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A variable thermal time of the double ridge to flag leaf emergence phase improves the predictive quality of a CERES-Wheat type phenology model

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ABSTRACT

A modified version of the widely used CERES-Wheat phenology model (CWm) was developed introducing variable thermal time from double ridge stage to flag leaf emergence and compared with the original model (CW V3.x). Both model versions were newly implemented and calibrated using routinely collected field ratings of phenological stages of winter wheat crops. Calibration for all parameters of both model versions was done using a step by step procedure thereby using different methods for parameter identification. For calibration and validation of the model a data set containing more than 6000 single observations of wheat phenology was used. The improved model version had a better prediction of phenological (BBCH) stages compared to the original CW approach for an independent validation data set. The average RMSE for BBCH 37 and BBCH 39 was decreased by two and five days, respectively. We could show that it was possible to calibrate the wheat phenology models using solely routinely available field ratings. Because the predictive quality for wheat phenology of actual wheat crop growth simulators without calibration especially often is still limited the presented approach may be seen as an approach for improving this type of models without especially designed experiments.

1. Introduction

The prediction of crop phenology is a prerequisite for many aspects of crop modeling and management. Many processes, like the partitioning of dry matter, are influenced by the development stage of the crop and the interaction between soil, climate, and management and therefore crop growth can only be predicted if a sufficiently accurate phenological model for the particular crop is available.

The principal governing factors of the developmental rate of winter annual crops (temperature, day length and degree of vernalization) are well known, and their quantitative effects have been successfully described using empirical functions (Hodges, 1991). Winter wheat thereby is one of the best studied crops regarding developmental physiology and its modeling (Angus et al., 1981; Hunt et al., 1996; Rickman et al., 1996; Cao and Moss, 1997; Kirby and Weightman, 1997; Weightman et al., 1997; Jamieson et al., 1998; Wang and Engel, 1998; McMaster et al., 2008). However, some structural aspects of phenology models are still subject of debate. The duration of phase until the initiation of the last leaf primordium (sowing to double ridge) may affect the length of later developmental stages, especially the duration from double ridge to ear emergence (Slafer and Rawson, 1994; Kirby et al., 1999). Despite that there seems to be experimental evidence for this "memory effect" (Kirby et al., 1999; Jamieson et al., 2007), it is not included in the phenology sub models of widely used wheat simulators like CERES wheat (Ritchie, 1991) and APSIM (Asseng et al., 2000). This may be caused by the fact that additional parameters like the plastochron have to be known in order to include the underlying mechanisms in a wheat phenology model which may be difficult to measure or estimate.

Even a simulation model containing all relevant processes influencing a certain goal variable will not deliver acceptable prediction accuracy without a proper calibration of its key parameters. A recent study (Palosuo et al., 2011) highlighted this using a set of recent wheat simulators. Because not always specially designed experiments with recent cultivars are available, the question arises which value routinely observations may have for the calibration of wheat phenology models.

The questions we want to clarify with our study therefore were twofold: is variable thermal time from double ridge stage to flag leaf emergence crucial for the predictive quality of wheat phenology models and is it possible to calibrate a wheat phenology model solely from easily obtained and widely available observations in field surveys?

For this purpose we re-implemented the algorithms of the CERES-Wheat (CW) phenology module into a simulation environment enabling parameter estimation. We then developed a modified model version (CWm) which has a variable thermal time from double ridge stage to flag leaf emergence resulting from an

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explicit simulation of leaf initiation and leaf emergence. For calibration and validation a very large multi-site and multi-year data set from Germany was used.

2. Material and methods

2.1. Data set

The main data set used in this study was obtained from surveys of phenological stages of wheat crops carried out yearly and routinely on different locations situated throughout Germany as a by-product of a phytopathological observation program. The geographical coordinates ranged from 48.2° to 54.4° northern latitude and corresponded to altitudes between 2 and 540 m a.s.l. The experimental sites were therefore located in contrasting climate regions throughout Germany, from the humid oceanic climate of the north, the dryer and winter cold medium continental climate of the east and the humid warm climate of the Upper-Rhine-Plane in the south west. A total sum of 848 data sets as a combination of location and year were available. However, the data were gathered by numerous persons who made ratings of wheat phenology at intervals not primarily motivated by the aim to analyse phenology. This inevitably limited the accuracy of any single data set (Weiss and Wilhelm, 2006). We divided the data set into two sub sets, for calibration and validation, respectively. A total of 84 location/year combinations from the years 1997 to 2003 were used for calibration. The validation data set contained additional data from the years 2002 to 2006. The phenological states were rated as BBCH stages (Witzenberger et al., 1989; Lancashire et al., 1991). This rating scheme has only minor differences compared with the Zadoks stages for Cereals (Lancashire et al., 1991; Zadoks et al., 1974). For a detailed definition of the BBCH stages including drawings see Meier (2001). During the rating tiller number was not differentiated between primary and secondary tillers. BBCH 30 was determined when the ear length elongated to approximately 1 cm above the basal node. BBCH 39 is defined as the time when flag leaf and ligule of the main stem are just visible. The number of nodes was identified by splitting the main stem. Single data sets did not always contain all significant phenological events. On average, seven to eight ratings of phenological stages were included in each data set. About 50 different varieties of winter wheat were used within the surveys and extreme early or late varieties were only used occasionally.

