

Impact of climate change on the timing of strawberry phenological processes in the Baltic States

Līga Bethere, Tija Sīle, Juris Senņikovs and Uldis Bethers

Laboratory for Mathematical Modelling of Environmental and Technological Processes, University of Latvia, Zellu 25, Riga, LV-1002; liga.bethere@lu.lv

Received 11 September 2015, accepted 11 January 2016

Abstract. Climate change has been shown to impact aspects of agriculture and phenology. This study aims to quantify changes in the timing of garden strawberry blooms and harvests in the Baltic States using Regional Climate Models (RCMs). First, parameters for a strawberry phenology model based on the growing degree day (GDD) methodology were determined. Growing degree days were calculated using a modified sine wave method that estimates the diurnal temperature cycle from the daily maximum and minimum temperature. Model parameters include the base temperature and the required cumulative GDD sum, estimated from phenological and meteorological observations in Latvia for the years 2010–2013 via iterative calibration. Then an ensemble of bias-corrected RCM results (ENSEMBLES project) was used as input to the phenological model to estimate the timing of strawberry phenological processes for the years 1951–2099.

The results clearly show that strawberry phenological processes can be expected to occur earlier in the future, with a significant change in regional patterns. Differences between coastal and inland regions are expected to decrease over time. The uncertainty of the results was estimated using the RCM ensemble spread, with northern coastal locations showing the largest spread.

Key words: thermal time model, growing degree days, strawberry phenology, regional climate models.

INTRODUCTION

Climate change has a direct and significant impact on vegetation phenology. Changes in growing season length and earlier onset of phenological events, such as leaf-out and blossoming of trees, crop stem elongation and green-up of land surface, have been documented in recent reviews (Cleland et al. 2007; Richardson et al. 2013). The length of the growing season and the timing of phenological events are directly linked to temperature change (Ahas et al. 2000; Chmielewski & Rötzer 2001; Linderhorm 2006; Fu et al. 2013).

Agriculture has been widely recognized as one of the sectors of the economy that will be affected by climate change (e.g. EC 2013), and the consideration of possible adaptation strategies requires robust scientific data. However, the assessment of possible impacts is complicated by the wide range of interconnected processes that are both relevant to agriculture and projected to be altered by climate change, e.g. water availability, land use and ecosystem properties (Falloon & Betts 2010).

The impacts are regionally varying; thus, projections for northern Europe suggest increased crop productivity and possible introduction of new crop types when suitability ranges extend northwards (Falloon & Betts 2010). In the northern Baltic Sea region the growing season

length is one of the main limiting factors on agriculture (Krug et al. 2015). However, it has been shown to be increased recently by earlier spring events and is projected to increase in the future also by autumn starting later (Christidis et al. 2007).

A wide range of indices have been proposed for the definition and quantification of the growing season length. They can be derived directly from meteorological events (e.g. frost-free days) or related to phenology or the hydrological cycle (Christidis et al. 2007).

The impact of climate change on the timing of plant phenology varies seasonally (depending on whether the plant blooms in spring, summer or autumn) and also between different plant species (Cleland et al. 2007; Richardson et al. 2013). Variation in the timing of phenological processes for different species is important in ecosystem ecology (Cleland et al. 2007).

A number of studies have addressed the timing of phenological processes in the Baltic countries. These studies analyse past observations of phenological events and use this information to either analyse changes or develop phenological models of trees, crops, potatoes and other plants (Ahas 1999; Ahas et al. 2000; Kalvāne et al. 2009; Kalvāns et al. 2014).

The mathematical modelling of phenological processes is not only useful but in some cases quite indispensable. Models can be used to estimate past

phenological data when observations are lacking or to account for spatial differences. Importantly, modelling is the only method that may provide future projections (Jaagus & Ahas 2000; Cleland et al. 2007). Thermal time models are widely used in vegetation phenology (Cleland et al. 2007). They are based on the accumulation of growing degree days (GDD) or heat units. The GDD methodology consists of defining a constant base temperature (e.g. 0°C) and then calculating the sum (integral) of those temperatures that exceed the base temperature in the temperature time series. The phenological event takes place when after a certain starting date a specified GDD amount has been accumulated. Therefore each GDD model has at least three parameters – the base temperature, the number of GDD that needs to be accumulated and a starting date. The input data for thermal time models consist of temperature time series.

General Circulation Models (GCMs) form the basis of future climate projections, however, they have insufficient spatial (grid) resolution for impact studies (Flato et al. 2013). Dynamical downscaling using Regional Climate Models (RCMs) is widely used to estimate the agricultural impacts of the climate change, for instance wheat yield, maize suitability, grass production, growing season length (Olesen et al. 2007; Kristensen et al. 2011; Ahmed et al. 2013).

The GCMs and RCMs represent the physical understanding of the climate, and although RCMs have shown reasonable performance representing the climate, they are known to have systematic biases that need to be addressed before applications (Teutschbein & Seibert 2012). The methods that compare and link model results with observations are called Model Output Statistics (MOS) methods that are part of the statistical downscaling. These methods either assume that the difference between models and observations in the future remains the same (bias correction methods) or that the increase in parameters shown by models should be applied to observations (delta change) (Wibig et al. 2015).

Strawberries are a commercially significant berry crop in the Baltic States and most produce is locally sold fresh. The short production period makes the timing of strawberry harvests important and there is interest in early and late cultivars (Laugale & Lepse 2007). In the region the production of organic strawberries also takes place responding to environmentally conscious consumers that are looking for (but not always receiving) health benefits or better taste (Tõnutare et al. 2014).

The aim of this study is to evaluate the possible impact of climate change on the timing of the phenological process using garden strawberry bloom and fruit ripeness times as examples. The GDD methodology is employed. The temperature-based model is chosen following the suggestions in Cleland et al. (2007) of

temperature being widely recognized as a significant factor in plant phenology. Other parameters such as CO₂ concentration and changes in rainfall have shown no influence (or only species- or region-specific impact) or have unclear or conflicting evidence about their role, while the inclusion of the photoperiod in phenological models requires further research (Cleland et al. 2007).

The study consists of several parts. First, the parameters for the strawberry development phase GDD model were estimated by combining meteorological temperature and phenological observations. Second, the bias-corrected RCM model ensemble data from the ENSEMBLES project under the A1B emission scenario (van der Linden & Mitchell 2009; Christensen et al. 2010) were used to calculate the timing of strawberry development for the period 1951–2099. Time slices for the past (1951–1980), present (2001–2030) and future (2070–2099) were visualized to analyse the spatial differences. Third, six locations representing coastal and inland climate were chosen for a more detailed analysis including the investigation of uncertainty.

