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How have thermal conditions changed in different phenological stages of apple (*Malus domestica*) in Northeastern Hungary?

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SUMMARY

In temperate climates, most fruit trees need cold weather, low temperatures in winter, and a certain amount of heat during the growing season until harvest. One of the most apparent effects of climate change is the elevated temperature in all seasons of the year. In our study, the changes in thermal conditions have been calculated in Hungary's most significant growing region of apples using the Chill Unit for winters and the Growing Degree Days for summers. The meteorological data were obtained from the gridded dataset of the Hungarian Meteorological Service on a 10 km × 10 km grid, so the whole studied area is well-covered over the last 50 years. The results show that the trees are more exposed to early budding than a few decades ago. Furthermore, the accumulated heat amount in summers has increased drastically, which may increase the heat stress and lead to higher yield losses.

Keywords: *apple; chill-unit; climate change; degree days; thermal conditions*

INTRODUCTION

Apple is one of the most important and popular fruits in the world. The temperate climate of Hungary provides the conditions for the successful cultivation of apples. Compared to the southern European areas with exceptionally high yields (60–70 t ha^{-1}), in Hungary, considering an average yield regarding all orchard types; 40–45 t ha^{-1} yields are considered excellent (Tamás, 2011). In Hungary, the growing area has significantly changed in the last decades. According to the Hungarian Central Statistical Office (KSH) data (KSH, 2022), the size of the apple production area before 1990 reached or exceeded 60000–70000 hectares. After the politicial restructuring in Hungary, the size of the growing area has decreased drastically. Recently, there was roughly 20500 ha of orchards in the country. However, the central region of apple production remains in Szabolcs-Szatmár-Bereg county (KSH, 2022).

The combined effect of abiotic factors significantly affects apple tree development and their general condition (Hauagge and Cummins, 1991). An essential element in achieving the desired yield is the optimal temperature in the winter for dormancy and in the summer for optimal growth. Dormancy is necessary first to cease the biological activity of the trees, which is called endodormancy and needs subfreezing temperatures. Meanwhile, ecodormancy is ruled by the optimal environmental condition, which leads to the budding and flowering of the trees (Lang et al., 1987). The transition between the two phases of dormancy has yet to be clearly described; however, it is known that the transition period becomes shorter under warming climates, even in temperate climates (Aguilera et al., 2014). The ecodormancy needs temperatures between 0 °C and 7 °C.

Different chill unit (CU) models have been introduced to quantify dormancy. In moderate and cold climates, the best model was developed by Richardson et al. (1974) (Dennis, 2003). Apples with low chill requirements such as 'Anna', 'Dorsett Golden' or 'Princissa' need 250–500 CU. The medium chill requirements are between 500–1000 CU for apples such as 'Gala', 'Fuji', or 'Primicia' (Alene, 2021), while the most compatible varieties to the climate of Hungary are apples with high chill requirements. Hungary's most widely produced apple varieties have chilling hours of 600–1100 CU for 'Idared', 'Florina and 'Jonagold'. In warmer climate on lower latitudes, the sufficient winter ecodormancy for apple trees was the limiting factor for selecting the growing area. Owing to global warming, the appropriate chilling requirements will be endangered in the future (Ramírez and Kallarackal, 2015; Delgado et al., 2021; Salama et al., 2021). In cold climates on higher latitudes, winters become milder with considerably more elevated temperatures, i.e. the duration of endo- and ecodormancy periods will change. As a consequence, temperatures will fall within the limits of ecodormancy at a higher rate; therefore, chilling requirements will be achieved on an earlier date (Chmielewski et al., 2012), resulting in the shifting of the whole phenology with earlier budding and flowering (Rochette et al., 2012).

The summer in a significant part of Europe and Hungary is expected to be warmer, with prolonged heat waves and drought by the end of the century (IPCC, 2022). Hence, the accumulated Growing Degree Days affecting apple trees will rise more than 700–800 °C in the second half of the century (Vujadinović Mandić et al., 2023). Consequently, introducing new fruit tree varieties or even new species will be necessary (Rochette et al., 2012).

