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Spatio-temporal patterns of phenological development in Germany in relation to temperature and day length

S. Siebert*, F. Ewert

Institute for Crop Science and Resource Conservation, University of Bonn, Katzenburgweg 5, 53115 Bonn, Germany

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ABSTRACT

Phenological development of crops has been extensively studied in field experiments but less so at larger scales for which data availability is often limited. To what extent the spatio-temporal variability of crop development can be explained by relationships derived from field studies such as the temperature sum concept used in many crop models is unclear but the question could entail the large scale application of these models. The aim of this study was to analyze the spatio-temporal patterns of crop phenological development in response to temperature and day length. We used a comprehensive dataset (656,234 phenological observations at 6019 observation sites) about the phenology of oat (*Avena sativa* L.) and related climate data from Germany for the period 1959–2009.

Our results show that the statistically significant warming trend since 1959 resulted in an earlier onset of all phenological stages and a shortening of most phenological phases with a 17-day earlier onset of yellow ripeness and a shortening of the "sowing to yellow ripeness" phase by 14 days. There was also a distinct spatial pattern in phenological development, with differences among eco-regions in the occurrence of development stages of 15–26 days and the length of the phases between stages of 6 and 21 days. Most of this spatio-temporal variability could be explained through the effects of temperature and day length. However, temperature sums (thermal times) and day length corrected temperature sums (photo-thermal times) also varied in time and space, pointing to the use of different varieties over time and across eco-regions. A considerable part of this variability in temperature sums and photo-thermal times could be explained by the mean temperature during the development periods. This may provide a means of modelling farmers' adaptation to climate change using varieties of different maturity types; but it requires further investigation. The good agreement of the thermal and photo-thermal requirements of oat computed in this study with relationships known from field experiments supports the use of the temperature sum concept for large scale application to simulate crop phenology in response to temperature and day length. The analysis should be extended to other crops and regions to further evaluate the observed spatio-temporal patterns in crop phenology and the relationships explaining these patterns.

1. Introduction

Phenological development of plants has received increasing attention as part of the research on climate change impacts (Challinor et al., 2007; Craufurd and Wheeler, 2009; Kalvāne et al., 2009; Luedeling et al., 2009a,b; Menzel et al., 2006a,b,c). The development rate of plants is mainly determined by genetically prescribed responses to temperature, photoperiod and vernalization or winter chilling (Luedeling et al., 2009b; McMaster et al., 2008; Saarikko and Carter, 1996; Slafer and Rawson, 1994). In general, plant development is fastest over a specific range of optimum temperatures and decreases with increasing deviation from this optimal temperature range (Craufurd and Wheeler, 2009; McMaster et al., 2008). Sensitivity to photoperiod and vernalization or chilling requirements protects plants from growing in unfavourable growing conditions (Körner and Basler, 2010). Despite the importance of temperature and day length for plant development there are also other factors such as drought that can affect development (McMaster and Wilhelm, 2003), though to a lesser extent. They will not be considered in this study. Although substantial progress has been made, the interplay of all these factors is still not completely understood and is subject to scientific research (Challinor et al., 2009; Craufurd and Wheeler, 2009; Slafer and Rawson, 1994).

The spatio-temporal patterns of plant phenological development at larger (than field) scale are mainly determined by the spatial and temporal variability and changes in climatic conditions (Estrella et al., 2009; Linderholm, 2006; Menzel et al., 2006a,b; Portmann et al., 2010; Sacks et al., 2010; Schleip et al., 2009b). For example, studies on phenophases of several European trees

* Corresponding author. Tel.: +49 228 733262; fax: +49 228 732870.
E-mail address: s.siebert@uni-bonn.de (S. Siebert).

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conducted by Rötzer and Chmielewski (2001) and Chmielewski and Rötzer (2002) showed that leaf unfolding, mayshoot and flowering begin on average 3 days later per 100 m altitude difference, 0.6 days later per 100 km displacement to the east and 2.4 days later per 100 km displacement to the north, with big differences between years with cold or warm spring seasons. Similarly, a large spatial and year-to-year variability in the occurrence of phenological stages has been reported for agricultural crops (Van Bussel et al., 2011). There are many studies showing that the observed warming trend due to global climate change has resulted in earlier onset dates for most phenological events across plant species and locations (Chmielewski et al., 2004; Estrella et al., 2007; García-Mozo et al., 2010; Hu et al., 2005; Kalvāne et al., 2009; Menzel et al., 2006a,b; Peltonen-Sainio and Rajala, 2007; Schleip et al., 2009a,b). Furthermore, increased mean temperature has caused a shortening of developmental phases of annual crops with effects on crop yields, because a shortening of the growing season results in less absorbed radiation and therefore less biomass and yield (Chmielewski et al., 2004).

