of the phenological process between sowing and harvest is advisable. In literature, different scaling methods for the phenological process are reported. Keller and Baggiani (1954) use capitals between A and W for scaling. Other authors use numerical values between 1 and 5 (Kuperman and Cirkov, 1970; Robertson, 1968), between 1 and 20 (FEKEES-scale) (Feekes, 1941), between 1 and 4 (Stenitzer, 1980), between 0 and 1 (Wernecke and Claus, 1992, 1996), between 0 and 1 for the vegetative part of phenology and between 1 and 2 for the generative part (Penning de Vries et al., 1982) and the decimal code between 0 and 100 (DC-scale (Zadoks et al., 1974); BBCH-scale (Hack et al., 1992)). An overview of different phenology scales of cereals is given by Heyland (1978). In Germany, the extended BBCH-scale is used mostly at present for the description of phenological stages of mono- and dicotyledonous crops (Kompendium, 1997).

Not only crop growth models but also operative, computer-aided decision support systems within plant production require a numerical description of the phenological process. In both cases, such dynamic phenological models operating at daily time step require to be sensitive to the main driving forces and management techniques (irrigation and nitrogen fertilisation). For winter wheat, different phenological models exist that take into account the temperature (real or above a crop dependent threshold) and the photo-period duration. An overview of existing phenological models is given by Mirschel and Kretschmer (1990a). For winter wheat, Mirschel et al. (1990b) describe a phenological model which additionally takes into account the water and nitrogen supply status of the crop stand. For winter rye and winter barley, only a few phenological models exist, describing phenology merely subject to the temperature and the photo-period (winter rye, e.g. Regener and Reuter, 1989; Roemer, 1988; winter barley, e.g. Wernecke and Claus, 1996). By extending the basic model algorithms of Regener (Regener and Reuter, 1989) for winter rye, dynamic phenological models for winter rye and winter barley are presented in the following. These models account for temperature and photo-period as well as water, nitrogen and vernalisation influences.

2. Materials and model development

2.1. Database

On the basis of the mostly used decimal scale (DC-scale) according to Zadoks et al. (1974), detailed observations of the phenological stages of different winter rye and winter barley field crop stands were used for model verification and validation. Table 1 gives an overview of the included experimental locations.

The phenological growth stage observations were carried out from 1991/1992 to 1996/1997 (Müncheberg and Hohenfinow) and during the 1970s and 1980s (Halle; Schliephake, 1984) in irrigated and non-irrigated field trials and in trials with different nitrogen fertilization levels (winter rye: 80–140 kg N ha$^{-1}$; winter barley: 100–168 kg N ha$^{-1}$). The sowing took place within a period of 15 days. All other management
Table 1
Overview of the locations used for model verification and validation

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Soil quality index</th>
<th>Annual precipitation (mm)</th>
<th>Annual mean temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Müncheberg</td>
<td>52°01′N</td>
<td>14°07′E</td>
<td>26</td>
<td>533</td>
<td>8.2</td>
</tr>
<tr>
<td>Hohenfinow</td>
<td>52°01′N</td>
<td>14°07′E</td>
<td>35</td>
<td>547</td>
<td>8.2</td>
</tr>
<tr>
<td>Halle</td>
<td>51°48′N</td>
<td>11°97′E</td>
<td>55</td>
<td>494</td>
<td>9.2</td>
</tr>
<tr>
<td>Dedelow</td>
<td>53°21′N</td>
<td>13°46′E</td>
<td>40</td>
<td>554</td>
<td>7.9</td>
</tr>
<tr>
<td>Mariensee</td>
<td>52°33′N</td>
<td>9°28′E</td>
<td>69</td>
<td>699</td>
<td>8.8</td>
</tr>
</tbody>
</table>

* The soil quality index which ranges from 1 to 100 is assessed on the basis of the parent material of the soil, its pedogenetic development stage and the hydrological boundary conditions. Lowest values are attributed to the poor diluvial sandy soils and highest values with the chernozoms from loess. The soil quality index was developed for the land evaluation of agricultural used land in Germany starting in the 1930s.

measures (tillage, plant protection, phosphorus and potassium fertilization) were realised to safeguard optimal growth conditions. At Müncheberg experimental station winter rye and winter barley were grown in a crop rotation with sugar beet and winter wheat and at Hohenfinow experimental station in a crop rotation with winter rape, winter wheat, maize and potatoes. The cultivars Pluto, Borellus and Clou were grown for winter rye and the cultivars Rubina and Grete were grown for winter barley. The meteorological values (temperature, precipitation, radiation) were measured by using the automatic micro-meteorological stations on the experimental fields. For model parameterisation and verification, 28 data sets were used for winter rye and 15 data sets were used for winter barley.