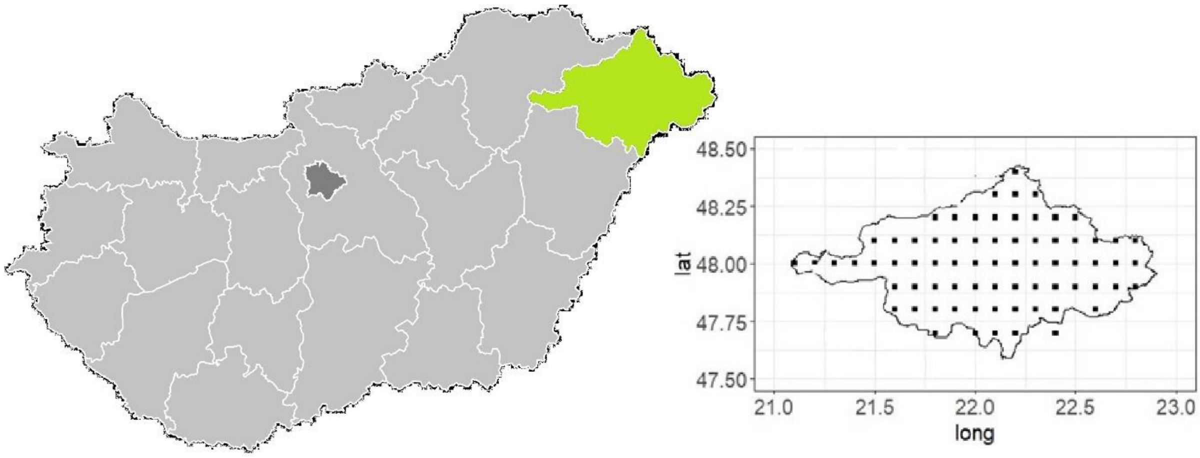
Our results, consistent with the previously mentioned studies, show that the chilling requirements in the winter and the Growing Degree Days in the growing season significantly increased between 1971–2020, which can contribute to the shift of the phenological phases such as budding, flowering, ripening, harvesting and the quality and quantity of the fruits.

MATERIALS AND METHODS

Study area

The validated meteorological data were obtained from the homogenized, gridded database of the Hungarian Meteorological Service. From the network of 1322 grid points covering Hungary, 72 grid points were selected over Szabolcs-Szatmár-Bereg county (*Figure 1*). The temporal coverage of the data was from 01.01.1971 to 31.12.2020. The spatial resolution was 0.1°x 0.1° (~10 km × 10 km). The meteorological parameters were the daily minimum, maximum, and mean temperatures (°C).

Figure 1. **Szabolcs-Szatmár-Bereg county is the study area (green), and the location of grid points inside the county (right)**



Calculation of Chill Unit

Table 1. **Average starting and ending day of certain phenological phases (Tamás, 2011)**

Phenological period	First and last day	Studied parameter
Winter chilling period	1 November – 15 March	Chill Unit (hours)
Growing season	15 March – 6 September	Heat Amount (°C)

According to the Utah model (Richardson et al., 1974), hourly temperature data are needed to calculate the cold effect in the winter chilling period (*Table 1*).

The temporal resolution of the validated meteorological data was sparser than needed; therefore, the only two daily temperature data were available. Therefore, to minimize the error, the Chill Unit (CU) was approximated by the following mathematical formula on each grid point:

$$CU_{daily} = 12 * CU_1 |(T_{min}) + 12 * CU_2 |(T_{max}), \tag{1}$$

where T_{min} was the daily minimum temperature (°C), T_{max} was the daily maximum temperature (°C), and t_0 was the biological zero temperature of the apple trees (5 °C). Furthermore, CU_1 was the Chill Unit defined by the minimum temperature, while CU_2 was the Chill Unit by the maximum temperature (*Table 2*). Using only the daily mean temperature should have smoothed out the daily temperature variation, which can be significant, especially in late autumn or early spring. Extending the minimum and maximum temperatures to a 12-hour time interval may lead to overestimation or underestimation; however, it is assumed that the sum of the errors converges to zero following the Law of Large Numbers. The Chill Unit for the whole winter season was estimated the following:

$$CU_{winter} = \sum CU_{daily}(t). \tag{2}$$

After that, the Accumulated Heat Amount (H) for the growing season (*Table 1*) was calculated by the following:

$$if\ T_{daily} \geq 5°C, then \tag{3}$$

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$$H = \sum_{t=15\ March}^{6\ September}(T_{daily} - T_0)(t). \qquad (4)$$