DATA AND METHODS

Data

Meteorological observations

The hourly air temperature observations for the years 2010–2013 were acquired from the Latvian Environment, Geology and Meteorology Centre for all available Latvian meteorological stations (see Fig. 1). Minimum and maximum daily temperature was calculated from hourly data and interpolated using kriging interpolation to the strawberry phenology observation locations (see Fig. 1).

Strawberry phenology observations

Observations of strawberry phenological processes for the years 2010–2013 were obtained from the Latvian

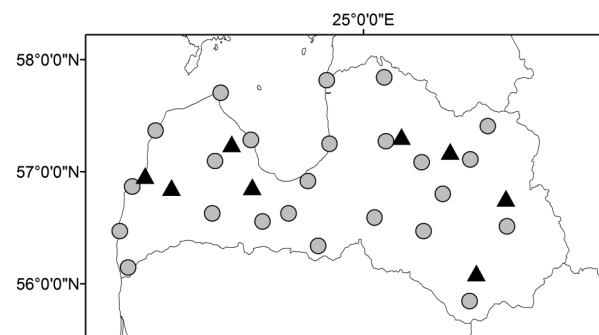


Fig. 1. Meteorological observation stations (circles) and strawberry phenological observation locations (triangles).

State Plant Protection Service (for locations of strawberry fields see Fig. 1). Observations by the State Plant Protection Service are carried out on a semiregular basis – fields are occasionally examined and the development stage is recorded, but some might be missed. The data were already classified using the BBCH (*Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie*) scale (Bleiholder et al. 2001). It is used for the unified classification of similar phenological stages of different plants. The code for each stage consists of two digits denoting the principal and the secondary growth stage, respectively. Descriptions of the growth stages given below are taken from Bleiholder et al. (2001).

Three groups of observations were selected and used in this study, with some phenological stages being grouped together:

1. Calendar date of bloom. Observations of the following two BBCH stages were grouped together with the second being used if the first was unavailable:
 - full flowering: secondary and tertiary flowers open, first petals falling (stage 65);
 - beginning of flowering: about 10% of flowers open (stage 61).
 2. Calendar date of the first harvest or the first fruits using only observations where the corresponding bloom date was also available. Observations of the following two BBCH stages were grouped together with the second being used if the first was unavailable:
 - main harvest: more fruits coloured (stage 87);
 - first fruits have cultivar-specific colour (stage 85).
 3. Calendar date of the second harvest or the second fruits, using only observations where the corresponding bloom and first fruit data were available. Only one BBCH stage was used for this group:
 - second harvest: more fruits coloured (stage 89).
- The total number of observations is shown in Table 1.

Regional Climate Model data

The source of the RCM ensemble data is the ENSEMBLES project (van der Linden & Mitchell 2009). Only members that had full time coverage over the period 1951–2009 were used (15 models, A1B

Table 1. The number of phenological observations by type. The columns (a) and (b) correspond to the first and the second choice of the BBCH stage

Process	a	b	Total
Bloom	12	7	19
First harvest	11	5	16
Second harvest	13		13

scenario; see Table 2 for the list of ensemble members). Continuous time series of daily minimum and maximum air temperature at 2 m were used for the GDD calculation. Before application, the time series for the years 1951–2009 were bias-corrected by employing the method described in detail in Sennikovs & Bethers (2009), using daily meteorological observations for the control period 1961–1990 (locations shown in Fig. 2). The

Table 2. List of the Regional Climate Model (RCM) ensemble members used (ENSEMBLES), showing the originating institution, the name of RCM, the driving General Circulation Model (GCM) and the grid size. For explanation of abbreviations see van der Linden & Mitchell (2009)

Institute	RCM	GCM	Resolution (km)
C4I	C4IRCA3	HadCM3Q16	25
ETHZ	CLM	HadCM3Q0	25
METO-HC	HadRM3Q0	HadCM3Q0	25
METO-HC	HadRM3Q16	HadCM3Q16	25
METO-HC	HadRM3Q3	HadCM3Q3	25
DMI	HIRHAM5	ECHAM5-r3	25
DMI	HIRHAM5	ARPEGE	25
KNMI	RACMO2	ECHAM5-r3	25
KNMI	RACMO2	ECHAM5-r3	50
KNMI	RACMO2	ECHAM5-r2	50
ICTP	REGCM3	ECHAM5-r3	25
MPI	REMO	ECHAM5-r3	25
CNRM	RM 5.1	ARPEGE	25
SMHI	SMHIRCA	ECHAM5-r3	25
SMHI	SMHIRCA	HadCM3Q3	25

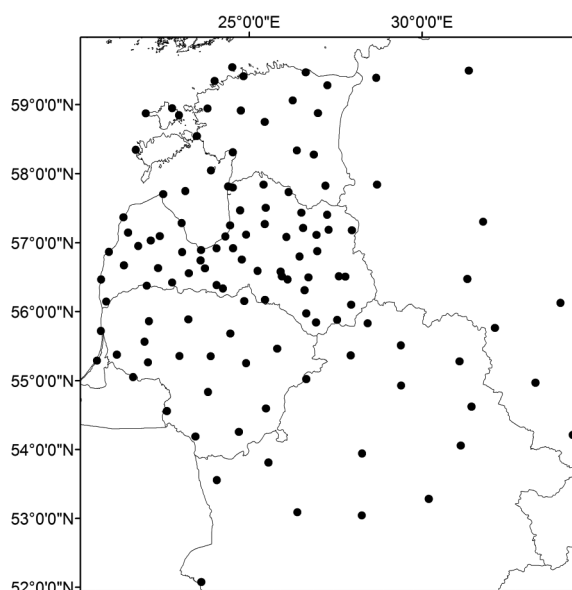


Fig. 2. Locations of meteorological stations used for bias correction of the RCM.

method uses quantile mapping and the cumulative distribution function is calculated for each day of the year using both the data for five days before and after the day of interest (11 days in total).

