HUNGARIAN UNIVERSITY OF
AGRICULTURE AND LIFE SCIENCES

# MATHEMATICAL-STATISTICAL MODELS FOR PLANT RESPONSES TO CLIMATE CHANGE

## Theses of the doctoral (PhD) dissertation

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## 1. Introduction and objectives

The current climatic and weather conditions have significant impact on the quantity and quality of agricultural production. Therefore, the analysis of the climate of the past decades and its possible changes is essential. In this approach, the temperature data-based estimation of the growing season schedule and the timing of blooming phenological phase plays an undoubtable important role.

One of the main purpose of my research was to perform a complex indicator analysis and a statistical evaluation of the frequency of extreme temperature and precipitation events for grapevine (*Vitis vinifera L. syn: Vitis vinifera* L. *ssp. sativa*) grown in Hungary using the predictions of climate models. The beginning and the end of the period above 10 °C, i.e. the thermally possible growing season may change significantly because of the climate change. Therefore, I aimed to calculate the indicators and extremes for the thermally possible growing season of each year. Instead of the widely used, fixed growing season that is based on the observations in the 20th century (i.e. the period from 1 April to 30 September or from 1 April to 30 October), I intended to introduce a more flexibly applied, temperature-based method. In connection with this subtask, I defined some new growing season calculation methods and selected two from nine methods that best fit the so-called reference method. Based on these two methods, I performed the spatial-temporal indicator analysis and the statistical evaluation of extreme event frequencies.

The other purpose of my research was to adapt Chuine's Unified Model to Hungarian apricot (*Prunus armeniaca,* L.*)* phenology data sets. This applied Unified Model describes both the chilling and forcing unit accumulations and can estimate the budburst or the blooming time of trees. I fitted the model to the blooming data sets of three apricot cultivars. I used the Simulated Annealing method to estimate the parameters of the model.

## 2. Materials and methods

### *2.1. Indicator analysis applied to grapevine (Vitis vinifera L. syn: Vitis vinifera* L. *ssp. sativa)*

For the indicator analysis and the statistical evaluation of temperature and precipitation extreme events, I used the daily minimum, maximum and mean temperature and daily precipitation outputs of three regional climate models. The RegCM (*Giorgi et al.,* 1993) and ALADIN (*Déqué et al.*, 1998) regional climate models were carried out in the framework of the European ENSEMBLES project (*van der Linden and Mitchell*, 2009) while the PRECIS regional climate model was developed by the UK Met Office Hadley Centre for Climate

Prediction and Research (*Wilson et al.*, 2007). These models were adapted to the Carpathian Basin (*Pieczka*, 2012) and modified with percentile-based bias correction technique (*Formayer and Haas*, 2010) by the correction of the simulated daily outputs (*Haylock et al.*, 2008). These regional climate models have a horizontal resolution of 25 km. The data refer to a flat surface, so the results do not take into account the extra radiation from the slope exposure. I performed my calculations for Hungary (for 228 grid points) and for three thirty-years periods (1961−1990 as reference period; 2021−2050 and 2071−2100[1]).

In my work, I selected the two methods that best approximated the reference method by the root mean square error (RMSE) from nine growing season calculation methods. The reference method produces an average year of a thirty-year period using daily temperature data. Then this average year dataset is smoothed by moving average method. The beginning or the end of the growing season are the first or the last day of this smoothed data series, respectively, when the average temperature is at least 10 ° C. I compared the results of nine methods to the reference method result. From the nine ones, one was the so-called interpolations method (‘int’; *Csepregi*, 1997) and were developed by myself newly: ‘3’, ‘5’, ‘3mid’, ‘5mid’, ‘MA3’, ‘MA5’, ‘MA3mid’, ‘MA5mid’. For the beginning of the growing season, I took the first („”) or middle („mid”) day of the first three-day or five-day period when the original („”) or smoothed („MA”) temperature dataset was at least 10 °C every day. I used similar methods to calculate the end of the growing season. The essence of the interpolation method is that the beginning or the end of the growing season can be determined based on the data series weighted by the monthly average temperatures of March and April or September and October, respectively.