Table 2. **Threshold values of hourly mean temperature and the corresponding values of Chill Unit based on the Utah model by Richardson et al. (1974)**

Tmean/hrs	Chill Unit
<1.4 ^{0}C	0.0 CU
1.5–2.4 ^{0}C	0.5 CU
2.5--9.1 ^{0}C	1.0 CU
9.2–12.4 ^{0}C	0.5 CU
12.5–15.9 ^{0}C	0.0 CU
16.0–17.9 ^{0}C	-0.5 CU
>18 ^{0}C	-1.0 CU

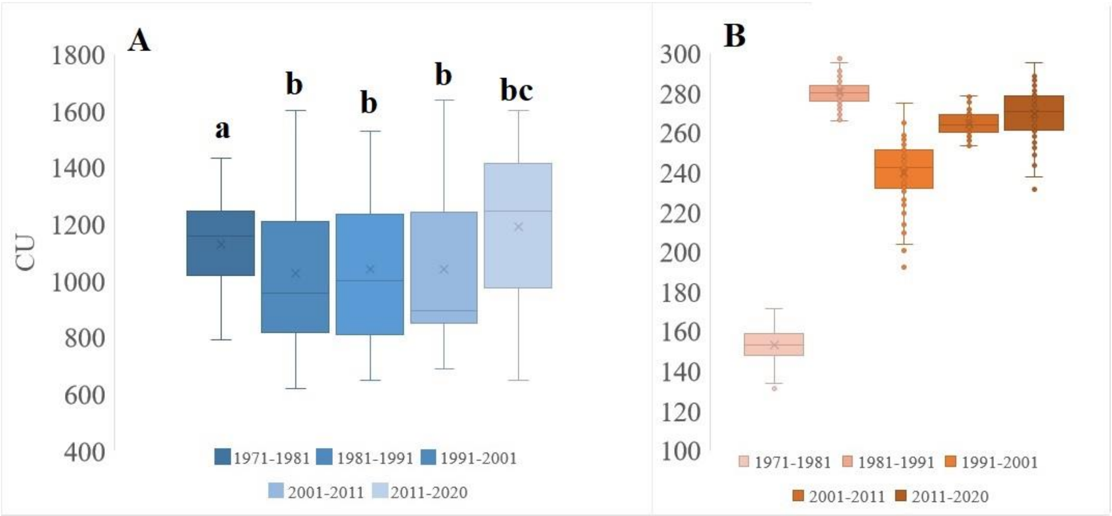
The hourly Chill Unit ranges from -1 CU to 1 CU. The highest scores belonged to the [2.5, 9.1] °C interval, which includes the biological zero point of apple trees (5 °C). The Temperatures as high as 16.0°C and above reduced the total Chill Unit because they had a negative effect on the winter dormancy of trees.

The calculations were performed with Windows Excel, and the visualization was achieved with R statistical software (R Core Team, 2022). One-way ANOVA and the post-hoc Duncan test was performed to determine the significant differences among thermal conditions in the studied time intervals (decades).

RESULTS AND DISCUSSION

The change in ecodormancy on apple trees during decadal periods is shown in *Figure 2A*. The Chill Unit exceeded 650 CU every year, which means that the apple varieties with medium and high chilling requirements can be grown with the highest certainty in the northeastern part of Hungary. Furthermore, the Chill Unit has generally increased owing to global warming (Campoy et al., 2011) because the hourly temperature fell most often in the interval with the highest Chill Unit score (*Table 2*). Consequently, the Chill Unit accumulates more rapidly and exceeds the threshold on an earlier date. The standard deviations of annual Chill Units per decade are shown in *Figure 2B*. It can be seen that, compared to the period 1971–1981, the following four decades show a more considerable variation in the Chill Unit. This suggests that winters were more predictable in the 1970s, as average CU values fluctuated within a smaller range (850–1500 CU) with a standard deviation of 150–170 CU. In comparison, the following three decades showed a significant increase in the annual variance.