Methods

The method of the GDD calculation depends on the type of available data. In this study the meteorological observations have hourly data, but for RCM results only daily values (mean, minimum and maximum) are available. This limits the available approaches if the same methodology is to be applied to both datasets. The calculation is straightforward from the hourly temperature data, but the daily average or minimum and maximum temperature can be used by making assumptions about the daily cycle (Baskerville & Emin 1969; Allen 1976; Johnson & Fitzpatrick 1977; Parton & Logan 1981; Cesaraccio et al. 2001). A comparison of different methods shows that even though the hourly approach is the most precise and is required in specific cases, using minimum and maximum temperature for approximating the diurnal cycle leads to reasonably good results (Reicosky et al. 1989). In addition, different sine wave methods or triangle methods using the minimum and maximum temperature are both simple and superior over the more basic approximations of the diurnal cycle using the average temperature (Roltsch et al. 1999; Cesaraccio et al. 2001), also in the climate in the Baltic Sea region (Kalvāns et al. 2014).

Vegetation models for perennial plants can include dormancy release that is based on the accumulation of chilling units similar to GDD but accounting for temperatures below a specified base temperature. However, it is suggested that methods with chilling requirements are not universally better due to the increased number of parameters that lead to over-calibration and result in poor performance with a test data set (Linkosalo et al. 2008; Richardson & O'Keefe 2009; Fu et al. 2012).

Daily temperature cycle and GDD sum

To estimate the diurnal cycle from the daily minimum and maximum temperature observations for GDD calculations, we used a method by Cesaraccio et al. (2001). This method was employed both to calculate the GDD values from observation data for the estimation of parameters for the strawberry phenology model and also to model the timing of strawberry phenological phases from the RCM temperature data.

First, it is assumed that the minimum temperature T_n occurs at the time of sunrise H_n and the maximum

temperature T_x is reached at the time H_x , four hours before sunset H_0 :

$$H_x = H_0 - 4. \quad (1)$$

The diurnal cycle in this model consists of three parts.

Two different sine functions describe temperature from the time of sunrise H_n to H_x , and from H_x to the time of sunset H_0 . Nighttime temperature until the next sunrise H_p (with the corresponding minimum temperature for the next day T_p) is described by a square-root function. Daily sunrise and sunset times were calculated for each location using a method by Teets (2003).

The temperature T_0 at the sunset time H_0 is calculated by the formula

$$T_0 = T_x - c(T_x - T_p), \quad (2)$$

where the parameter c is equal to 0.39.

The hourly temperature $T(t)$ is calculated using the expressions

$$T(t) = \begin{cases} T_n + \alpha \cdot \sin \left[\left(\frac{t - H_n}{H_x - H_n} \right) \frac{\pi}{2} \right], & H_n \leq t \leq H_x \\ T_0 + R \cdot \sin \left[\frac{\pi}{2} + \left(\frac{t - H_x}{4} \right) \frac{\pi}{2} \right], & H_x < t < H_0 \\ T_0 + b \sqrt{t - H_0}, & H_0 \leq t \leq H_p. \end{cases} \quad (3)$$

Here t is the local time, and α , R and b are calculated as follows:

$$\alpha = T_x - T_n, \quad (4)$$

$$R = T_x - T_0, \quad (5)$$

$$b = \frac{T_p - T_0}{\sqrt{H_p - H_0}}. \quad (6)$$

An example of this approximation of the diurnal cycle $T(t)$ is shown in Fig. 3.

The amount of GDD for each day was calculated as the area between the diurnal temperature cycle and the base temperature T_{base} and converted from hours to days (see Fig. 3):

$$\text{GDD}_{\text{daily}} = (I1 + I2 + I3)/24. \quad (7)$$

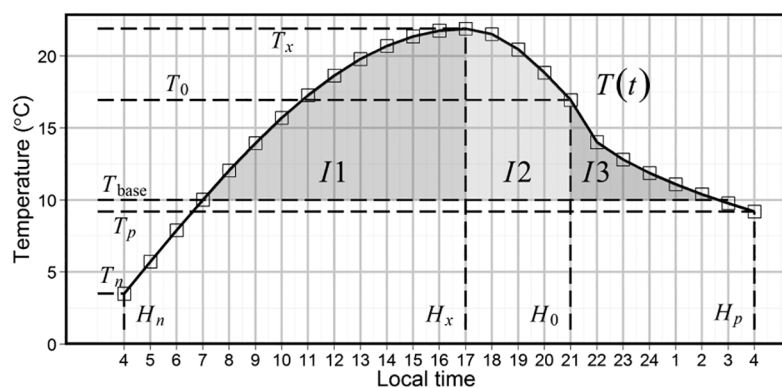


Fig. 3. Sample diurnal temperature cycle and GDD calculation, adapted from Cesaraccio et al. (2001).

The area of each segment I_1 , I_2 and I_3 was calculated using the integral of (3) for the part of the diurnal temperature cycle that is above the base temperature. When the hourly temperature is below the base temperature, the GDD value is zero.

Methodologies of GDD calculation often include an upper threshold at which the rate of plant development begins to decrease (Allen 1976; Wilson & Barnett 1983). However, this approach does not necessarily increase the accuracy of the model (Baskerville & Emin 1969; Wilson & Barnett 1983), and therefore it was decided that the upper threshold is not necessary for the cool climate of the Baltic countries.

Base temperature and total GDD sum estimation

The iteration method has shown good results in estimating the base temperature and the required cumulative sum of GDD from field observations (Snyder et al. 1999).

To account for the non-uniform response to temperature during different plant growth stages and varying base temperatures that are mentioned as possible issues with regard to the GDD methodology (Wang 1960; Bonhomme 2000), strawberry bloom, the first harvest and the second harvest were considered separately, with three different sets of base temperature and cumulative GDD sum. The GDD values for bloom for each year and location were summed from the 1st of January. For the first harvest this summation is carried out from the date of bloom observation and for the second harvest from the observation of the first fruits.

The iteration process through different base temperatures and GDD sums was carried out for minimum and maximum temperature observations with the aim of minimizing the root-mean-square-error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (c_i - o_i)^2}{n}}, \quad (8)$$

where c_i – calculated day of the year for a specific event, o_i – observed day of the year for a specific event, n – number of observations.

The iteration procedure for each phenological event is carried out for a range of base temperatures until the combination of the base temperature and GDD sum that gives the smallest overall RMSE for a specific phenological event is found. The acquired base temperature and GDD sum values as well as the minimum RMSE in calendar days and the number of observations can be seen in Table 3.

The RMSE values in Table 3 can be interpreted as the average error in calendar days between the observed and modelled days of the phenological event. The aforementioned methodology of field observations (ambiguity in the definition of the first harvest) can also contribute to the RMSE – the day of observations does not necessarily represent the first day of the phenological event, instead it shows a day when the event was present. This could introduce a positive bias – the model showing the events after they have actually taken place. It can be noted that RMSE values are not larger than the duration of the corresponding phenological process (e.g. the period when the first berries are produced).

