ASSESSING ACCUMULATED HEAT UNITS FOR BBCH-SCALED GROWTH STAGES OF *QUERCUS CERRIS* L. IN BAB FOREST

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Abstract

Quercus cerris L. is a common tree species in the lowland forests of Central Europe, and its temperature requirements for the full annual growth cycle have not been assessed enough. This study recorded the BBCH-scaled growth stages of *Q. cerris* in Bab Forest near Nitra, Slovakia, during 2025, and calculated the accumulated heat units (AHU) required to complete all growth phases. AHU was calculated from daily air temperature data with a base temperature of 5 °C. Findings confirmed that full foliage required the most AHU 1,569.8 °C in the duration of 109 days, fruit development at 1,067.7 °C, and fruit maturation at 789.1 °C, respectively. Spring phases completed their growth cycle in a short duration, with budburst in early spring and leaf development in late spring, and these stages recorded the lowest AHU values, along with the senescence phase. Phenophase duration and AHU showed a positive Spearman correlation (ρ = 0.74). The AHU values for *Q. cerris* assessed in this study will be useful in phenological modelling and climate adaptation planning.

Keywords: BBCH, phenology, Quercus cerris, oak, accumulated heat units, temperature

INTRODUCTION

Phenology has long been used to assess, how trees respond to seasonal temperature changes. The individual phases of the life cycle - bud burst, leaf unfolding, flowering, and leaf senescence are significantly influenced by temperature factors, which makes temperature the central variable in any phenological studies (Mcmaster and Wilhelm, 1997). Spring phenological events across Europe have been shifted earlier by approximately 2.5 days per decade, and this regional trend has been observed in recent years (Cleland *et al.*, 2007; Cornelius *et al.*, 2011). Such shifts in seasonal timing affect forest carbon uptake, growing season length, and competitive dynamics among tree species. Understanding these responses at the species level is important for predicting how individual forest tree species will adjust to continued warming (Fu *et al.*, 2015). Accumulated heat units (AHU) measure the total heat a plant receives during a given period by summing daily mean temperatures above a base temperature (Bonhomme, 2000). This approach is more useful than using days of the year alone, because the same growth stage can occur at different times of the year. The Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie BBCH scale has provided decimal codes for plant growth stages from dormancy to final senescence (BBCH Monograph, 2018).

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BBCH-coded observations are used to assess thermal requirements with AHU calculations and compare them across species, sites, and years in a standardized way. *Quercus cerris* L. is a warm-adapted deciduous oak species with a natural range extending from southeastern to central Europe (Novák *et al.*, 2020). It is ecologically important in the Pannonian region, where it occupies dry to mesic lowland and sub-montane forest stands. Bab Forest near Nitra in southwestern Slovakia represents a typical locality for this species. Despite its regional significance, there is a lack of information on AHU values for the complete annual cycle of BBCH-coded growth stages of *Q. cerris* under these conditions. The objective of this study was to determine AHU requirements for each BBCH-defined growth stage of *Quercus cerris* during the 2025 growing season in Bab Forest.

MATERIALS AND METHODS

The study was carried out at the Báb eLTER site (https://deims.org/79e10639-dd60-4f30-9c43-7b2bae0f359a), situated in the Nitra District of Slovakia. The site is located in the Podunajská nížina lowland at an altitude of 160–210 m. The site has a warm continental climate, with mean July temperatures of 20.5 °C and mean January temperatures of -3 °C. Annual precipitation ranges from 500 to 600 mm (Pilková, 2014). *Quercus cerris* is one of the dominant tree species at this locality and was selected as the target species for this study. Phenological growth stages of Quercus cerris were recorded using the BBCH scale (BBCH Monograph, 2018) with decimal codes (0-9) to the growth stages from dormancy to senescence, and those main growth stages were then further divided into sub-stages. The extended version of the scale was applied to capture vegetative stages, including leaf coloration and dry-period senescence. Phenological recordings were made from 6 March to 30 December 2025. During the early growing season, stages were recorded twice per week, and after full foliage was reached, observations were reduced to once per week, as recommended in the standard phenological monitoring practice (Miller-Rushing *et al.*, 2010; Cornelius *et al.*, 2011). Daily maximum and minimum air temperature data for 2025 were recorded at the meteorological station of the Slovak Academy of Sciences, located approximately 500 m from the study site. A base temperature of 5 °C was applied for *Q. cerris*, as the standard threshold values used for temperate tree species (Dimitra and Tsitsoni, 2022). AHU for each phenophase was calculated as:

$$AHU = \sum_{i=1}^{n} \left(\frac{T_{max} + T_{min}}{2} - T_b \right) \quad . \qquad (1)$$

Here, T_{max} and T_{min} are daily maximum and minimum air temperatures (°C), T_b is the base temperature (5 °C), and n is the number of days of each phenophase. Days with a negative daily mean contribution were set to zero. The relationship between phenophase duration and AHU was tested using Spearman rank correlation (ρ) (Singh *et al.*, 2023).