Using the two best temperature-based growing season calculation methods (’5mid’ and ’int’), I determined the spatial and temporal changes of four indicators and six temperature and precipitation extremes for Hungary for the period 1951–2100:

- adjusted Winkler index,
- adjusted Huglin’s heliothermal index,
- adjusted hydrothermal coefficient,
- sum of precipitation during the growing season,
- the longest unbroken rainy period during the growing season,
- the longest unbroken dry period during the growing season,
- the number of years when the maximum daily temperature was above 35 °C,

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[1] In the case of the PRECIS model, due to its shorter simulation time range, we calculated the indicators for the period 2069–2098.

• the number of minimum temperatures below -1 °C during the first part of the growing season,

• the number of minimum temperatures below -17 °C or -21 °C during the dormancy.

For the statistical analysis, I used one-way completely randomized analysis of variance (ANOVA) and Bonferroni's correction.

### *2.2. Model-based estimation of blooming time applied to apricot (Prunus armeniaca, L.)*

To estimate the blooming time, I used the string stage and blooming dates of three Hungarian apricot cultivars ('Ceglédi bíborkajszi'; 'Gönci magyar kajszi'; 'Rózsakajszi C.1406'). The data were recorded by the research team of the Department of Fruit Growing Research of the predecessor institutes the Hungarian University of Agricultural and Life Science in the Experimental Farm (Szigetcsép and Soroksár) in the time period 1994 – 2020.

I used the daily mean temperatures observed in the synoptic station of Marczell György Main Observatory of Hungarian Meteorological Service in the time period 1994 – 2020.

The primarily for forestry trees developed but also widely used for fruit trees model named 'Unified Model' (UM) was introduced by *Chuine* (2000). It uses two different functions to determine the endodormant chilling effect, i.e. chill accumulation and the ecodormant forcing effect, i.e. heat accumulation (Figure 1).

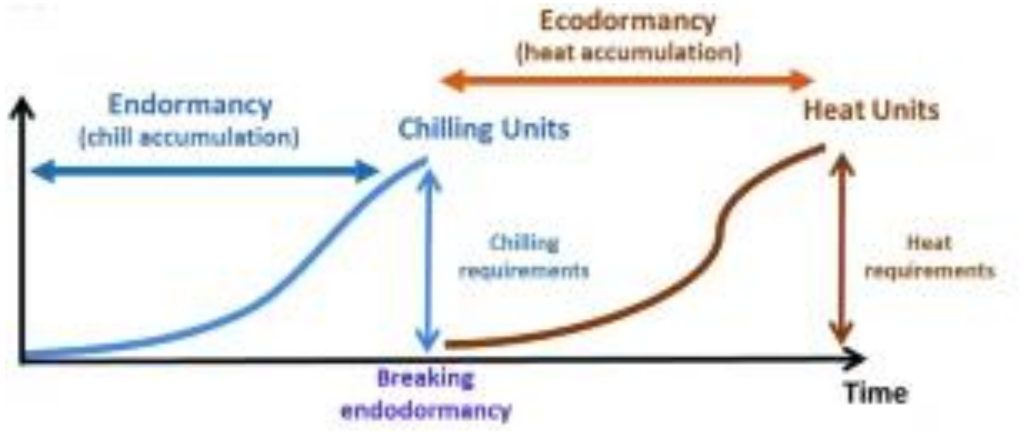

Figure 1: Schematic diagram of endodormant chill accumulation and the ecodormant heat accumulation (source: Campoy et al., 2020)

The Unified Model describes the daily temperature dependence of endodormant chill accumulation with a bell curve (Fig. 2a), while the daily temperature dependence of ecodormant heat accumulation with a sigmoidal curve (Fig. 2b). The maximum point of the bell curve expresses the optimal chilling effect. The sigmoid function expresses that the increasing temperature has an accelerating effect on blooming. The parameters of the curves can be determined by optimization. The model also describes well that with the more chilling unit accumulated, the ecodormant heat accumulation is required for blooming.