Data sets from the locations Dedelow (2000/2001–2001/2002) and Mariensee (1995/1996) were used for model transfer investigations. The short characteristics of these two locations are shown in Table 1.

2.2. Model description

2.2.1. Vernalisation

Concerning winter cereals, cold temperature conditions during wintertime are a necessary prerequisite for triggering off the formation of blooms and finally for an optimal plant development that leads to maturity. Dependent on the plant type, the sum of cold periods has to be of a defined intensity and length. This process is called vernalisation. Weir et al. (1984) obtained that regarding winter cereals, optimal vernalisation rates are only realised within a temperature range of +3 and +10 °C. Temperatures between −4 and +3 °C as well as +10 and +17 °C only give smaller vernalisation rates. According to Waring and Phillips (1981), the temperature range between −1 and +9 °C is optimal for vernalisation.

For the description of vernalisation processes of winter rye and winter barley, the principal algorithm of Regener and Reuter (1989), which is already parameterised for winter rye, is used. For winter barley, the algorithm is modified. Compared to winter rye, winter barley requires a smaller sum of cold periods and has a narrower temperature range for optimal vernalisation. The vernalisation process (VERN) is described for the period between emergence (DC 10) and shooting (DC 30). It is normalised to the interval [0, 1]. If VERN=1, complete vernalisation is reached.

The following equation describes the vernalisation process:

\[ \text{VERN}_t = \text{VERN}_{t-1} + A_V f_V(T_M) \]  

where \( A_V \) is a crop dependent parameter and \( f_V(T_M) \) the daily vernalisation rate function dependent on mean temperature. \( A_V \) is 0.08 and 0.07 for winter rye and winter barley, respectively. Both vernalisation rate functions are shown in Fig. 1. Outside the appropriate temperature range, vernalisation rates are 0.

2.2.2. Phenology

The phenology of winter rye and winter barley is modelled by using a dynamic semi-empirical approach. This approach follows the basic model algorithms for winter rye by Regener and Reuter (1989). They were modified and extended including terms to take into account drought stress and nitrogen availability influences on phenology. Above, they are newly parameterised for both, winter rye and winter...
barley. The phenological model takes into account the daily mean temperature, the length of photo-period as well as the water, nitrogen and vernalisation statuses. Calculated in the model as a state variable, phenology (ON) is transformed into the FEEKES-, DC- and BBCH-scales using special transfer functions.

The phenological model distinguishes between three phenological phases:

1. germination phase (sowing (DC 0), emergence (DC 10));
2. vegetative phase (emergence (DC 10), shooting (DC 30));
3. generative phase (shooting (DC 30), maturity (DC 92)).

According to the three phenological phases, the state variable ON of the phenological model is described for every day \((t)\) as follows:

\[
ON_t = \begin{cases} 
A_t, & 0 \leq DC < 10, \\
V_t, & 10 \leq DC < 30, \\
31G_t, & DC \geq 30
\end{cases}
\]

**2.2.2.1. Phenology during the germination phase (DC 0–DC 10).** Phenology during the germination phase is described as follows:

\[
A_t = A_{t-1} + f(TM_t, T_{\text{min}(1)}, T_{\text{opt}(1)}, \alpha_{(1)})
\]

where \(TM\) is the daily mean temperature (°C), \(f(\cdot, \cdot)\) is a temperature dependent phenology rate function (see Eq. (9)), \(T_{\text{min}(1)}\) the minimum temperature for the germination phase (°C), \(T_{\text{opt}(1)}\) the optimum temperature for the germination phase (°C) and \(\alpha_{(1)}\) the maximum phenology rate for the germination phase.

The starting value for \(A_t\) at sowing is 0.1 for winter rye and 0.37 for winter barley. For both, winter rye and winter barley, emergence is reached if \(A_t = 1\).

