

MODEL OF TEMPERATURE THRESHOLDS INFLUENCE ON GRAPE SEASONAL DEVELOPMENT

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Abstract

Phenology is an important indicator of climate changes and informs us about the compliance of the variety with climatic conditions. Plant phenology is most often predicted by the sum of degree days, but the accuracy of forecasts is insufficient, especially in conditions of climate change. Regression analysis of 71 grape varieties from Y. I. Potapenko Don ampelographic collection (Russia) in 1981-2014 revealed relationship between grape phenodates (bud break, flowering) and dates of transition air temperatures above temperature thresholds of these phases. On this basis, we have created a simple dynamic model of grape phenology. The time from flowering to ripening was assumed constant for variety. In was realized as a computer program SEASONS. The purpose of this work was to verify and validate the model. Model was parametrized and verified for 12 grape varieties in 1981-2014. Model was validated on the test period of 2015-2017. The approximation error of the SEASONS was 3-5 days for the date of bud break and flowering and 6-9 days for ripening, or 5.1-8.0% for production period duration. The forecast error for production period for the model was 4%, on the base of DD was 11%. This result confirms the quality of the model and its suitability for forecasting.

Keywords: grape, phenology, temperature thresholds, dynamic model

1. INTRODUCTION

Plant phenology integrates climate-biosphere interactions and serves as an indicator of climate changes [1], however, there is still a problem of low accuracy of phenology models, the 2-week errors are common [2]. In a moderate climate, phenology is mainly temperature-driven [3]. It is most often modelled based on the accumulated degree days (DD) above a specified temperature threshold value [2; 4; 5]. Phenology forecasts is a basis of grape cultivation efficiency under climate change conditions [6; 7]. Grape phenology models mainly based on DD above 10°C, often with corrections for ballast temperatures above 22-25°C [7-11]. In addition to DD, there are other temperature factors of grape phenology, revealed by regressions, such as dates of temperature increase over 15°C, 20°C [8, 12]. Above DD and regressions, mechanisms of adaptation to temperature changes are modeled in dynamical models [12; 14].

While performing the regression analysis of phenodates for 71 grape varieties from the Ya.I. Potapenko Don ampelographic collection of the All-Russian Research Institute for Viticulture and Winemaking (Rostov Region, 47°25' N; 40°03' E) in 1981-2014, we have found that the bud break data strong positive correlated with day of temperature transition over 10-11°C (average correlation coefficient for the varieties $r=0.85$), flowering – over 14-15°C ($r=0.88$). At the same time phenological events was observed several weeks later the temperature transitions [15; 16]. These observations have lead us to a hypothesis that the adaptation of the grape plant follows the air temperature with a limited rate. The bud break and flowering occur almost simultaneously in different varieties. Varietal differences were revealed after flowering and time from flowering to ripening was rather stable from one year to another.

Our model [15] is based on the assumption, that plant's condition may be described by a temperature the plant is currently adapted to (T_{in}). It followed after air temperature (T_{out}) with delay. The more the difference ($T_{out}-T_{in}$), the higher the rate of T_{in} change. For a time Δt change in T_{in} is: $\Delta T_{in}=q \cdot (T_{out}-T_{in})$,

where q is a constant of response rate to temperature increase. In case of temperature decrease, the development cannot be reversed. The parameter q is different in time of sap flow (q_s) and bud break (q_b). When the plant reaches the temperature thresholds for bud break and flowering, these phases will begin. The time from flowering to ripening assumes constant for a variety.

SEASONS software was created in Delphi 2.6 based on a difference scheme according to the equation with a day increment (Fig.). The approximation and prediction quality of the model was assessed by mean absolute error (MAE).