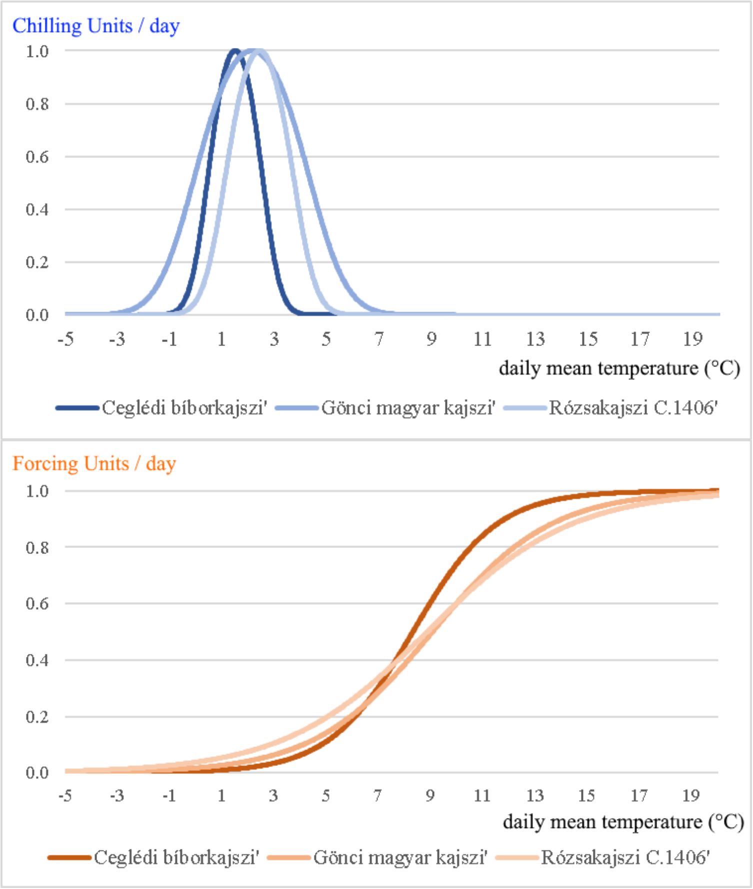

Figure 2: The sematic diagram of the chilling unit (a; above) and forcing unit (b; below) accumulation depending on the daily mean temperature for ’Ceglédi bíborkajszi’, ’Gönci magyar kajszi’ and ’Rózsakajszi C.1406’.

## 3. Results

### *3.1. Indicator analysis applied to grapevine (Vitis vinifera L. syn: Vitis vinifera* L. *ssp. sativa)*

In my dissertation, the indicator analysis and the statistical results were illustrated in 11 detailed tables and 23 figures (maps) showing spatial-temporal changes. In the Appendix, I supplied 8 additional tables and 20 figures to give a deeper insight.

### *3.2. Model-based estimation of blooming time applied to apricot (Prunus armeniaca, L.)*

Using the available phenology and temperature data, I adapted Chuine’s Unified Model. I simplified the original nine-parameter model into a six-parameter model, making the parameter estimation more robust. To optimize the parameters, I used the Simulated Annealing method (*Press*, 2007; *Weise*, 2009) that handles global optimum search problems with multiple local extremes well by avoiding being stuck in local optima (Table 1).

Table 1: The most important optimal parameters and the error of our estimates (RMSE) for ‘Ceglédi bíborkajszi’, ‘Gönci magyar kajszi’ and ‘Rózsakajszi C.1406’.

| | ’Ceglédi bíborkajszi’ | ’Gönci magyar kajszi’ | ’Rózsakajszi C.1406’ |
|---|---|---|---|
| The optimal chilling effect (°C) | 1.50 | 2.13 | 2.42 |
| The inflexion point of the sigmoid curve (°C) | 8.30 | 9.04 | 8.84 |
| The speed parameter of heat accumulation | 2.14 | 2.08 | 2.07 |
| RMSE (error, day) | 2.37 | 2.10 | 1.49 |

Comparing the speed parameter of the heat accumulation with the data in the literature, I found that the effect of endodormant chilling accumulation on the ecodormant heat accumulation is more pronounced in the case of the apricot cultivars grown in the studied area.

## 4. Conclusions

### *4.1. Indicator analysis, study applied to the grape (Vitis vinifera L. syn: Vitis vinifera* L. *ssp. sativa) plant*

My research has shown that regional climate change can have a significant impact on viticulture in Hungary. During the 21st century, it may become possible to plant varieties with a longer vegetation period and red wine varieties with a higher heat demand. Significant reductions in frost damage during the dormant period is expected. Although, mild winters will reduce the frost resistance of the buds and increase the chances of pathogen survival, which can pose a risk to the cultivations. In addition, extreme high temperatures and long dry periods during the growing season can also bring a serious risk in the 21st century. Consequently, growing quality grapes in Hungary will continue to be possible in the future, but it may be necessary to change the variety assortment and the cultivation methods.