**2.2.2.2. Phenology during the vegetative phase (DC 10–DC 30).** Phenology during the vegetative phase is subdivided into two periods. The first stretches from emergence (DC 10) to the beginning of tillering (DC 21) and the second from beginning of tillering (DC 21) to the beginning of shooting (DC 30). The rate functions used in both periods differ only in parameters. Phenology during the vegetative phase (V) is described as follows:

\[
V_t = V_{t-1}(3 - f(WS_t) - f(NS_t)) \\
\{ 1 + f(TM_t, T_{\text{min}(2)}, T_{\text{opt}(2)}, \alpha_{(2)}), 10 < DC \leq 21, \\
1 + f(TM_t, T_{\text{min}(3)}, T_{\text{opt}(3)}, \alpha_{(3)}), 21 < DC \leq 30
\}
\]

where \(f(WS_t)\) is the drought stress factor (see Eq. (11)), \(f(NS_t)\) the nitrogen availability factor (see Eq. (12)), \(TM_t\) the daily mean temperature (°C), \(f(\cdot, \cdot)\) is a temperature dependent phenology rate function (see Eq. (9)), \(T_{\text{min}(2)}\) and \(T_{\text{min}(3)}\) are the minimum temperatures for the phenological phases (DC 10–DC 21) and (DC 21–DC 30), respectively (°C), \(T_{\text{opt}(2)}\) and \(T_{\text{opt}(3)}\) the optimum temperatures for the phenological phases (DC 10–DC 21) and (DC 21–DC 30), respectively (°C) and \(\alpha_{(2)}\) and \(\alpha_{(3)}\) the maximum phenology rates for the phenological phases (DC 10–DC 21) and (DC 21–DC 30), respectively.

**2.2.2.3. Phenology during the generative phase (DC 30–DC 92).** Phenology during the generative phase is described as follows:

\[
G_t = G_{t-1}(3 - f(WS_t) - f(NS_t)) \\
\{ 1 + f(TM_t, T_{\text{min}(2)}, T_{\text{opt}(2)}, \alpha_{(2)}), 10 < DC \leq 21, \\
1 + f(TM_t, T_{\text{min}(3)}, T_{\text{opt}(3)}, \alpha_{(3)}), 21 < DC \leq 30
\}
\]

where \(f(WS_t)\) is the drought stress factor (see Eq. (11)), \(f(NS_t)\) the nitrogen availability factor (see Eq. (12)), \(TM_t\) the daily mean temperature (°C), \(f(\cdot, \cdot)\) is a temperature dependent phenology rate function (see Eq. (9)), \(T_{\text{min}(2)}\) and \(T_{\text{min}(3)}\) are the minimum temperatures for the phenological phases (DC 10–DC 21) and (DC 21–DC 30), respectively (°C), \(T_{\text{opt}(2)}\) and \(T_{\text{opt}(3)}\) the optimum temperatures for the phenological phases (DC 10–DC 21) and (DC 21–DC 30), respectively (°C) and \(\alpha_{(2)}\) and \(\alpha_{(3)}\) the maximum phenology rates for the phenological phases (DC 10–DC 21) and (DC 21–DC 30), respectively.

The starting value for \(G_t\) at the beginning of the generative phase is 0.1 for winter rye and 0.37 for winter barley. For both, winter rye and winter barley, flowering is reached if \(G_t = 1\).
To take into account the influence of temperature during the first sub-period of the generative phase, a further variable \( V_1 \) is introduced incipient at emergence (DC 10):
\[
V_1 = V_{1,\text{-}1} + \Delta V_1, \quad (5)
\]
with a daily rate \( \Delta V_1 \) of
\[
\Delta V_1 = f_2(TM, \delta)
\]
where \( f_2(\cdot, \cdot) \) is a temperature dependent phenology rate function (see Eq. (10)).