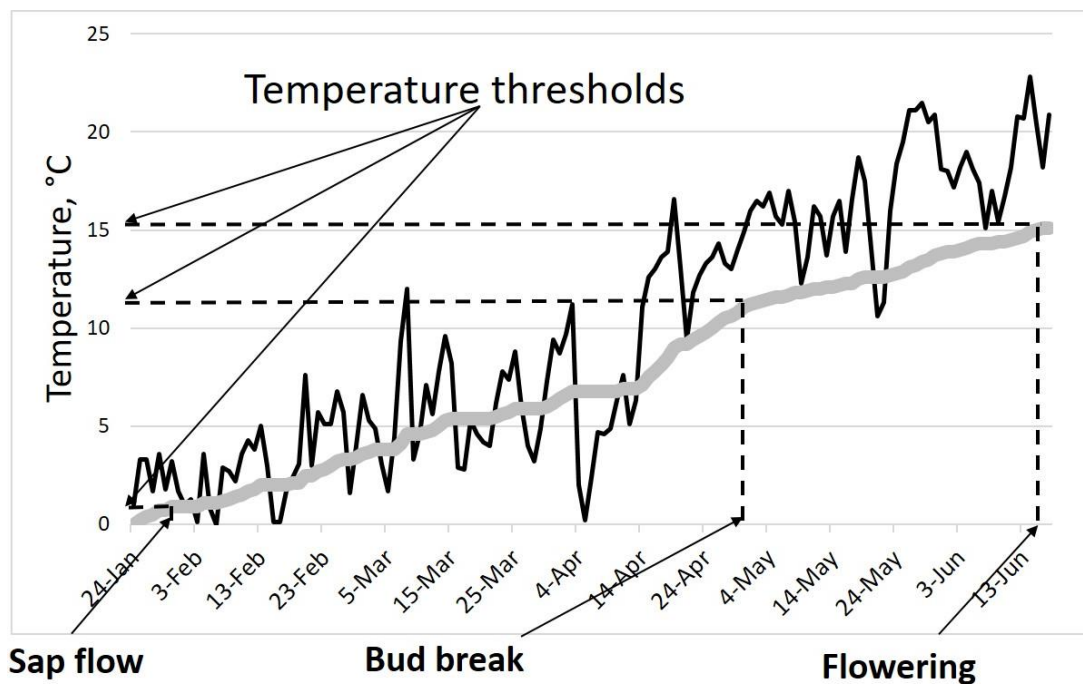


Fig. 1. An example of the dynamics of the state of the grape plant. Black solid line – temperature (T_{out}), grey line – plants condition (T_{in})

The model parameters were selected by MAE minimization in the learning sample of 1981-2014 observations. The calculation was performed by grid of two parameters: T_{min} in the range of 10-25°C with an increment of 1°C and q from 0.01 to 0.05 with an increment of 0.001. The calculation was started from the day of stable temperature increase over 1°C which assumed to correspond to sap flow beginning [14]. The plant condition was assumed to be in a slight delay with respect to ambient conditions and corresponding to 0°C. The parameters of different varieties in the period “sap flow beginning – bud break – flowering beginning” were similar, and a single set of parameters was further used for all the groups: $q_s=0.07 \text{ day}^{-1}$, $T_b=11^\circ\text{C}$, $q_b=0.02 \text{ day}^{-1}$; $T_f=15^\circ\text{C}$.

The purpose of this work was to verify and validate the model and compare it accuracy with sums of daily temperatures and DD method.

2. MATERIALS AND METHODS

2.1. Materials

The subject of research was bud break, flowering and ripening dates of 12 grape varieties from the Ya.I. Potapenko Don ampelographic collection of the All-Russian Research Institute for Viticulture and Winemaking (Table 1) corresponding to very early to middle-late ripening. The varieties under study included Tason, Vostorg, Moldova (table varieties), industrial varieties, mainly covered ones (except

for Vostorg), of different environmental and geographic origin. The learning sample of 1981-2014 was used to calculate average duration of the period from flowering to ripening to be used in SEASONS model, sums of daily temperatures and degree days from bud break to ripening for each variety.

2.2. Methods

The SEASONS software was used to calculate common model dates of bud break and flowering for 2015, 2016, 2017 for all varieties. A model ripening date was calculated for each variety by adding to the flowering model date the long-time average annual value, a 3-year mean MAE was computed.

Ripening dates for 2015, 2016 and 2017 and mean errors were calculated based on the long-time average annual $\sum T$ and DD from actual bud break dates; MAE was compared between the three calculation methods.

3. RESULTS

The average duration of production period in 1981-2014 of varieties differ from 103 to 149 days. Table 1 confirms that the main intervarietal differences were observed during the flowering – ripening (65-111 days); and in the bud break-flowering the variation was small (35-39 days). The maximum interannual variability corresponded to the bud break – flowering (average coefficient of interannual variation $v=22.4\%$). $\sum T$ was more stable an indicator of active vegetation duration ($v=5.9\%$) as compared to DD (10.0%).

The approximation error of SEASONS model for this sample was 3-5 days for bud break and flowering dates, 6-9 days for ripening date, or 5.1 to 8.0% of the productive period duration. The approximation error within 8% confirmed high quality of the model.