Use of RCM data

The bias-corrected ensemble of the RCM time series was used for two separate but similar sets of calculations to analyse the change in the timing of phenological processes over time. In the first case calculations were

Table 3. Calculated optimal base temperature (T_{base}) and GDD sum values

Process	T_{base} (°C)	GDD sum	Number of observations	RMSE (days)
Bloom	0	586	19	4.3
First harvest	6	284	16	7.3
Second harvest	10	95	13	2.2

done for three 30-year periods (Figs 4–6) for each observation station (Fig. 2). In the second case a number of locations were chosen (Fig. 7) for further analysis and time series of the timing of the phenological event with a step of 10 years were calculated (Figs 8, 9). In these time series a time moment corresponds to the middle point of a 30-year calculation period (e.g. year 2015 corresponds to the period 2001–2030).

Calculations corresponding to each 30-year period for each location and phenological process were carried out using the following steps:

1. for a member of the RCM ensemble, for each of the 30 years in the required interval and for each

location the day of the occurrence of the phenological process (the bloom, first harvest and second harvest) was calculated;

2. the 30-year mean was calculated;
3. steps 1 and 2 were performed for all models (15 in total);
4. the median was calculated from 15 acquired values and further used as the estimation of the phenological process for the required location and 30-year period;
5. in addition, the 20th and 80th percentiles from the acquired 15 values were calculated for additional time series analysis (Fig. 9).

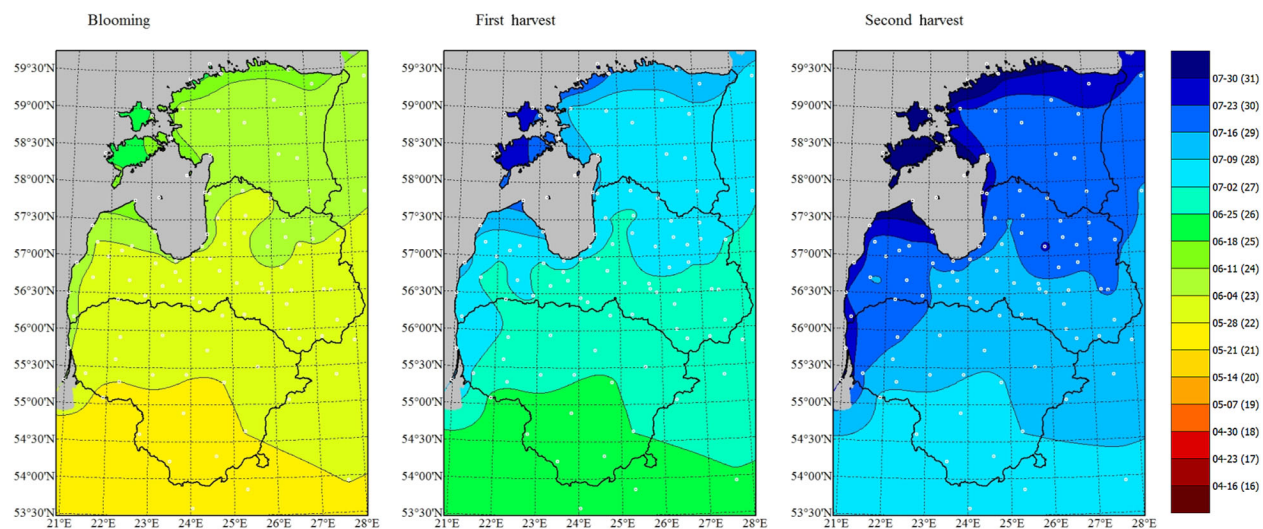


Fig. 4. Timing of strawberry development, weeks of the year, past climate (1951–1980). White dots show the locations of stations used for RCM data bias correction.

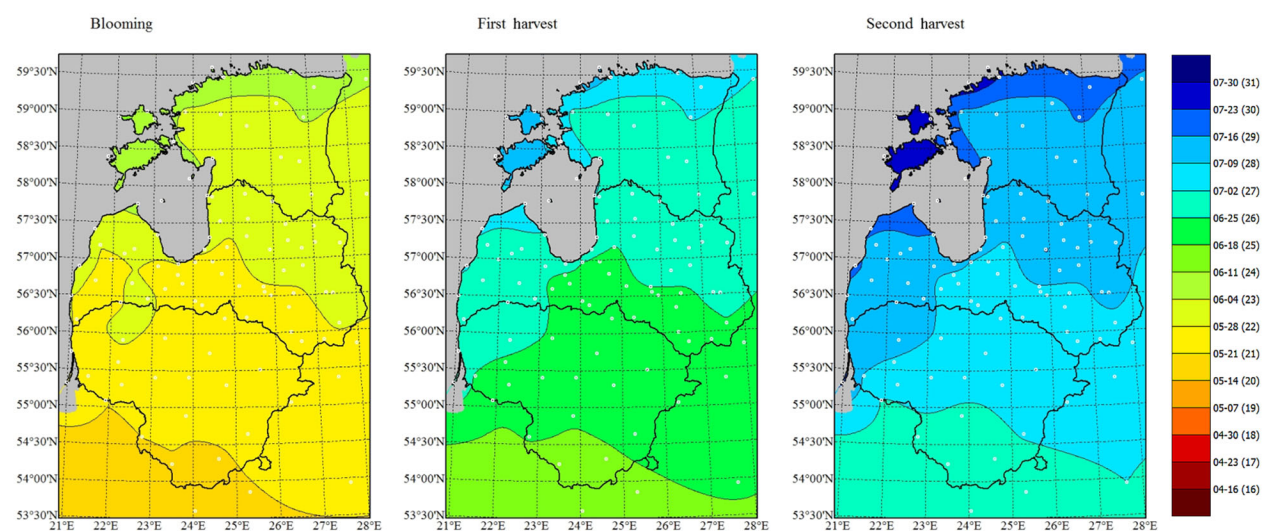


Fig. 5. Timing of strawberry development, weeks of the year, present climate (2001–2030). White dots show the locations of stations used for RCM data bias correction.