Due to the influence of vernalisation and temperature regime during the vegetative phase, the daily rates of the phenology variable for the generative phase \( \Delta G_t \) are also calculated incipient at emergence (DC 10). \( \Delta G_t \) is given by
\[
\Delta G_t = \begin{cases} 
G_t + \text{VERN} \left( \frac{\beta \left( 600 \text{DL} - \gamma \frac{G_{t,\text{-}1}}{H_1 + \text{VERN}} \right)}{30 < \text{DC} \leq 65}, 
\frac{G_{t,\text{-}1} + \Delta G_t (1 + 0.1 (1 - f(\text{WS}_i)) + (1 - f(\text{NS}_i)))}{65 < \text{DC} \leq 92}, 
\frac{G_{t,\text{-}1} + \Delta G_t (1 + 0.25(1 - f(\text{WS}_i)) + (1 - f(\text{NS}_i)))}{\text{DC} \leq 30}, 
\frac{G_{t,\text{-}1} + \Delta G_t (1 + (1 - f(\text{WS}_i)) + (1 - f(\text{NS}_i)))}{\text{DC} \geq 92}
\end{cases}
\]
where \( TM \) is the daily mean temperature, \( f_2(\cdot, \cdot) \) is a temperature dependent rate function, \( \beta, \gamma, \varepsilon, H_1 \) are function parameters, DL is the length of photo-period which can be calculated by algorithms according to Goudriaan (1978) or Kersebaum (1989), VERN is the vernalisation state, \( H_2 \) is a normalising parameter for temperature, \( H_1 \) a normalising parameter for the phenology rate, \( f(\text{WS}_i) \) the drought stress factor (see Eq. (11)) and \( f(\text{NS}_i) \) is the nitrogen availability factor (see Eq. (12)).

The phenology rate function \( f_1(\cdot, \cdot, \cdot) \) used for the germination and the vegetative phase is an optimum function and defined as
\[
f_1(TM, T_{\text{min}(i)}; T_{\text{opt}(i)}, a_{\alpha(i)}) = a_{\alpha(i)} \exp \left( -4.605 \frac{T_{\text{min}(i)} + 273.15 \cdot (TM - T_{\text{opt}(i)})^2}{TM + 273.15 \cdot (T_{\text{opt}(i)} - T_{\text{min}(i)})^2} \right)
\]
Fig. 2. Courses of the phenology rate functions \( f(\cdot, \cdot, \cdot) \) and \( f(\cdot) \) dependent on temperature \( TM \) is daily mean temperature; \( T_{\text{min}(i)} \) and \( T_{\text{opt}(i)} \) are phase dependent minimum and optimum temperatures, respectively; \( a_{\alpha(i)} \) is the phase dependent maximum phenology rate using the parameter set for winter rye.

\[\text{TM} \leq 31\degree \text{C}, \quad f_2(TM, \delta) = \frac{\delta}{(TM - 31)^2}, \quad \text{TM} > 31\degree \text{C}, \quad f_2(TM, \delta) = 0,\]
where \( TM \) is the daily mean temperature, \( T_{\text{min}(i)} \) the phase dependent minimum temperature, \( T_{\text{opt}(i)} \) the phase dependent optimum temperature, \( a_{\alpha(i)} \) the phase dependent maximum phenology rate and \( \delta \) is a function parameter. The index \( i \) describes the parameter assignment to the different phenological phases.
Dependent on temperature, Fig. 2 shows the courses of the phenology rate functions $f_1(\cdot, \cdot, \cdot)$ and $f_2(\cdot)$ using the parameter set for winter rye.

Separately for winter rye and winter barley, Table 2 gives an overview of the parameters used in Eqs. (3)–(10).

Drought and not enough nitrogen availability have accelerated effects on phenology (Idso et al., 1978; Brisson et al., 2003). Effects of lack in water and nitrogen are very much linked to what happens to the canopy energy balances when there is a problem with these resources. It means that these effects are not direct effects on phenology but indirect effects via a changed canopy microclimate caused by water and nitrogen stresses. Drought closes stomata and reduces the transpiration that then leads to a reduction in the latent heat flux and to an increase in crop and canopy temperatures, the most probably reason for an increase in phenology. These indirect effects on phenology can take into account using stress factors (Brisson et al., 2003). Here during vegetative and generative phases the influence of drought and nitrogen stresses is described using normalized daily drought ($f(WS_t)$; $0 \leq f(WS_t) \leq 1$) and nitrogen ($f(NS_t)$; $0 \leq f(NS_t) \leq 1$) factors. The algorithms describing these stress factors take into account temperature dependences; for water stress, for instance, the potential and actual evapotranspiration.