### *4.2. Model-based estimation of blooming time applied to apricot (Prunus armeniaca, L.)*

With my adapted Chuine’s Unified Model, compared to the estimations of available in the literature we can give a more accurate estimation in the future for the blooming time of the apricot varieties in the studied area.  Therefore, the preparation for frost-hazardous conditions can become notably more effective. Since the blooming time of apricot varieties in Hungary are quite close to each other and the climatic conditions of apricot growing areas are also very similar, my results can easily be adapted to other Hungarian varieties and regions.

## 5. Theses

The results of my research can be summarized in the following thesis points:

1. **I have proposed several new methods for determining the vegetation period of grapes (*Vitis vinifera L. syn: Vitis vinifera* L. *ssp. sativa*), which are more suitable for the (e.g. indicator-based) study of the effects of climate change due to their flexibility.**

   Instead of the calendar-based method, the temperature-based '5mid' and 'int' (interpolation) methods I introduced gave the best estimate of the reference method according to the on the root mean square error (RMSE).

2. **With the '5mid' method I developed, I made statistically significant statements on the change in the thermally possible vegetation period in the 21st century.**

   A significant ($p<0.05$) prolongation of the period permanently above 10° C (38–48 days) is expected in the 21st century, which starts on average 19 to 20 days earlier and ends on average 18 to 27 days later. This means that it may be possible to plant and grow varieties with a longer growing season.

3. **I clarified the limitations of the 'int' (interpolation) method.**

   If the monthly mean temperatures in March and April are very close and the mean temperature in April is well below 10 °C, then the interpolation method gives erroneous results. Similarly, the method should not be used if the monthly mean temperatures in September and October are very close and the mean temperature in October is much higher than 10 °C.

4. **Examining the indicator analysis and the probability of extreme weather events statistically, I made conclusions about the future risk of growing grapevine. I made a proposal to change the variety composition and plant protection works of Hungarian viticulture.**

   - I showed a significant ($p <0.05$) increase in the heat sum indicators (the modified Winkler index and the modified Huglin's heliothermal index) during the 21st century, which may lead to a wider planting of red wine varieties and varieties with higher heat demand.
   - I showed significant increase in the number of years with a maximum daily temperature above 35 °C and in the length of the dry periods during the growing season (with daily precipitation below 1 mm) during the 21st century. It may be a serious risk factor in cultivation.

- I have shown that the frequency of the occurrence of extremely low minimum temperature events during dormancy decreases significantly, which may have a positive effect on cultivation due to less frost damage in the 21st century.
- The milder winters reduce the frost resistance of the buds and increase the chances of pathogen survival, which poses a risk to cultivation.

5. **I adapted Chuine's Unified Model to three Hungarian apricot cultivars ('Ceglédi bíborkajszi'; 'Gönci magyar kajszi'; 'Rózsakajszi C.1406') and estimated the blooming time with an average error of less than 2.5 days.**
6. **I reduced the number of estimated parameters of Chuine's Unified Model from nine to six which made the estimation of the parameters more efficient.**

   During the adaptation, I proved that two of the parameters of the parameter-reduced Chuine's Unified Model applied to the three apricot varieties in Hungary are related, so I suggested fixing one of these parameters before further calculations.
7. **Based on the twenty-six-year blooming data series of three Hungarian apricot cultivars, I determined the local optimum of the parameters and the global optimum parameter vector of the parameter-reduced Chuine's Unified Model by Simulated Annealing method.**

   Based on the global optimum parameter vector, I determined the daily temperature dependence and annual course of chilling and forcing unit accumulation by varieties, as well as the critical sum of chilling units needed for endodormancy break and the critical sum of forcing units needed for blooming.
8. **Comparing the speed term of heat accumulation with the data in the literature, I established that the effect of endodormant chill accumulation on ecodormant heat accumulation is more pronounced in the case of apricot cultivars grown in the studied area.**

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