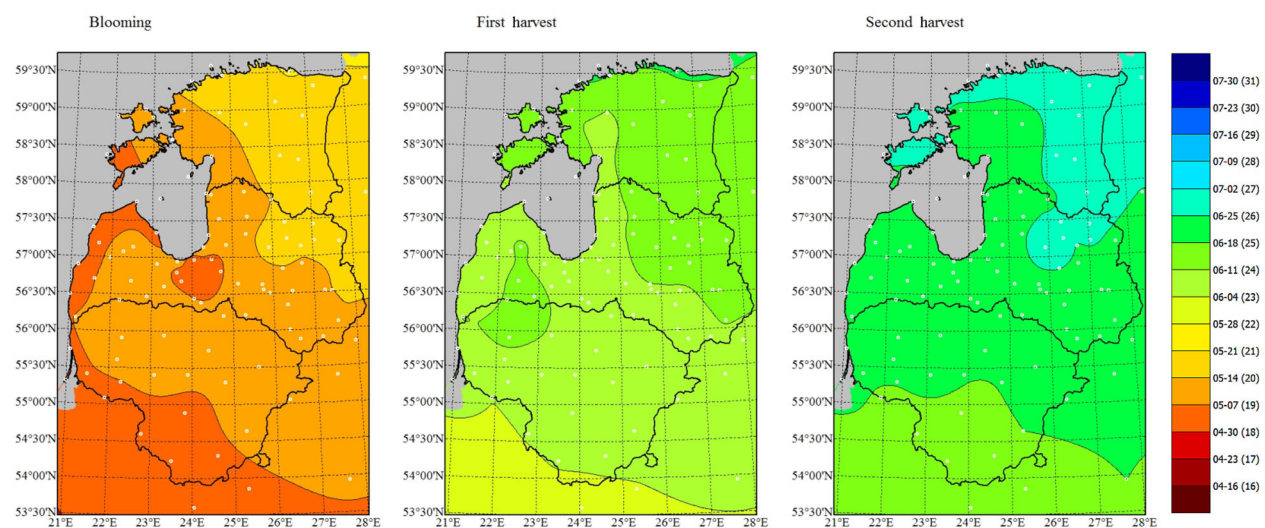


Fig. 6. Timing of strawberry development, weeks of the year, future climate (2070–2099). White dots show the locations of stations used for RCM data bias correction.

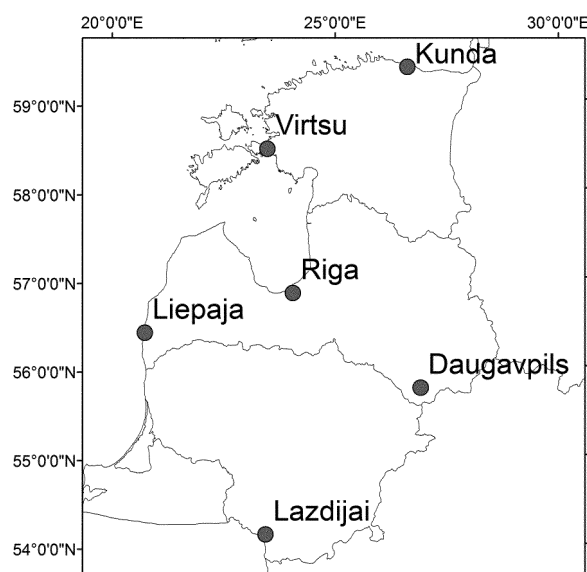


Fig. 7. Stations representing coastal or inland climate, used in further analysis.

RESULTS AND DISCUSSION

Overview

The timing of strawberry phenological processes in the past (1951–1980), present (2001–2030) and future (2070–2099) was calculated for a number of station locations (Fig. 2) and interpolated over the Baltic states (see Figs 4–6) using kriging interpolation.

All events first take place in the south of Lithuania and then the front of blooming strawberries or ripe fruit (terminology borrowed from meteorology) moves northwards, covering 200–300 km a week. In Latvia and Estonia the difference between the north and the south is strongly modified by the Baltic Sea.

The bloom in the present climate typically takes place between the middle of May and the middle of June (weeks 20–24), while in the past it happened a week or two later (weeks 21–26). In the future bloom events may be expected as early as the end of April (weeks 18–22).

The first fruits in the present climate appear from the middle of June until the middle of July (weeks 24–29). In the past this period was later (weeks 25–31). In the future this event may take place two weeks earlier, starting at the end of May (weeks 22–26) and the difference in timing between northern and southern regions is expected to decrease.

Similar conclusions can be drawn about the second harvest that happens from the end of June to the end of July in present climate (weeks 26–31), but will take place in June and the beginning of July in all Baltic States (weeks 24–28).

The results for the present climate in Latvia are consistent with the published literature that describes blossoming starting at the end of May and harvesting – at the end of June (Laugale 2000).

To correctly interpret the results in coastal areas, one must consider the locations of the observation stations that have provided data for bias correction and are the

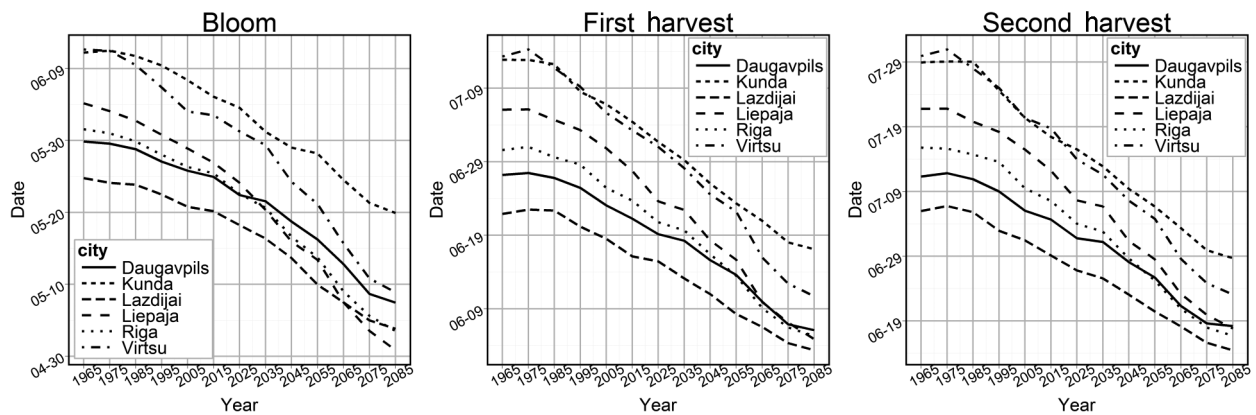


Fig. 8. Comparison of time series between locations shown in Fig. 7 for each phenological process. Lines show ensemble median.

