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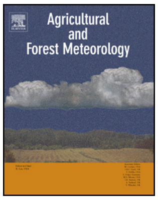

Performance of models for the beginning of sweet cherry blossom under current and changed climate conditions

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ABSTRACT

Six phenological models, two simple forcing (F)-models and one sequential chilling/forcing (CF)-model, each with and without day length (DL)-term in the forcing approach were optimised (2001–2010) and validated (2011–2015) on very accurate blossoming data of an experimental sweet cherry orchard at Berlin-Dahlem (cultivar 'Summit'). In parallel, in 3 seasons (2011/2012–2013/2014) climate chamber experiments were performed in order to determine the end of dormancy for 'Summit', which is usually an unknown or uncertain parameter in phenological modelling. Additionally, in the season 2013/2014 an *in situ* climate change experiment on three trees in the sweet cherry orchard were arranged, which was used to validate the phenological models for distinctly warmer climate conditions at the experimental site. On the basis of our climate chamber experiments we quantified the chilling requirement of 'Summit' trees. Thus, we were able to identify a CF-model for the beginning of sweet cherry blossom which is mostly physiologically based and works well for current and for future climate conditions at the experimental site. This paper also shows how phenological models can fail under warmer climates, if either the model is too simple or the model parameters are wrong. Additional, we confirmed that phenological models with DL-term in the forcing approach clearly surpassed the conventional phenological models without this parameter. The reason for this behaviour is extensively discussed.

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1. Introduction

Phenological models are important subroutines in climate and climate-impact models. Unfortunately, the models have sometimes great shortcomings. For instance, in terrestrial biosphere models, which are part of climate models, plant development is sometimes still fixed or only represented by temperature thresholds or simple Growing-Degree-Day (GDD) approaches (Robertson, 1968; Cannell and Smith, 1983). A comparison of 14 terrestrial biosphere models showed that most of the models calculate a too early beginning and a too late end of growing season. This can lead to an over-estimation of gross ecosystem photosynthesis (Richardson et al., 2012). A time-offset of growing season would additionally lead to an incorrect calculation of sensible and latent heat fluxes as well as to wrong radiation fluxes. Feedback mechanisms in climate models can increase these errors and even lead to wrong climate projections (Richardson et al., 2012, 2013). The same will happen if only very simple or not physiological proofed vegetation models are incorporated in impact models such as water-budged, growth and yield models.

Generally, three categories of phenological models exist. *Statistical models* describe the relationship between phenological events and climatological or meteorological parameters. It could be simple and multiple regression equations or even more complex calculations (Cenci and Ceschia, 2000; Linkosalo, 2000; Chmielewski and Rötzer, 2001; Ruml et al., 2012). Currently in phenology, *semi-mechanistic* (process-orientated) *models* are used which consider some basic rules of plant development, e.g. the chilling demand of trees during autumn and winter and the forcing requirement in spring (Schwartz, 1990, 1997; Cannell and Smith, 1983; Cesaraccio et al., 2004; Hänninen and Kramer, 2007; Chuine et al., 1998; Chuine, 2000, 2010; Schwartz et al., 2013). Many of the model parameters must be optimised on phenological data. In the case of a pure forcing (F) model at least 2–3 parameters must be estimated (base temperature of forcing T_{BF}, forcing requirement F^*, beginning of forcing accumulation t_1). If t_1 is fixed in the model, only 2 parameters must be optimised. Combined chilling/forcing (CF) models require at least 3 (chilling requirement C^* or date of dormancy release $t_0{}^*$, and T_{BF}, F^*) or much more parameters. For

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instance Caffarra et al. (2011b) published a model for the budburst of *Betula pubescens* which is based on altogether 11 parameters. Nine of them had to be optimised on phenological data. *Mechanistic models*, in which all parameters are directly derived from observations or experiments, would be desirable. However, these models are currently not available. For this reason at present the optimisation of semi-mechanistic models is necessary. A problem of these models is that it is sometimes uncertain if all optimised parameters are physiologically relevant and correct in magnitude. Thus, the calculated models must be carefully validated on independent years or different sites. The uncertainties considerably increase if the models will be used to calculate possible shifts in the timing of phenological events due to climate change. In this case the date of dormancy release (t_0^*) could shift, depending on the chilling requirement of the plant, the current local climatic conditions, and the expected temperature change (Luedeling et al., 2009; Chmielewski et al., 2012; Guo et al., 2015). The starting date of forcing accumulation (t_1) is another sensitive model parameter which can also lead to a failure of the model under changed climate conditions.

According to Chuine et al. (2013) in current phenological models the basic biochemistry and biophysics of certain phases is sometimes incompletely understood, which is especially true for the dormancy phase. For low-chill species in mid and higher latitudes, release of endodormancy and beginning of ontogenetic development is separated by a long period of ecodormancy, a period of unfavourable environmental conditions such as low temperatures and short days during winter. This is one reason why it is difficult to optimise physiologically sound models only on observations, because the model optimisation routines cannot sufficiently handle this period, so that the chilling requirement in the models can be overestimated. For this reason some authors state that simple GDD models perform better than complex, theoretically justified CF-models (e.g. Fu et al., 2012).