2015-2017 were warmer 1981-2014: the sum of temperatures above 10°C in 1981-2014 was 3494°C on average; in 2015, 2016, and 2017 it was 3665°C, 3742°C, 3564°C, respectively. August temperatures showed the highest variation: in 1981-2014, the average temperature was 23.0°C, and in the test years, it was 25.2°C, 26.7°C, 27.0°C. However, there was no significant increase in spring temperatures, and the temperature increase over 10°C occurred on 14.04.15, 02.04.16 and 15.04.17, the long-time average annual point being April 14. The bud break also started with 16-day difference, on 02.05.15, 17.04.16, 27.04.17. The temperature growth in the Rostov Region was accompanied by decreased precipitation: the total precipitation for the period of temperatures above 10°C in 1981-2014 was 280 mm on average, and in the test years it was 134 mm, 371 mm, 187 mm.

The SEASONS model reflected contrasts of the years: the calculated dates were 29.04.15, 15.04.16, 30.04.17, i.e. 2-week variation was also present. The bud break and flowering for 2015-2017 (Table 2) was predicted with a 12-variety average accuracy of 3-4 days (2 to 5 days for different varieties), the full ripening of berries – of 5 days (1 to 14 days); the bud break - flowering period duration error was 4.1% (1.2-10.7%). The relative error of productive period duration prediction did not exceed 11% for all the varieties, i.e. the model is adequate and suitable for prediction. The dynamic model of Ferguson et al. [14] showed a root mean square error (RMSE) of the bud break date prediction of 7.3 days in the test sample; the SEASONS model proved to be more accurate (RMSE of 3.1 day on average for 12 varieties).

The methods based on the sums of temperatures do not enable to calculate bud break dates. The flowering dates were best modelled by DD method with the error from 1 to 2 days, however, the calculation was based on the known actual bud break date, and in SEASONS model a calculated date was used. SEASONS showed the lowest error of the bud break – flowering period duration, or 4.1%; the $\sum T$ method was more accurate (9.0%) than DD (11.0%), which agrees well with Table 1 data on lower variability of $\sum T$ than DD in the productive period.

Variety	Origin	Bud break – ripening, days	Bud break – flowering, days	Flowering - ripening, days	∑T, °C	DD, °C
Tason	Russia	103±8 (7.5%)	37±9 (23.6%)	65±7 (10.8%)	2,169±104 (4.8%)	1,143±92 (8.1%)
Vostorg	Russia	108±10 (9.5%)	37±9 (22.9%)	71±6 (9%)	2,310±159 (6.9%)	1,226±103 (8.4%)
Sibirkovy	Russia	131±12 (8.9%)	38±9 (24.8%)	93±10 (10.2%)	2,801±151 (5.4%)	1,490±146 (9.8%)
Dimatskun	Armenia	132±13 (9.8%)	35±9 (25.8%)	98±12 (12.4%)	2,875±167 (5.8%)	1,551±133 (8.6%)
Pukhlyakovsky white	Russia	136±12 (8.8%)	35±9 (25.6%)	101±10 (10.3%)	2,987±230 (7.7%)	1,630±188 (11.5%)
Riesling	Germany	140±10 (7.4%)	36±8 (23%)	104±7 (6.8%)	2,958±135 (4.6%)	1,553±168 (10.8%)
Plechistik	Russia	141±10 (7%)	35±8 (22.5%)	106±8 (7.6%)	3,076±192 (6.2%)	1,663±181 (10.9%)
Krasnotop zolotovskiy	Russia	142±12 (8.6%)	38±7 (19.6%)	104±10 (9.7%)	2,990±168 (5.6%)	1,570±145 (9.2%)
Tsimlyansky black	Russia	142±10 (7.3%)	36±8 (23.6%)	106±9 (8.5%)	3,030±217 (7.2%)	1,611±197 (12.2%)
Moldova	Moldova	147±12 (7.8%)	39±8 (19.5%)	109±9 (8.6%)	3,151±171 (5.4%)	1,679±140 (8.4%)
Cabernet Sauvignon	France	148±9 (5.9%)	37±7 (19.8%)	111±7 (6.7%)	3,125±177 (5.7%)	1,647±170 (10.3%)
Magarach Ruby	Russia	149±10 (6.7%)	39±7 (18.4%)	110±8 (7.5%)	3,019±176 (5.8%)	1,534±182 (11.9%)
Mean		135±11 (7.9%)	37±8 (22.4%)	98±9 (9.0%)	2,874±171 (5.9%)	1,525±154 (10.0%)