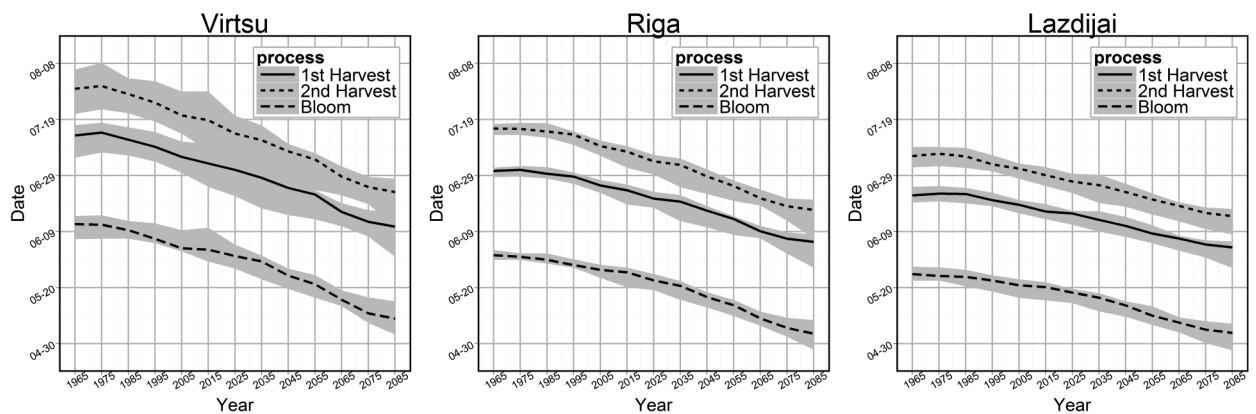


Fig. 9. Ensemble spread in the timing of strawberry phenological processes; lines show median values and grey areas show the interval between the 20th and 80th percentiles.

source for spatial interpolation. It is possible that the stations lying very close to the coastline represent a narrower zone of transition between the water body and land than is reflected in the interpolation. Therefore, results for the Estonian archipelago, where only coastal stations are available, should be interpreted with caution.

Although the Baltic States are comparatively flat (the highest elevation about 318 m) and small-scale regional differences are influenced by station location, some features of the spatial distribution inland may be explained by orography. Typically the strawberries arrive later in uplands as opposed to lowlands or plains. It can be observed by comparing results for the Vidzeme upland (eastern Latvia) with the Zemgale plains (central Latvia).

The changes are markedly different between inland and coastal regions. In the past and present phenological processes happen later in the coastal areas than in the inland regions, in the future, however, the difference

will diminish or in some cases the order will be reversed. To analyse this phenomenon, some locations were investigated further.

Time series in inland and coastal locations

Six locations were selected for further analysis (see Fig. 7). Liepaja, Kunda, Virtsu and Riga represent coastal climate, Daugavpils and Lazdijai – inland.

The time series of phenological processes for these locations are shown in Figs 8 and 9. Values for each year were calculated as the ensemble median and the 30-year central running average with a step of 10 years. Figure 8 presents the comparison between different locations for each phenological process. Figure 9 shows more distinctly the change in phenological processes for three representative locations (from Estonia, Latvia and Lithuania) with the addition of percentiles demonstrating the ensemble spread for each location.

In all cases the change in the timing of phenological processes in the 21st century is mostly linear and similar for blooming, the first harvest and the second harvest. The calculated slopes of linear trends for the whole period in days per decade are shown in Table 4.

With the exception of Virtsu and Liepaja, these slopes of linear trends are comparable to those calculated for tree blossoming from past observations for 1961–2000 in Germany, where the respective values are -2.0 and -2.2 (Chmielewski et al. 2004). However, results for Estonia for the years 1919–1996 (Ahas 1999) show slightly lower trend values of -0.5 to -1.7 days per decade.

Coastal locations have the largest change in bloom times that in some cases lead to reversal in bloom order with respect to the inland points. Let us compare Lazdijai, Daugavpils, Riga and Liepaja. In the past the bloom occurred earlier in inland locations (Lazdijai, Daugavpils). Then, around 2030 (corresponds to the climatic time slice 2016–2045), the bloom in three of these locations will happen simultaneously. By the end of the century the order will be reversed – in coastal Liepaja the bloom will happen first, even before more southern Lazdijai, and, similarly, Riga will precede Daugavpils.

In the previous century the timing of bloom in Virtsu was similar to timing in Kunda. However, at the end of this century it will be closer to inland Daugavpils, despite Virtsu lying significantly further north.

Similar conclusions can be drawn for the first and the second harvest. In the past harvest happened at slightly different times in each of the locations. However, the differences in harvest times decrease towards the end of the century. A grouping of events can be observed for locations in each of the Baltic countries, showing that in the future the latitude will be more important than the distance to the sea.

These results may be related to the circumstance that the RCM results for temperature obtained by the ENSEMBLES project have shown larger increase in temperature over the body of the Baltic Sea than over the adjacent land areas. This has to be considered in the context of the fact that typically formulations of RCM

include only the atmosphere component with boundary conditions for sea surface temperature being prescribed directly by the forcing GCM of low resolution (Christensen et al. 2015). It has been shown that the inclusion of the ocean component in the regional climate system modifies the projected change (Meier et al. 2011), but better understanding is still needed.

The ensemble spread is similar for all three phenological processes, but larger in northern and smaller in southern locations. The temperature spread in RCM is similar in all regions and the interpretation requires consideration of the whole model chain. Effectively, the spread of daily temperature is first translated into the spread of daily GDD values, then daily GDD values are summed to acquire cumulative GDD values and their spread is finally translated into a spread in calendar days. Analysis suggests that the spread in cumulative GDD values is similar in all locations, but the lower amount of daily GDD in northern locations at the time of the phenological event leads to a larger spread when the calendar days are calculated.

CONCLUSIONS

Calculations combining the temperature time series from RCM ensemble and the GDD-based phenological model show the following results:

- Advancement of the timing of strawberry phenological processes both from the past to present and from the present to future. These results largely agree with the existing literature concerning generally earlier onset of the growing season.
- The regional differences between northern and southern or coastal and inland regions will decrease in the future; it is possible that events which nowadays occur earlier inland will occur first in coastal regions by the end of the century. Also different impact on the timing of strawberry phenological processes can be observed in relatively close geographical locations.
- The uncertainty of the time occurrence of the phenological event is higher in the northern locations. The results for coastal regions should be interpreted cautiously, taking account of the fact that warming over the Baltic Sea may be overestimated in regional climate models.