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Winter rye</th>
<th>Winter barley</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{min}(1)}$</td>
<td>-4.579</td>
<td>-1.0</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{\text{opt}(1)}$</td>
<td>15.0</td>
<td>14.0</td>
<td>°C</td>
</tr>
<tr>
<td>$\alpha_{(1)}$</td>
<td>0.1217</td>
<td>0.081</td>
<td>day$^{-1}$</td>
</tr>
<tr>
<td>$T_{\text{min}(2)}$</td>
<td>-1.2</td>
<td>-8.6</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{\text{opt}(2)}$</td>
<td>15.0</td>
<td>3.4</td>
<td>°C</td>
</tr>
<tr>
<td>$\alpha_{(2)}$</td>
<td>0.1217</td>
<td>0.1</td>
<td>day$^{-1}$</td>
</tr>
<tr>
<td>$T_{\text{min}(3)}$</td>
<td>-4.0</td>
<td>-8.0</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{\text{opt}(3)}$</td>
<td>20.0</td>
<td>12.0</td>
<td>°C</td>
</tr>
<tr>
<td>$\alpha_{(3)}$</td>
<td>0.1217</td>
<td>0.04</td>
<td>day$^{-1}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$3.4 \times 10^{-4}$</td>
<td>$5.09 \times 10^{-4}$</td>
<td>day$^{-2}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$9.455 \times 10^{-4}$</td>
<td>$9.615 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\delta$</td>
<td>$0.35 \times 10^{-4}$</td>
<td>$0.255 \times 10^{-4}$</td>
<td>day$^{-1}$ °C$^{-1}$</td>
</tr>
<tr>
<td>$H_1$</td>
<td>10.0</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>$H_2$</td>
<td>4.0</td>
<td>4.0</td>
<td>°C</td>
</tr>
<tr>
<td>$H_3$</td>
<td>92.0</td>
<td>50.0</td>
<td></td>
</tr>
</tbody>
</table>

The drought stress factor $f(WS_t)$ is given by

$$f(WS_t) = \begin{cases} 
1, & \frac{AET_t}{PET_t} \geq WL_t, \\
\frac{AET_t}{PET_t} - \frac{WTHR}{WL_t - WTHR}, & WTHR < \frac{AET_t}{PET_t} < WL_t, \\
0, & \frac{AET_t}{PET_t} \leq WTHR
\end{cases}$$

where $AET_t/PET_t$ is the daily ratio of actual to potential evapotranspiration calculated by using the soil water and evapotranspiration model BOWET (Mirschel et al., 1995a). $WL_t$ the phenology dependent threshold below which an increase in phenology is induced (see Fig. 3). $WTHR$ the AET$_t$/PET$_t$ threshold below which transpiration is stopped ($WTHR=0.1$ for both, winter rye and winter barley).

The nitrogen stress factor $f(NS_t)$ is given by

$$f(NS_t) = \begin{cases} 
1, & NABM_t \geq NL_t, \\
\frac{NABM_t - NTHR}{NL_t - NTHR}, & NTHR < NABM_t < NL_t, \\
0, & NABM_t \leq NTHR
\end{cases}$$

where $NABM_t$ is the nitrogen availability and $NL_t$ the nitrogen level threshold below which nitrogen availability is low ($NL_t=0.5$ for winter rye; $NL_t=0.2$ for winter barley).

The parameters in Table 2 were optimized for each crop type using the parameter optimization procedure.
where NABM$_t$ is the daily nitrogen content in the above-ground biomass calculated by using the agro-ecosystem models AGROSIM-WR for winter rye and AGROSIM-WG for winter barley (Mirschel et al., 1995b) which include a soil nitrogen module taking into account the residual N from previous crops also, N$_{L,t}$ the phenology dependent nitrogen content limit in the above-ground biomass below which the further not enough nitrogen availability induces an increase in phenology (see Fig. 4), N$_P$ is a curvature parameter (N$_P$ = 0.8 if DC $< 30$, N$_P$ = 2.5 if 30 $\leq$ DC $< 65$ and N$_P$ = 2 if 65 $\leq$ DC $\leq$ 92 for both, winter rye and winter barley) and NTHR is the nitrogen content threshold in the above-ground biomass below which assimilation is stopped (NTHR = 0.015 if DC $< 30$, NTHR = 0.005 if 30 $\leq$ DC $< 65$ and NTHR = 0.002 if 65 $\leq$ DC $\leq$ 92 for both, winter rye and winter barley).

The parameters used in Eqs. (11) and (12) are determined on the basis of a large number of field experiments conducted with different cropping intensities, various N-fertilisation levels, with and without irrigation (Mirschel and Reining, 1995; Mirschel et al., 2001).