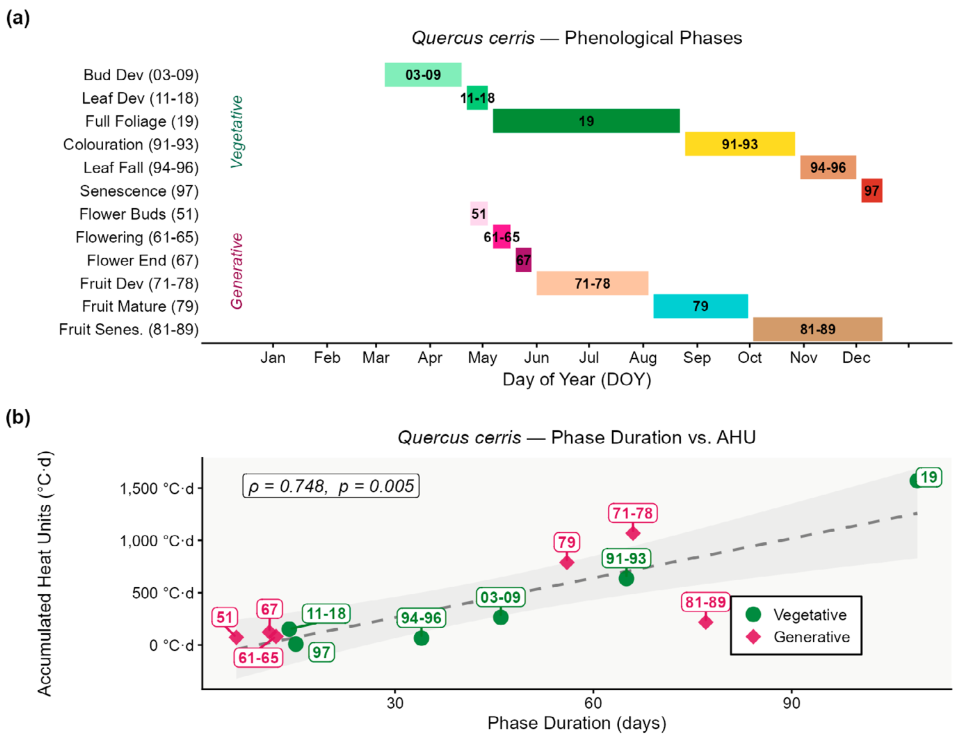
RESULTS AND DISCUSSION

We calculated the AHU requirements for the 12 BBCH-defined growth stages of *Quercus cerris* recorded in Bab Forest during 2025 (Tab. I). Throughout all phenophases, both the duration and AHU values varied significantly, reflecting the uneven thermal conditions associated with each seasonal period. The bud development stage lasted 46 days (Fig. 1a) and required 264.9 °C. This phase begins in early spring when temperatures are still low and rise gradually, so the heat accumulates slowly over a relatively long period. Leaf development was much shorter at 14 days, with an AHU of 152.4 °C, indicating a rapid transition once buds had opened.

A comparable pattern of rapid leaf expansion and bud burst has been reported in other European oak species, in which the unfolding phase tends to initiate once sufficient forcing temperatures are reached (Novák *et al.*, 2020). Full foliage stage lasted 109 days and recorded the highest AHU of the year at 1,569.8 °C. This phase covers the peak summer months, so heat accumulates continuously throughout the season. Fruit development in oaks demands considerable thermal input, and the high AHU of 1,067.7 °C recorded for fruit development (Tab. I) is consistent with findings reported in previous literature for thermally demanding reproductive phases in

I: *Phenological phases of Quercus cerris, phase duration (days), and accumulated heat units (AHU, °C) for 2025*

Phenophase (BBCH)	Days	AHU (°C)
Bud development (03–09)	46	264.9
Leaf development (11–18)	14	152.4
Full foliage (19)	109	1,569.8
Leaf colouration (91–93)	65	635.7
Leaf fall (94–96)	34	66.2
Senescence (97)	15	9.3
Flowering buds (51)	6	73.4
Flowering (61–65)	12	82.1
Flowering end (67)	11	123.7
Fruit development (71–78)	66	1,067.7
Fruit maturation (79)	56	789.1
Fruit senescence (81–89)	77	218.4



1: *(a) BBCH-scaled Phenological Phases timeline of Quercus cerris and (b) Spearman's correlation between phenophases duration and AHU* temperate oaks (Wolkovich *et al*., 2012). Flowering buds required only 73.4 °C, and full flowering required 82.1 °C over 12 days. Spring flowering in oaks occurs for a short period of time with very low heat requirements, similarly low heat requirements for anthesis have been reported in other *Quercus species* (Novák *et al*., 2020). Autumn senescence stages showed the lowest AHU values of the year. Leaf fall accumulated only 66.2 °C, and senescence recorded just 9.3 °C over 15 days, as daily temperatures were close to the base threshold during this period. Leaf coloration lasted 65 days and required 635.7 °C, reflecting the gradual onset of autumn cooling. The decrease in AHU from leaf coloration to senescence showed patterns similar to those of temperate deciduous species in Central Europe, where autumn phenology is influenced by decreasing temperatures and a shortening photoperiod (Basler and Körner, 2012). A positive Spearman rank correlation between phenophase duration and AHU accumulation ($\rho = 0.748$) indicates that longer phases generally accumulate more heat (Fig. 1b). These findings have provided species-specific heat requirements for *Q. cerris* for its full annual growth cycle, and the AHU values reported here can be useful for phenological modelling under changing climate conditions.

CONCLUSION

The study concluded that *Quercus cerris* has distinct AHU requirements during the annual growth cycle. The summer vegetative and reproductive phases required higher temperatures than spring bud development or late autumn senescence. The AHU values recorded in this study showed the heat sensitivity of each phenophase and provided quantitative data that can support phenological modelling and forest management decisions for this species in Central European conditions. As climate change shifts seasonal temperature patterns, species-specific AHU data will become increasingly relevant for predicting changes in oak growth timing.

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