The methodology used in this study can be directly applied to other crop types and the need for datasets useful in adaptation and mitigation strategy could lead to further application of RCMs to calculate more indices relevant to agriculture.

This study has a number of limitations. First, the results far from phenological observation stations (Fig. 1) should be interpreted with caution. Second, the

Table 4. Slopes of linear trends in phenological event timing, days per decade

Location	Bloom	First harvest	Second harvest
Virtsu	-2.9	-2.9	-3.4
Kunda	-2.0	-2.4	-2.8
Riga	-2.4	-2.3	-2.7
Liepaja	-3.0	-2.8	-3.1
Daugavpils	-1.9	-1.9	-2.2
Lazdijai	-1.9	-1.8	-2.0

phenological model is temperature-based, therefore the clarified influence of the photoperiod could alter the validity of results.

The climate change impact on crop yields is of great interest although it falls outside the scope of this study. Late frosts damage the strawberries (Laugale 2000) and paradoxically climate change leading to earlier phenological events can also mean increased exposure to frosts (Inouye 2008). Thus, the changes in crop production require further investigation, especially due to the influence of irrigation on crop yields.

Acknowledgements. This work is part of the project ‘Development of the postprocessing methods of synoptic forecasts’, co-funded by the European Reconstruction and Development fund and University of Latvia, Contract No. 2013/0058/2DP/2.1.1.0/13/APIA/VIAA/008 Observational data from the Latvian Environment, Geology and Meteorology Centre and State Plant Protection Service. The ENSEMBLES data used in this work were funded by the EU FP6 Integrated Project ENSEMBLES (Contract No. 505539), whose support is gratefully acknowledged. The authors would like to thank the two anonymous reviewers for their comments that helped to improve the manuscript.

REFERENCES

- Ahas, R. 1999. Long-term phyto-, ornitho- and ichthyophenological time-series analysis in Estonia. *International Journal of Biometeorology*, **42**, 119–123.
- Ahas, R., Jaagus, J. & Aasa, A. 2000. The phenological calendar of Estonia and its correlation with mean air temperature. *International Journal of Biometeorology*, **44**, 159–166.
- Ahmed, K. F., Wang, G., Silander, J., Wilson, A. M., Allen, J. M., Horton, R. & Anyah, R. 2013. Statistical downscaling and bias correction of climate model outputs for climate change impact assessment in the US northeast. *Global and Planetary Change*, **100**, 320–332.
- Allen, J. C. 1976. A modified sine wave method for calculating degree days. *Environmental Entomology*, **5**, 388–396.
- Baskerville, G. L. & Emin, P. 1969. Rapid estimation of heat accumulation from maximum and minimum temperatures. *Ecology*, **50**, 514–517.
- Bleiholder, H., Weber, E., Lancashire, P. D., Feller, C., Buhr, L., Hess, M., Wicke, H., Hack, U., Meier, U., Klose, F. R., van den Boom, T. & Stauss, R. 2001. *Growth Stages of Mono and Dicotyledonous Plants. BBCH-Monograph*. Federal Biological Research Centre for Agriculture and Forestry, 158 pp.
- Bonhomme, R. 2000. Bases and limits to using ‘degree.day’ units. *European Journal of Agronomy*, **13**, 1–10.
- Cesaraccio, C., Spano, D., Duce, P. & Snyder, R. L. 2001. An improved model for determining degree-day values from daily temperature data. *International Journal of Biometeorology*, **45**, 161–169.
- Chmielewski, F.-M. & Rötzer, T. 2001. Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology*, **108**, 101–112.
- Chmielewski, F.-M., Müller, A. & Bruns, E. 2004. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agricultural and Forest Meteorology*, **121**, 69–78.
- Christensen, H. J., Kjellström, E., Giorgi, F., Lenderink, G. & Rummukainen, M. 2010. Weight assignment in regional climate models. *Climate Research*, **44**, 179–194.
- Christensen, H. J., Kjellström, E. & Zorita, E. 2015. Projected change – atmosphere. In *Second Assessment of Climate Change for the Baltic Sea Basin* (Bolle, H.-J., Menenti, M. & Rasool, S. I., eds), pp. 217–233. Springer International Publishing.
- Christidis, N., Stott, P. A., Brown, S., Karoly, D. J. & Caesar, J. 2007. Human contribution to the lengthening of the growing season during 1950–99. *Journal of Climate*, **20**, 5441–5454.
- Cleland, E. E., Chuine, I., Menzel, A., Mooney, H. A. & Schwartz, M. D. 2007. Shifting plant phenology in response to global change. *TRENDS in Ecology and Evolution*, **22**, 357–365.
- [EC] European Commission. 2013. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. An EU Strategy on Adaptation to Climate Change. *COM (2013)*, **216**, 1–11.
- Falloon, P. & Betts, R. 2010. Climate impacts on European agriculture and water management in the context of adaptation and mitigation – the importance of an integrated approach. *Science of the Total Environment*, **408**, 5667–5687.
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Glecker, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C. & Rummukainen, M. 2013. Evaluation of climate models. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Stocker, T. F., et al., eds), pp. 741–866. Cambridge University Press.
- Fu, Y. H., Campioli, M., Van Oijen, M., Deckmyn, G. & Janssens, I. A. 2012. Bayesian comparison of six different temperature-based budburst models for four temperate tree species. *Ecological Modelling*, **230**, 92–100.
- Fu, Y. H., Campioli, M., Deckmyn, G. & Janssens, I. A. 2013. Sensitivity of leaf unfolding to experimental warming in three temperate tree species. *Agricultural and Forest Meteorology*, **181**, 125–132.
- Inouye, D. W. 2008. Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology*, **89**, 353–362.
- Jaagus, J. & Ahas, R. 2000. Space-time variations of climatic seasons and their correlation with the phenological development of nature in Estonia. *Climate Research*, **15**, 207–219.
- Johnson, M. E. & Fitzpatrick, E. A. 1977. A comparison of methods of estimating a mean diurnal temperature curve during the daylight hours. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B*, **25**, 251–263.
- Kalvāne, G., Romanovskaja, D., Briede, A. & Bakšiene, E. 2009. Influence of climate change on phenological phases in Latvia and Lithuania. *Climate Research*, **39**, 209–219.