In phenological or crop growth models, phenology values are scaled to a model interval interval which usually is $[0, 1]$. In order to compare simulated values and observed phenological stages, it is therefore necessary to transform the model internal values into the values of the observation scales, such as FEEKES, BBCH or DC.

Here, these monotonously increasing transformation functions are table functions with a linear interpolation between table values. Fig. 5 shows these transformation functions for winter rye and winter barley.

### 3. Results and discussion

Since phenology functions as a biological time control not only in reality but also in operative decision support systems for plant production and in complex crop growth models, it is necessary to describe this process with high accuracy. The model verification and parameterisation is based on detailed phenological field crop stand observations from experimental sites in Müncheberg (1992/1993 and 1993/1994) and Hohenfinow (1991/1992) as well as on literature data from Halle (70th and 80th years; Schliephake, 1984).
The HohenFINow data from 1992/1993 to 1996/1997 were used for model validation. For both, model verification and validation, data sets from 14 different years were used for winter rye and 10 for winter barley. A special written software in TURBO PASCAL is used for model parameter optimisation based on the square error minimisation method. The method consists a stepwise parameter variation within a given parameter value range in three parameter groups according to the three phenological phases (germination, vegetative phase, generative phase). In every group the model is run with all possible parameter combinations for finding that parameter set which gives the minimum square error. For finding the minimum square error all DC-scaled phenological observations belonged to each phase are taken into account. The parameter groups fitted together are marked in Table 2. Using such a very time expensive method gives the guarantee to find the global minimum within the given parameter ranges and not only a local one.

For phenological model transfer investigations, simulation runs with six winter barley and four winter rye data sets were carried out at two different German locations — Dedelow, which is located in North East Brandenburg, and Mariensee, which is located near Braunschweig/Brunswick in Niedersachsen/Lower Saxony (see Table 1).

### 3.1. Model verification and validation

For five different phenological phases, the summarised model verification results are shown in Figs. 6 and 7 as well as in Table 3 as a model-experiment-comparison, separately for winter rye and winter barley.

For both, winter barley and winter rye, there is a good correspondence between calculated and observed phenological stages during the different phenological phases (see Figs. 6 and 7 and Table 3). In most cases the slope of the linear regression is near 1. An insufficient agreement between model calculated and observed phenological stages only occurred during the tillering phase. The tillering phase covers from DC 21 to DC 29 (as a maximum), i.e., DC 21 is the beginning of the tillering process with the formation of the first tiller and DC 29 is the tillering stage with the formation of the ninth tiller per plant. The second digit in the tillering stage of the DC-scale characterises the tiller.

### Table 3

Comparison of calculated and observed phenological stages (basis: day of the year) during five different phenological phases for winter rye and winter barley by means of linear regression ($y = mx + b$, $y$ is the field observation, $x$ the model calculation).  

<table>
<thead>
<tr>
<th>Phenological phases</th>
<th>$N$</th>
<th>$R^2$</th>
<th>$m$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter rye</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sowing, emergence</td>
<td>23</td>
<td>0.995</td>
<td>1.064</td>
<td>-17.438</td>
</tr>
<tr>
<td>Emergence, tillering</td>
<td>43</td>
<td>0.956</td>
<td>0.998</td>
<td>4.901</td>
</tr>
<tr>
<td>Tillerng, shooting</td>
<td>81</td>
<td>0.119</td>
<td>0.268</td>
<td>117.318</td>
</tr>
<tr>
<td>Flowering, maturity</td>
<td>244</td>
<td>0.867</td>
<td>1.115</td>
<td>-20.952</td>
</tr>
<tr>
<td>Winter barley</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sowing, emergence</td>
<td>11</td>
<td>0.995</td>
<td>1.002</td>
<td>-0.797</td>
</tr>
<tr>
<td>Emergence, tillering</td>
<td>13</td>
<td>0.492</td>
<td>1.048</td>
<td>-18.230</td>
</tr>
<tr>
<td>Tillerng, flowering</td>
<td>16</td>
<td>0.486</td>
<td>0.694</td>
<td>34.351</td>
</tr>
<tr>
<td>Flowering, maturity</td>
<td>54</td>
<td>0.930</td>
<td>1.042</td>
<td>-5.602</td>
</tr>
<tr>
<td>Flowering, maturity</td>
<td>33</td>
<td>0.921</td>
<td>0.923</td>
<td>12.644</td>
</tr>
</tbody>
</table>
number per plant. The development of the maximum tiller number per plant mainly depends on winter barley and winter rye cultivars; a high number of tillers per plant is unusual. So, there is an open end in scaling the tillering phase and it is very difficult to model this fact. Knowing all this and knowing the complexity of plant, soil and meteorological factors which are responsible for tiller formation the insufficient agreement between modelled and observed tillering stages is understandable. A significant overestimation during tillering by the model exists for winter rye (see Fig. 6 and Table 3), i.e. the calculated tillering is faster than the observed tillering. Only in cases of an early sowing data and a warm autumn the observed tillering is faster than the calculated tillering. The phenological stages following tillering, however, are again estimated with good accuracy (see Table 3).