The air temperature data were taken from the nearest available weather station. The distance between the experimental sites and the weather stations varied from 2 to 60 km.

2.2. Phenological model

In our study we used the existing phenological CW model for winter wheat and adopted it according to the results obtained from the analysis of our experimental data. Briefly, the hypotheses and the theoretical logic of the existing and proposed model are given.

The phenological process in CW is divided into nine developmental or growth stages (GSs) according to Ritchie (1991) (Table 1). We simplified the model by pooling together the stages eight and nine, which represent the germination and emergence processes, because no data were available to distinguish between both events. The redefined parameter P9, which now governs the rate of development during the time from sowing to emergence, was calculated from the average of thermal time from sowing to emergence.

The CW model mainly describes phenological development through the change of GS over time. In CWm we added an explicit simulation of three additional state variables, the leaf number on the main stem (nL_{MS}), the number of initiated leaves on the main stem (inL_{MS}) and the BBCH stage.

At emergence nL_{MS} is set to one and inL_{MS} is set to 4 (Brooking and Jamieson, 2002). This is because the embryo at the time of sowing has already three leaf primordia (Bonnet, 1936; Roth, 1957; Kirby et al., 1985) and that an additional primordium is assumed to be produced until emergence.

The rate of change of number of initiated leaves is calculated according to Eq. (1) from emergence until the last leaf primordium is formed:

$$\frac{dinL_{MS}}{dt} = \frac{\max(0, T - T_b)}{Plast} \tag{1}$$

where *Plast* is the plastochron (°Cd) *T* is the air temperature and *Tb* is the base temperature.

The formation of leaf primordia which produce leaves is finished some time before the double ridge stage (Bonnet, 1935, 1936; Muschik, 1957). The time of the cessation of leaf primordia initiation, however, is not exactly coupled to a certain GS in the CW model and is also not linked to a certain BBCH stage. From available data of BBCH 37, i.e. the time when the last leaf appears, it was possible to estimate an approximate GS corresponding to the formation of the final leaf primordium (GS_{flp}) '*ex post*'.

The number of visible leaves on the main stem nL_{MS} is calculated accordingly:

$$\frac{dnL_{MS}}{dt} = \frac{\max(0, T - T_b)}{Phyll} \tag{2}$$

where *Phyll* denotes the phyllochron (°Cd).

Temperature, vernalization, photoperiod, and phyllochron interval determine the development rate during GS 1. According to CW the lowest value of two functions, depending on the vernalization stage and the actual photoperiod in interaction with the actual effective temperature limits the development rate (Table 1). Zadoks stages or equivalent BBCH values, however, are not calculated in the original phenology model of CERES-Wheat up to Version 3.0.

At early development stages (BBCH < 30) they are determined by the number of leaves and tillers present. At BBCH 13.5 there is a switch to BBCH 21, because simultaneously to the appearance of the fourth leaf the first tiller is emerging and mainstem leaf appearance is then associated with tiller appearance until BBCH 30. The phyllochron (*Phyll*), which has the same meaning as the parameter PHINT of the CW model, was calculated from BBCH data < BBCH 30 and the accumulated temperature for that period.

Within the model (Table 1) the implicit and simplifying assumption is made that terminal spikelet stage is more or less closely associated with BBCH 30 (Baker and Gallagher, 1983a,b) (Table 1).

Both models (CW, CWm) differ in the calculation of the length of GS 2 (Table 1). In the CW model daily temperature divided by three phyllochrons, is used for the calculation of the rate of change of GS. This implies a fixed duration of GS 2 in terms of thermal time. The BBCH stage then is estimated by linear interpolation. According to the definition of the BBCH stages, however, the development stage during this period depends on the number of nodes on the main stem. In the CWm model we therefore calculated a rate of node emission and introduced a parameter we called 'TSumInternode' analogous to the phyllochron. The numerical value of this parameter is the inverse of the slope of the relation of node numbers to the temperature sum from BBCH 30. This calculation is performed until BBCH 37 is reached and the final leaf begins to emerge. This developmental event is reached when the number of emerged leaves is equal to the number of leaf primordia minus two. The subtraction of two leaf primordia was made in accordance to the assumption that at least the last two vegetative primordia may not produce visible leaves, they are therefore sometimes called labile primordia (Griffiths et al., 1985). The length of