- Kalvāns, A., Bitāne, M. & Kalvāne, G. 2014. Forecasting plant phenology: evaluating the phenological models for *Betulapendula* and *Padusracemosa* spring phases, Latvia. *International Journal of Biometeorology*, **59**, 165–179.
- Kristensen, K., Schelde, K. & Olesen, J. E. 2011. Winter wheat yield response to climate variability in Denmark. *The Journal of Agricultural Science*, **149**, 33–47.
- Krug, J., Eriksson, H., Heidecke, C., Kellomäki, S., Köhl, M., Lindner, M. & Saikkonen, K. 2015. Socio-economic impacts – forestry and agriculture. In *Second Assessment of Climate Change for the Baltic Sea Basin* (Bolle, H.-J., Menenti, M. & Rasool, S. I., eds), pp. 399–409. Springer International Publishing.
- Laugale, V. 2000. Strawberry production in Latvia. *IOBC wprs Bulletin*, **23**(11), 11–16.
- Laugale, V. & Lepse, L. 2007. Research trials on strawberry cultivars in Pūre Horticultural Research Station (Latvia) during the last 10 years. *Sodininkystē ir Daržininkystē*, **26**, 81–92.
- Linderhorm, H. W. 2006. Growing season changes in the last century. *Agricultural and Forest Meteorology*, **137**, 1–14.
- Linkosalo, T., Lappalainen, H. K. & Hari, P. 2008. A comparison of phenological models of leaf bud burst and flowering of boreal trees using independent observations. *Tree Physiology*, **28**, 1873–1882.
- Meier, H. M., Höglund, A., Döscher, R., Andersson, H., Löptien, U. & Kjellström, E. 2011. Quality assessment of atmospheric surface fields over the Baltic Sea from an ensemble of regional climate model simulations with respect to ocean dynamics. *Oceanologia*, **53**, 193–227.
- Olesen, J. E., Carter, T. R., Diaz-Ambrona, C. H., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Miguez, M. I., Morales, P., Palutikof, J. P., Quemada, M., Ruiz-Ramos, M., Rubaek, G. H., Sau, F., Smith, B. & Sykes, M. T. 2007. Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. *Climatic Change*, **81**, 123–143.
- Parton, W. J. & Logan, J. A. 1981. A model for diurnal variation in soil and air temperature. *Agricultural and Forest Meteorology*, **23**, 205–216.
- Reicosky, D. C., Winkelman, L. J., Baker, J. M. & Baker, D. G. 1989. Accuracy of hourly air temperature calculated from daily minima and maxima. *Agricultural and Forest Meteorology*, **46**, 193–209.
- Richardson, A. D. & O'Keefe, J. 2009. Phenological differences between understory and overstory: a case study using the long-term Harvard forest records. In *Phenology of Ecosystem Processes* (Noormets, A., ed.), pp. 87–117. Springer, New York.
- Richardson, A. D., Keenan, T. F., Migliavacca, M., Ryu, Y., Sonnentag, O. & Toomey, M. 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agriculture and Forest Meteorology*, **169**, 156–173.
- Roltsch, W. J., Zalom, F. G., Strawn, A. J., Strand, J. F. & Pitcairn, M. J. 1999. Evaluation of several degree-day estimation methods in California climates. *International Journal of Biometeorology*, **42**, 169–176.
- Sennikovs, J. & Bethers, U. 2009. Statistical downscaling method of regional climate model results for hydrological modeling. In *Proceedings of the 18th World IMACS/MODSIM Congress, Cairns, Australia 13–17 July 2009* (Anderssen, R. S., Braddock, R. D. & Newham, L. T. H., eds), pp. 3962–3968.
- Snyder, R. L., Spano, D., Cesaraccio, C. & Duce, P. 1999. Determining degree-day thresholds from field observations. *International Journal of Biometeorology*, **42**, 177–182.
- Teets, D. A. 2003. Predicting sunrise and sunset times. *The College Mathematics Journal*, **34**, 317–321.
- Teutschbein, C. & Seibert, J. 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. *Journal of Hydrology*, **456**, 12–29.
- Tönutare, T., Keert, K., Szajdak, L. & Moor, U. 2014. Composition of commercially produced organic and conventional strawberries. *Nutritional and Food Science*, **44**, 562–575.
- Van der Linden, P. & Mitchell, J. E. 2009. *ENSEMBLES: Climate Change and Its Impacts: Summary of Research and Results from the ENSEMBLES Project*. Met Office Hadley Centre, Exeter, 160 pp.
- Wang, J. Y. 1960. A critique of the heat unit approach to plant response studies. *Ecology*, **41**, 785–790.
- Wibig, J., Maraun, D., Benestad, R., Kjellström, E., Lorenz, P. & Christensen, O. B. 2015. Projected change – models and methodology. In *Second Assessment of Climate Change for the Baltic Sea Basin* (Bolle, H.-J., Menenti, M. & Rasool, S. I., eds), pp. 189–215. Springer International Publishing.
- Wilson, L. T. & Barnett, W. W. 1983. Degree-days: an aid in crop and pest management. *California Agriculture*, **37**, 4–7.

Kliimamuutuse mõju aedmaasika fenoloogiliste faaside saabumisele Baltimaades

Līga Bethere, Tija Sīle, Juris Seņņikovs ja Uldis Bethers

Kliima muutumine on avaldanud märgatavat mõju nii põllumajandusele kui ka taimede fenoloogilisele arengule. Käesolevas uuringus on kindlaks tehtud, kuidas kliima teisenedes Baltimaades muutuksid aedmaasika õitsemise ja valmimise ajad. Kliima muutumise võimalikud stsenaariumid on saadud regionaalsete kliimamudelite abil. Aedmaasika fenoloogiline mudel põhineb efektiivsete temperatuuride summadel. Mudeli parameetrid määrati fenoloogiliste ja meteoroloogiliste vaatlusandmete abil, mis saadi Lätist aastatel 2010–2013. Projekti ENSEMBLES raames välja-töötatud regionaalsete kliimamudelite tulemusi kasutati fenoloogilise mudeli sisendiks. Mudeli abil arvutati välja aedmaasika fenoloogiliste faaside saabumisajad perioodil 1951–2099. Tulemused näitasid selgelt, et kliima soojenemise korral tulevikus nihkuvad aedmaasika fenoloogilised faasid varasemaks. Erinevused ranniku- ja sisemaa-alade vahel peaksid järk-järgult vähenema.