The four different phenological stages emergence, beginning of shooting, flowering and maturity are important for the entire process control within crop growth models and have to be calculated with high accuracy. For these stages, the difference between calculated and observed phenology is shown in Table 4, subdivided into the results of model verification and validation.

Fig. 8 shows a model-experiment-comparison for phenology courses of different model validation variants separately for winter rye and winter barley grown in Hohenfinow (growing periods: 1992/1993–1996/1997; winter rye cultivars: Pluto, Borellus; winter barley cultivars: Rubina, Grete). The model validation is realised without any parameter recalibration.

In almost all validation growing periods, phenological velocity is slightly overestimated by the model in the case of winter barley, i.e. the calculated phenology is faster than the observed phenology, and slightly underestimated by the model in the case of winter rye, i.e. the calculated phenology is slower than the observed phenology.

The results in Figs. 6–8 and Tables 3 and 4 show, that the most important phenological stages and phases (the tillering phase excluded) can be estimated by the model with sufficient accuracy. In comparison with winter barley, the deviation between calculated and observed phenology during the tillering phase is greater with regard to winter rye. The tillering phase usually extends over a long time period lasting from late autumn over winter up to early spring with more or less long veng-

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**Table 4**

<table>
<thead>
<tr>
<th>Phenological stages</th>
<th>Model verification</th>
<th>Model validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter rye</td>
<td>Winter barley</td>
</tr>
<tr>
<td>Emergence</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Flowering</td>
<td>4.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Maturity</td>
<td>4.9</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>Winter rye</td>
<td>Winter barley</td>
</tr>
<tr>
<td>Emergence</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Flowering</td>
<td>3.4</td>
<td>5.7</td>
</tr>
<tr>
<td>Maturity</td>
<td>7.0</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Fig. 8. Comparison of calculated (lines) and observed (full squares) phenology courses (in DC-scale) for winter barley and winter rye grown in Hohenfinow.
etation stops and very slow daily phenology rates. On the basis of a 3-year experiment with winter cereals for getting phenological observations, Palfner (1991) stated that cultivar differences are not the main reason for the deviations within the tillering phase. The accelerated simulated phenology during tillering described by the model is without any influence on the calculation accuracy of the later phenological stages like shooting, flowering and maturity.

In all cases, the emergence stage is calculated with very good accuracy (see Tables 3 and 4) not only with respect to the normal sowing variant but also to the early and late sowing variants. Compared to winter rye, phenological calculations of winter barley have a higher accuracy with respect to the period from the beginning of shooting until maturity.

3.2 Model transfer

A model transfer to other locations, other growing time periods and other cultivars is realised without any model parameter changes. Only the model inputs and driving forces differ with regard to specific locations and growing periods. Model transfer investigations are a very good possibility for a quality evaluation of the whole dynamic phenological model.

For the locations Dedelow and Mariensee, Fig. 9 shows a comparison of calculated and observed phenological stages between emergence and maturity regarding winter barley (growing periods: 1995/1996, 2000/2001 and 2001/2002; cultivar: Bombay) and winter rye (growing period: 2000/2001 and 2001/2002; cultivars: Avanti, Ursus). For Dedelow, two different nitrogen fertilisation splitting regimes were taken into account regarding both, winter rye (160 kg N ha\(^{-1}\) (80/50/30), (120/40)) and winter barley (180 kg N ha\(^{-1}\) (80/50/50), (120/60)).

