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Climate and management interaction cause diverse crop phenology trends

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ABSTRACT

Growing evidence suggests that the warming trend observed in many parts of the world has considerably modified crop phenology during the last decades but little is known about the impact of changes in crop management on crop phenology and possible interactions with temperature increase, and whether responses can be generalized across crop types. Here we evaluate the effects of climate and management on crop phenology by using observations for winter rapeseed and winter rye obtained in Germany for the period 1960–2013 by using piecewise linear regressions of temperature and phenology data on year. We show that long-term trends in crop phenology are crop-specific. The length of the vegetative phase of winter rapeseed declined by 4.8 days per decade in the period 1979–2013. However, the corresponding decline for winter rye was only 1.3 days per decade in the period 1978–2013 with the difference caused by change in management practices such as the introduction of early flowering cultivars of winter rapeseed or changes in sowing date of winter rapeseed and winter rye during the last decades in Germany. The length of the reproductive phase of winter rye declined by 0.9 days per decade between 1976 and 2013 in response to the warming trend in that period. In contrast, the extended use of late maturing cultivars with a longer grain filling period and changed planting densities over-compensated for the effect of increasing temperature on the length of the reproductive phase of winter rapeseed and caused an increasing trend of 2.0 days per decade between 1992 and 2013. The sowing date of winter rye advanced by 1.3 days per decade in the period 1972–2013. The length of the phase between maturity and harvest increased considerably for both crops and compensated partly for the effect of increasing temperature to shorten the preceding phenological phases. We conclude that it is essential to account for interactions between climate and crop management in climate change impact analysis and assessment studies and that differences among crops need to be considered.

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1. Introduction

The warming trend observed during the last decades is projected to continue and to further accelerate in the future (Alexander et al., 2006; Easterling, 1997; Hansen et al., 2006; Mann et al., 2004; Paeth et al., 2015). Due to the sensitivity of plant development rates to temperature (Hay and Kirby, 1991; Porter et al., 1987; Slafer and Rawson, 1994), plant phenology is one of the most accurate and sensitive indicators of climate change (Brown et al., 2012; Chmielewski et al., 2004; Tao et al., 2006). Temperature rise has reduced global crop production (Lobell et al., 2011), with a 6% decline of global wheat production per degree Celsius increase in temperature (Asseng et al., 2015). The shortening of the growing period by increased temperature has contributed to yield reduction (Craufurd and Wheeler, 2009; Tao et al., 2012, 2006), but has also reduced heat stress intensity in winter wheat due to shift of the period around anthesis to the cooler spring season (Rezaei et al., 2015). Because of the complex relationship between climate change, crop phenology and crop yield it is essential to consider changes in crop phenology when assessing climate change impacts on crop productivity.

The development rate of crops is mainly determined by the temperature during the growing period with a maximum development rate around an optimum temperature range differing between crops and development phases (Peñuelas et al., 2002; Porter and Gawith, 1999; Slafer and Rawson, 1994). Flowering of plants advanced by 4 to 5 days per °C of temperature increase across Europe, but responses of later phenological stages such as maturity to temperature increase have been diverse (Bertin, 2008).

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For temperatures observed in Germany, crop development rate and temperature typically show a positive relationship so that increasing temperature results in a shorting of phenological phases (Estrella et al., 2007; Menzel et al., 2006; Siebert and Ewert, 2012). During the early vegetative phase, the response of the development rate of winter crops to temperature is affected by vernalization and photoperiod (Siebert and Ewert, 2012; Slafer and Rawson, 1994). This response buffers the impact of inter-annual variability in weather conditions (Craufurd and Wheeler, 2009; Hay and Kirby, 1991) and avoids unfavorable conditions for plants reaching the reproductive phase.

Long term changes in crop phenology are not only determined by climate change but also influenced by management practices such as sowing density, the timing of sowing and harvest (Tao et al., 2006) or cultivar choice and breeding strategies (Ceccarelli et al., 2010). For example, the sowing date of winter wheat in Germany has advanced by 5.1 days in the period 1951–2009 and contributed to the earlier occurrence of subsequent phenological stages like day of heading (Rezaei et al., 2015). The sowing date of maize advanced by 0.3 to 0.8 day per decade in central US over the period 1979 to 2005, mainly due to improvements of cultivars, planting equipment and time-saving management practices like conservation tillage (Kucharik, 2006). Earlier sowing also affects all subsequent phenological stages and is therefore considered as an adaptation measure to climate change. For example, earlier sowing could offset the negative impact of climate change on maize in the US corn belt (Iizumi et al., 2014) or on maize and pearl millet grown as fodder in Northeast Iran (Eyshi Rezaei et al., 2015) by shifting the reproductive growth stage to the cooler part of the growth season. Planting density also affects the length of the period until full maturity of rapeseed (Morrison et al., 1990) because of producing more branches in low planting densities which needs more time to reach maturity, so that changes in planting density may impact crop phenology as well.