Although the general response of plants to increasing temperatures in the above studies was similar, the magnitude of the response was different among plant species, locations and analyzed time periods. A relatively strong response to changing temperatures was found for wild trees and fruit trees while the reported responses of annual crops were smaller (Estrella et al., 2009; Menzel et al., 2006c). There are several reasons for the different magnitude in the response of annual crops as compared to trees. Vitasse et al. (2009), for example, found large differences in the phenological sensitivity to temperature between seven woody species in Europe but no differences between populations of the same species. In contrast, farmers have access to a large number of different cultivars with different sensitivities to temperature, photoperiod and vernalization and can change cultivars from year to year, while perennial crops like fruit trees are often cultivated for decades and forest trees for even longer periods. Therefore there is a greater possibility of planned or autonomous adaptation in the cultivation of annual field crops to changing climate conditions (Reidsma et al., 2007, 2010). Another possible reason for the smaller response of annual crops to the warming trend is that the sowing date does not only depend on site-specific temperature but also on other factors like workability of the soil, availability of machinery and manpower or crop rotation effects which affect farmers' decisions and mask the climate change effect. The sowing date, however, influences the timing of all the subsequent phenological events.

The complexity of the interaction of all these effects on the duration of the phenological development of agricultural crops makes it very unlikely that changes in temperature can be converted directly into changes in crop phenology or that the possible impact of future climate change on crop phenology and crop yields can be derived directly from relations observed for the past (Challinor et al., 2009; Craufurd and Wheeler, 2009). Therefore many attempts have been made to model crop phenology and the impact of climate change on it for different crops, cultivars, locations and scales, mainly based on the concept of temperature sums (e.g. Challinor et al., 2007, 2009; Craufurd and Wheeler, 2009; Ewert et al., 1996, 1999; Harrison et al., 2000; McMaster and Wilhelm, 2003; McMaster et al., 2008; Peltonen-Sainio and Rajala, 2007; Porter et al., 1987; Slafer and Rawson, 1994; Yan and Wallace, 1998). However, model parameterization is challenging, given the diversity of crops and cultivars, and so far mainly based on results from field experiments. Accordingly, in this study we analyze long-term temperature records in conjunction with a large data set of crop phenology observations of an example crop, oat (*Avena sativa* L.), grown across Germany during the period 1959–2009. We aim to determine the spatial patterns and temporal changes in the timing of phenological events and in the duration of phenological phases and to explain the observed variability by the effects of temperature and day length. The results should support the large scale application of the concept of temperature sums, originally derived from field experiments and used in many crop phenology models.

2. Materials and methods

2.1. Phenological data

Data on the earliest observation of the stages of sowing, emergence, shooting, heading, milk ripeness, yellow ripeness, harvest by hand, full ripeness, and harvest by combine were provided by the Germany National Meteorological Service (DWD) for the period 1951–2009 (Deutscher Wetterdienst, 2010a). The records were collected by a network of voluntary observers. According to the instructions for observers, the observation area should have a radius of 1.5–2 km, the observed fields must not differ more than 50 m in altitude from the mean altitude of the observation area and irrigated crops or crops in greenhouses are excluded (Deutscher Wetterdienst, 1991). The total number of records collected by the DWD-network for oat at 6019 phenology observation areas (referred to below as sites) was 656,234, of which 652,937 were considered correct after a quality check by the DWD. The number of available records differed among years, phenological stages (Fig. S1) and sites. For each site additional attributes such as geographical coordinates and altitude were available. Based on the handbook of German eco-regions, i.e. regions of similar characteristics with regard to climate, topography, hydrography, soil and geology (Meynen et al., 1953–1962), each site was assigned by the DWD to one of the 86 eco-regions delineated in Fig. 1 and to one of 505 so-called eco-units which represent a subdivision of eco-regions.

Further analysis of the records considered correct by the DWD showed that the validity of many observations was questionable (e.g. observations were assigned to the wrong season or different phenological stages fell together on the same date for the same site and year). Therefore a procedure was developed to filter out these questionable observations for the subsequent analysis. Mean values and standard deviations for the stages sowing, emergence, heading, yellow ripeness and harvest by combine (hereafter referred to as harvest) and for the length of the periods sowing to emergence, emergence to heading, heading to yellow ripeness, yellow ripeness to harvest and sowing to harvest were computed for each of the eco-regions separately (Table S2). Then, observations were flagged as outliers when they fell outside the range of the mean value ± 2 times the standard deviation computed for the respective eco-region. Records were used in this study only, when none of the observations at the same site and the same year was flagged as outliers. By using this procedure 21% of the records were filtered out. The application of the filtering routine had little effect on the mean value of the observations but significantly reduced variability in comparison to the original data (Table 1). Furthermore we decided to limit this study to the period 1959–2009 and to the stages sowing, emergence, heading, yellow ripeness and harvest. The period 1959–2009 was selected because observations for harvest by combine started in 1959. Records for the stages 'milk ripeness' and 'full ripeness' and 'harvest by hand' were not considered because these observations were only available for a limited period of time (either before 1991 or after 1990, see Fig. S1). Observations for 'emergence' and 'heading' were preferred to observations for 'shooting', because the exact beginning of shooting is more difficult to observe in the field, adding a larger subjective error to the data. The number of records finally considered in this study for observed phenological stages varied between