Beginning of dormancy is induced by shorter days and sinking temperatures in autumn (Heide, 2008; Schoot and Rinne, 2011) and steered by the formation of phytohormones in the buds (Arora et al., 2003; Welling and Palva, 2006; Rinne et al., 2011; Cooke et al., 2012; Meier et al., 2012; Götz et al., 2014). Dormancy is released when trees are exposed to a certain amount of chilling temperatures during autumn and winter (Crabbé, 1994). Statistically, this stage can be described by chilling models which calculate chilling hours (Weinberger, 1950) or chill units (Richardson et al., 1974; Linsley-Noakes et al., 1995) and which based on experimental findings (e.g. Erez and Lavee, 1971; Anderson and Seeley, 1992; Caffarra and Donnelly, 2011; Caffarra et al., 2011a,b). A more physiologically based model was developed by Fishman et al. (1987a,b). Here chill portions are calculated which consider the sequence of cool and warm temperatures as well as the chill-enhancing effect of moderate temperatures (Erez et al., 1979a,b; Erez and Couvillon, 1987). In this model it is assumed that the degree of dormancy completion depends on the level of certain dormancy-breaking substances, which accumulate in buds in a two-step process (Linsley-Noakes et al., 1995). Since this concept is probably the most physiological one (Luedeling and Brown, 2011; Darbyshire et al., 2011) we used it in this study. A lack of chilling causes effects such as bud drop, less bud break, delayed and weak flowering with economic consequences in fruit production (Legave et al., 1982; Viti et al., 2010).

This paper will show how additional information, derived from climate chamber experiments, can help to select a physiologically proofed model for the beginning of sweet cherry blossom (*Prunus avium* L.). The focus in this study is mainly aligned to the date of dormancy release, which is usually unknown and highly variable among fruit crops and cultivars. Over and above this we will show how phenological models, which can be used to calculate the beginning of blossom for current climate conditions, can fail for warmer conditions at the same experimental site.

2. Material and methods

In this study, 6 phenological models for the beginning of sweet cherry blossom (BBCH 60) were optimised (2001–2010) and validated (2011–2015) on very precise phenological observations (data from one orchard, daily observations, the same experienced observer in all years) from an experimental orchard at Berlin-Dahlem (52.47°N, 13.30°E, $h = 51$ m). The orchard comprises 80 cherry trees of the cultivars ‘Summit’, ‘Regina’ and ‘Karina’, which grow in 8 rows with 10 trees each, aligned in N–S direction. Trees are grafted on Gisela-5 rootstocks. For this study we only used the cultivar ‘Summit’ (origin in British Columbia), for which phenological observations between 2001 and 2015 were available. Meteorological observations for model optimisation and validation were used from a weather station which is located in the orchard.

For the model comparison, we optimised two simple forcing (F)-models with a fixed (M10: t_1 = 1 January) and optimised starting date (M20). These models assume that dormancy is always released before the accumulation of forcing rates $R_f(T_i)$ starts at t_1. For both models, a version with (M10b, M20b) and without (M10a, M20a) a day length-term in the forcing approach was calculated. For models (M10a, M20a) we calculated the well-known growing-degree-days (GDD, Eqs. (1) and (2)).

$$S_f(t) = \sum_{i=t_1}^{t} R_f(T_i) \tag{1}$$

with t_2: smallest t for which $S_f(t_2) \geq F^*$

$S_f(t)$: state of forcing, $R_f(T_i)$: forcing rate function; F^*: forcing requirement

$$R_f(T_i) = \max(0, T_i - T_{BF}), \qquad \text{in GDD} \tag{2}$$

T_i: daily mean air temperature, T_{BF}: base temperature.

For the models M10b, M20b we used as forcing approach photo-thermal-units (PTU, Eq. (3)) instead of GDD, because in a previous study we have shown that simple GDD-models with a fixed starting date have generally shortcomings (Blümel and Chmielewski, 2012).

$$R_f(T_i) = \max(0, T_i - T_{\mathrm{BF}}) \cdot \left(\frac{\mathrm{DL}}{10\,\mathrm{h}}\right)^{EXPO}, \qquad \text{in PTU} \tag{3}$$

EXPO: weighting factor for day length (DL)-term, which regulates the accumulation of GDD; 10 h: normalisation parameter to make the magnitude of F^* in PTU comparable with the GDD in Eq. (2).

M30a/b are sequential chilling/forcing (CF)-models which combine the accumulation of chill portions (CP) with the forcing approaches in Eq. (2) (M30a) and Eq. (3) (M30b). The hourly temperatures which are necessary to calculate chill portions were generated with the sine-log equations of Linvill (1990) from daily values. Chill portions were calculated from 1 September (DOY 244), because in German climate, temperatures before September do not contribute to chilling. Model performance was evaluated and compared by using the traditional root mean square error (RMSE). Since for model optimisation only 10 years of flowering observations were available we tested the robustness of the model parameters by a sensitivity study. For this purpose, we optimised the model parameters 10 times and skipped always one year after the other during the optimisation. As a result, we received 10 further parameter realisations, which show the variability of parameter estimation within these 10 years, given as standard deviation in Table 1.

Since no information on the date of dormancy release for ‘Summit’ at Berlin-Dahlem was available, in each season between

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