The model-experiment-comparison results of the model transfer investigations show, that it is possible to transfer the phenological model to other locations and growing periods maintaining sufficient accuracy. The regression line through the point of origin between modelled and observed phenological stages (slope: 1.003; \(R^2 = 0.982; N = 82\)) is near the 1:1 line.

In Fig. 10 the modelled and observed phenology courses at the location Dedelow during the growing periods 2000/2001 and 2001/2002 are compared separately for winter barley (N-fertilization: 180 kg N ha\(^{-1}\) (80/50/50)) and winter rye (N-fertilization: 160 kg N ha\(^{-1}\) (80/50/30)). During these two growing periods phenomenological velocity is slightly overestimated by the model in the case of winter barley, i.e. the calculated phenology is faster than the observed phenology, and slightly underestimated by the model in the case of winter rye, i.e. the calculated phenology is slower than the observed phenology. This fact is quite similar to the model validation results (see Fig. 8).

3.3 Influence of drought stress and not enough nitrogen availability

Drought and not enough nitrogen availability situations have an accelerating influence on phenology during both, the vegetative and generative phenological phases. Exemplary for winter rye at the location Dedelow, the influence of drought and not enough nitrogen availability on phenology is investigated during the cropping period from September 2001 until August 2002 which is free from drought stress situations with a good nitrogen availability (precipitation sum: 574.8 mm, N-fertilisation: 160 kg N ha\(^{-1}\)). After a wet winter and spring period, significant drought and not enough nitrogen availability situations were simulated starting in May 2002 (the end of the shooting phase) until July 2002. The results show that the drought stress induced acceleration of phenology is dominant in comparison with the not enough nitrogen availability induced acceleration of phenology. Compared
to the situation free from stresses, an N-fertilisation lower than 80 kg N ha\(^{-1}\) induces a two day phenology acceleration in the simulation. In the case of drought stress induced with a 131 mm lower precipitation sum, the simulated acceleration of phenology is 6 days. When combining both stress situations, a phenology acceleration of 7 days is simulated. Zoomed to the time period between May and July the phenology course of this case is shown in Fig. 11 and compared to the phenology course of the variant free from stress.

The simulated acceleration of phenology induced by drought stress and not enough nitrogen availability of about 1 week is in very good accordance with experimental results for winter cereals (Künkell et al., 1985) and with climate model simulation results for winter rye grown in Brandenburg, Germany (Mirschel et al., 1997). In both cases, phenology accelerations are mainly based on drought stress caused by a precipitation deficit.

4. Conclusion

The dynamic phenological model for winter barley and winter rye described above is able to reproduce the whole phenology process between sowing and maturity. It is the first to take into account the accelerating influences of drought stress and not enough nitrogen availability on the phenology process during the vegetative and generative phenological phases. All in all the model describes the phenology process with quite sufficient accuracy. The deviations between calculated and observed phenological stages of winter rye and winter barley are in the same range as in the phenological model for winter wheat developed by Mirschel et al. (1990b).
An insufficient agreement between simulated and observed phenological stages only occurred during the tillering phase. This is connected with the specific tiller formation process. However, the phenological stages following tillering are again estimated with good accuracy.

The validation and model transfer investigation results show that only in the case of winter barley, the phenology up to the beginning of maturity is slightly overestimated by the model. A better parameter optimisation procedure using an even greater basis of observed phenology data sets can solve this little problem in future.

Under the typical conditions of agricultural practice in Germany, the soil moisture conditions in the upper soil layers are sufficient for the germination process of winter rye and winter barley. It is only for this reason that the influence of temperature is considered for the period of germination. Thus, for a Europe — wide model transfer, it would be necessary to also include the effects of drought stress in order to consider continental climate conditions. This additional term has to describe slowed down or halted/interrupted phenology caused by dry soil conditions during germination. For the elaboration and parameterisation of such a term, special data sets are necessary, i.e. special drought experiments or long-term data sets from regions with continental climate conditions.

At German locations, the model-experiment-comparison results of the model transfer investigations show, that it is possible to transfer the phenological model to other locations and other growing periods with sufficient accuracy.

Comparison results of calculated and observed phenological stages and statements on model accuracy also depend on the observation method and the experience of those dealing with phenological observations in field crop stands. It is difficult to observe the day of the beginning of a special phenological stage in field crop stands because of the crop stands' heterogeneity. For reliable phenological observations, long-term experiences are necessary.

Acknowledgements

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