The occurrence of phenological stages is also affected by cultivar selection. The temperature sum above a crop-specific base temperature required from sowing to maturity is cultivar-specific. For several crops it has been shown that temperature sum requirements of currently used cultivars are related to seasonal mean temperature (Olesen et al., 2012; Siebert and Ewert, 2012) or to the annual temperature sum at the place of cultivation (Deryng et al., 2011) with higher requirements in warm regions. New cultivars with a longer grain filling period have also been proposed as an adaptation strategy to climate change (Ceccarelli et al., 2010; Martín et al., 2014). In China, the temperature sum of spring wheat cultivars required for crop development from sowing to maturity has risen even though the length of the growing period declined in the period 1981–2007 (Tao et al., 2012). Management decisions can also influence the period between physiological maturity and harvest. For spring oat grown in Germany, the length of the period between yellow ripeness and harvest has prolonged from 9.4 days in year 1959 to 14.2 days in year 2009 (Siebert and Ewert, 2012). Similar to this, negative trends in the occurrence of yellow ripeness calculated for winter wheat, winter rye and winter barley grown in Germany in the period 1951–2004 were stronger than negative trends for the day of harvest (Estrella et al., 2007) indicating that the length of the period between maturity and harvest has increased for these crops as well.

The combined effects of climate and crop management on crop phenology are a challenge for climate change impact research because the signal of climate change seen in phenological observations is modified or even reversed by the effects of crop management. In addition, changes in crop management may already be a response to changing climate. Process based crop models, which are often used in assessments of climate change impacts on crop production, typically account for the effects of changing temperature on crop phenology but management practices and cultivars are often considered static or assumed to be optimal for achieving high crop yields (Deryng et al., 2011; Elliott et al., 2015; Rosenzweig et al., 2014; Teixeira et al., 2013). Only recently, efforts were made to disentangle the effects of climate change and crop management on crop phenology (Iizumi et al., 2014; Olesen et al., 2012; Siebert and Ewert, 2012; Tao et al., 2016, 2012; van Oort et al., 2012; Zhao et al., 2016). These studies investigated specific crops and were constrained to specific management impacts such as sowing date or thermal time requirements of cultivars but no attempt has been made so far to systematically compare effects of climate change and change in management among crops.

Here we analyze and compare effects of changing climate and management on the phenology of winter rapeseed (*Brassica napus* L.) and winter rye (*Secale cereale* L.) by using extensive observations made in Germany for the period 1960 to 2013. We detect climate change effects by comparing changes in the occurrence of the true phenological stages (the stages not directly impacted by farmer's activities) emergence, heading, flowering, and maturity (Δ Phenology) to changes of the mean temperature at the phenology observation sites (Fig. 1). Effects of management are subdivided into change of sowing date (Δ Sowing date), change of the period between maturity and harvest, and change of cultivar characteristics (Δ Cultivars) investigated by calculating temperature sums above a specific base temperature between true phenological stages (Fig. 1). The objectives of the study are to quantify the response of crop phenology to combined changes in climate and management and to understand possible differences between crops to point to critical aspects when generalizing relationships between climate change and crop phenology.

2. Materials and methods

2.1. Analysis of trends in crop phenology

2.1.1. Processing of phenological data

Phenology observations of winter rapeseed and winter rye including day of sowing, beginning of emergence, beginning of heading (winter rye), beginning of flowering (winter rapeseed), beginning of yellow ripeness (winter rye), beginning of maturity (winter rapeseed), and day of harvest were obtained from the phenological observation network of the German Meteorological Service (Kaspar et al., 2015) for the period 1960 to 2013. To filter out potential outliers, mean values and standard deviations for the phenological stages and the length of the phases between the stages were calculated for each of the 86 eco-regions in Germany. Observations were flagged as potential 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 potential outlier (Siebert and Ewert, 2012). We restricted our analysis to 8 federal states in western Germany (Fig. S1) because we found that the time series of observations was incomplete in the other states for all considered phenological stages except of beginning of flowering of rapeseed. The total number of observations after applying the filtering process was 131646 for winter rapeseed and 227312 for winter rye obtained from 4824 sites across the study region (Fig. S3). Observations of the maturity date of winter rapeseed were only available since 1992.

We interpolated phenology observations for each year to a 1 km $\times$ 1 km grid by using inverse distance weighting method (Fig. S2). The spatial interpolation was applied to fill data gaps caused by varying density of observations in space and time to obtain uniform data coverage (Fig. S3). The development rate of winter rapeseed and winter rye is sensitive to temperature and day length

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