Figure 2. **A) the boxplot of accumulated Chill Unit (CU) per decade in winters between 1971–2020, B) the standard deviation of CU per decade between 1971–2020**



The spatial distribution of Chill Units in Szabolcs-Szatmár-Bereg country followed a circum-symmetrical pattern of a gradient with the lowest CU values in the south-central part of the growing region with around 1000 CU in 1971–1980 (*Figure 3*). This was owing to the colder winters when the temperature did not exceed so often the hourly mean temperature of 1.4 °C in the winter season. The highest values of CU were around 1080–1100 CU. Gradual warming can be observed over the decades. After 2000, the highest CU values exceeded 1160 CU, while there were also regions with 1000 CU or below; however, the spatial extent of these areas has been significantly reduced by 2011–2020. This explains the high variability of CU in the last decades (*Figure 2B*).

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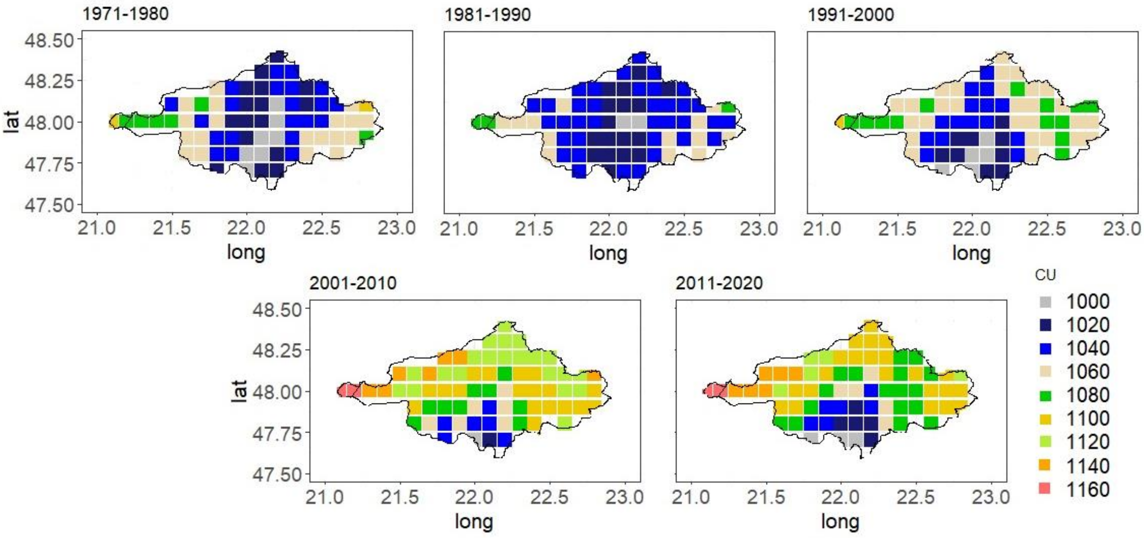
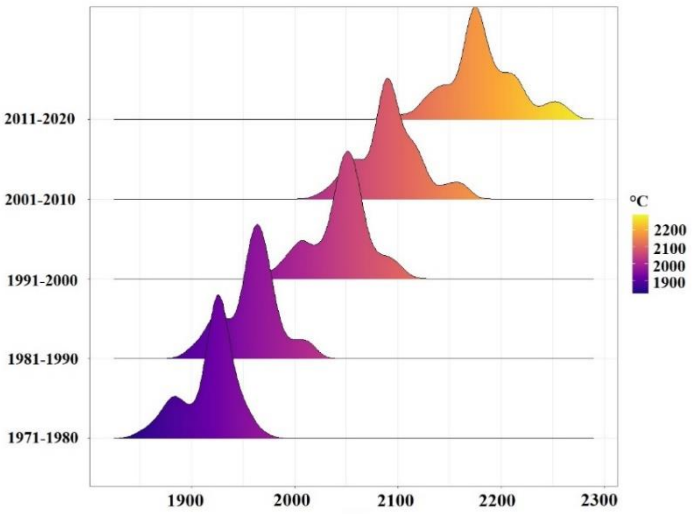
Figure 3. **The decadal average of CU in Szabolcs-Szatmár-Bereg County between 1971–2020**