Table 1. Characteristics of 12 grape varieties, 1981-2014, Rostov Region. Mean ± stand. dev. The varieties are arranged in the order of production period increasing. Designations: ∑T – sum of average daily temperatures for the productive period, °C; DD=∑(T-10), °C

Variety	SEASONS				∑T			DD		
	DB, days	DF, days	DM, days	L, %	DF, days	DM, days	L, %	DF, days	DM, days	L, %
Tason	2	3	2	1.2	3	9	7.6	2	9	8.0
Vostorg	4	4	7	10.1	5	8	7.2	2	6	5.7
Sibirkovy	2	4	3	4.0	3	8	5.6	2	10	7.6
Dimatskun	2	5	14	10.7	4	4	3.2	2	4	3.4
Pukhlyakovsky white	3	4	3	0.9	3	14	9.2	1	14	9.8
Riesling	3	4	7	6.3	4	17	10.9	1	22	14.3
Plechistik	3	3	9	4.7	3	19	12.2	1	22	14.2
Krasnotop zolotovskiy	3	3	3	2.0	3	13	9.0	3	16	11.0
Tsimlyansky black	4	3	6	3.2	4	18	11.5	2	24	15.3
Cabernet Sauvignon	5	4	2	2.8	6	17	10.5	2	20	12.4
Moldova	2	2	1	1.6	3	14	8.9	1	18	11.4
Magarach Ruby	3	4	1	1.2	4	19	12.1	2	30	18.9

Mean	3	4	5	4.1	4	13	9.0	2	16	11.0
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Table 2. Forecast errors in 2015-2017 of differ methods. Designations: DB – bud break date, DF – flowering date, DM – ripening date, L – bud break-ripening duration

4. DISCUSSION

High quality of the SEASONS model was confirmed in the sample of 12 varieties in 1981-2014: the approximation error was from 3 to 5 days for bud break and flowering dates, 6 to 9 days for ripening date, or 5.1 to 8.0% of the productive period duration. The bud break and flowering for test years 2015-2017 was predicted with a 12-variety average accuracy of 3 days, the full ripening of berries – of 5; the bud break-flowering period duration error was 4.1% (1.2-10.7%), i.e. the model is adequate and suitable for prediction. The SEASONS model showed a higher prediction accuracy for the ripening date as compared to methods based on the sums of daily temperatures or degree days. The bud break-ripening duration error was 4.1% with SEASONS model, 9.0% with the method based on the sums of daily temperatures, and 11.0% with the DD method. So adequacy of the model's principal provisions was confirmed.

The proposed model is correlated with the existing models by different aspects. The model is most closely related to dynamic models of frost resistance in winter dormancy [13; 14; 17]. These models directly step by step calculate the dynamics of frost resistance and related to the frost-resistance plant phenological events at the beginning of active vegetation.

There are models that directly count the date of the beginning of flowering after a certain number of days from the date of stable transition of temperatures through 15°C and the veraison from the date of transition of temperatures through 20°C [8], but our model allows us to more realistically take into account the influence of temperatures between dates.

Temperature thresholds in one form or another are present in most models of the phenology of grapes. [7-10; 18]. A significant proportion of that models take into account the slowdown in plant growth rate by high temperatures, with some researchers calling the upper threshold of optimal temperatures 19°C. Moreover, the best results of the DD model are given for vegetative development phases, before flowering [11]. Our studies have also confirmed the role of temperature before flowering. Our model takes into account the ballast high temperatures, assuming a constant duration of the flowering-ripening, falling on high summer temperatures. The biological meaning of the model-the plant seeks to provide flowering, as the most sensitive phase, optimal temperature conditions.

To improve the accuracy of SEASONS model, it is necessary to introduce temperature dependence of the time from ripening beginning to full ripening of berries, as it corresponds to low autumn temperatures in late varieties.

5. CONCLUSIONS

The SEASONS model was verified and validated, so adequacy of the model's principal provisions was confirmed: the condition of grape plants of different varieties follows outside temperature during the period of spring temperature increase; the temperature thresholds of 11°C and 15°C play a regulatory role for the onset of bud break and flowering, respectively; the flowering – ripening period duration may be approximated using a variety-specific constant.

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