Another critical period is the growing season and its thermal conditions. The prolonged high temperatures combined with insufficient water supply may lead to water shortage and yield losses. This study analyzed the change in temperature conditions, so the Growing Degree Days were calculated based on the biological zero temperature of 5 °C from 15 March to 6 September. The distribution of heat amount (°C) per decade for the whole region can be seen in *Figure 4*. In the first decade (1971–1980), the most frequent values were around 1940 °C with a secondary maximum of around 1900 °C. The maximums of the distribution functions moved continuously toward higher values while the variance increased, which indicates a shift toward extremes. Values above 2300 °C had been characteristic of Hungary's warmer and more arid southern regions. However, these high Growing Degree Day values have recently appeared in all Hungary regions (Somfalvi-Tóth, 2021). The increased heat amount over the growing season suggests that apple trees are exposed more often to elevated temperatures, which can inhibit the development of the fruits. The question emerges, where is the threshold above which we can consider a damaging and stressful cumulative thermal effect on apple trees?

Figure 4. **Distribution of accumulated heat amount in the growing season per decade, including all grid points between 1971–2020**



CONCLUSIONS

Climate change is significantly impacting crop production, as temperature and precipitation patterns have changed in recent decades and need to be adapted to, so the spatial distribution of apple production is changing as well. In the lower latitude and warmer regions, the amount of winter ecodormancy has been significantly reduced, while the heat stress has increased in the summer, i.e. the area of apple production regions with appropriate climate has been declining (Funes et al., 2016; Rodríguez et al., 2019; Helder and Santos João, 2021). Conversely, the northern countries are gaining broader ground for apple production due to global warming. Recent studies show that the growth of specific apple varieties will be possible up to the 63°N in Norway (Vujadinović Mandić et al., 2023) and up to 66°N in Finland (Kaukoranta et al., 2010) by the middle of the century. The results of our study support this latter trend. The heat affecting the apple trees has increased in the winter and summer, with a particularly marked change in the last two decades. In Hungary, the northeastern part of the country is one of the most rapidly warming regions, with an increase in mean annual temperature of 1.6–1.8 °C compared to 1980 (IPCC, 2022), within which the winter period temperature, especially the proportion of temperatures falling in the 0–5 °C temperature interval, has increased (Wypich et al., 2017), which explains the increase of Chill Unit over the decades as well. The same result was found by Szabó et al. (2017). According to their study, the mean temperature of March has increased in the last decades, which has influenced the start of the blooming of the apple trees in the northeastern part of Hungary. If the monthly mean temperature rises by 1 °C in March, the blooming shifts two days earlier. As for the summer season, the Growing Degree Days have increased by an average of 400 °GDD, and this trend is very likely to be continued in the future, and it can exceed 2500–2700 °C by the end of the century (Vujadinović Mandić et al., 2023), so apple varieties with higher water shortage and heat-stress tolerance have to be prioritized in the future. Tworkoski (2004) carried out a study comparing apple rootstocks (M9; M11) and varieties (Gala, Fuji) under drought stress conditions. They found that M111, while inducing a stronger root system, was more resistant to drought over the longer term. M9 rootstock, on the other hand, is physiologically adaptable for short-term drought stress due to increased levels of abscisic acid, which plays a key role in regulating stomatal function under drought conditions. Between the two varieties tested, Gala yielded better results on M9 rootstock. Furthermore, in case of apple varieties genetic work on finding suitable genes for heat stress tolerance is currently being done. It was found that apple MdATG18a, a key autophagy protein, improves drought tolerance. Transgenic apple (*Malus domestica*) plants overexpressing MdATG18a were heat stressed in this study, however autophagy protected them (Huo et al., 2007).

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