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DETERMINING METHOD FOR THE PHENOLOGICAL STAGE OF SPRING ESTABLISHED CROPS OF *HORDEUM VULGARE* L., *HORDEUM DISTICHON* L. AND *AVENA SATIVA* L. BY USING ATMOSPHERIC TEMPERATURE

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Abstract: Barley, two–rowed barley and oat crops covers an area of approximately 500 thousand hectares in Romania and produce 1.3 million tons of grains. Due to thermo–hydric stress, sometimes it is necessary for these cultures to be established in the spring instead of autumn. The aim of the work is to create a decision support based on a method for determining the phenological stages of spring crops using the mathematical correlations between atmospheric temperature and biological parameters. With this method, digital simulations can be made regarding the phenological phase, plant height, water content and crop progress. The proposed method is useful for the digitization process in agriculture in order to optimize the consumption of fertilizers and pesticides

Keywords: barley, oat, spring, temperature, BBCH

INTRODUCTION

Knowledge of the phenological stages of plants is useful for determining the optimal timing of agronomic care and harvesting activities. Since plants are dependent on ambient temperature, the calendar period from sowing to harvest may exhibit variations that can lead to suboptimal crop management. For a better assessment of the biological age and phenological stages of plants, the concept of thermal time was introduced as the sum of effective temperature degrees (GDD) (Arnold *C.,1959,1960; McMaster G.S. and Wilhelm W., 1997*).

As early as 18th century, the term "heat units" (*Re'aumur, 1735*) was used in agriculture to assess the development stage or age of the plant. Using this concept, thermal constants of plants were defined. Initially, a simple calculation was used, represented by the product of the average daily temperature and the number of days corresponding to the period from sowing to the point of interest. Over time, it was observed that certain factors, such as soil temperature or extreme values of atmospheric temperature, could introduce errors in accurately determining the biological age. In the case of atmospheric temperature values lower or higher than the favorable temperatures for the species, summing the degrees can result in different accumulated values for the same phenological stage. This led to the introduction of a new parameter called biological threshold, representing the temperature value at which a species begins to have metabolic activity or accumulate biomass. Thus, the calculation formula became (1):

$$GDD = [(T_{MAX} + T_{MIN})/2] - T_{BASE} \qquad (1)$$

where *GDD* is growing degree days, T_{MAX} and T_{MIN} are the maximum and minimum daily temperatures, and T_{BASE} is the threshold temperature.

By using this formula, the threshold temperature value is extracted from the atmospheric temperature, and the remaining value is taken into account when summing up the useful or effective degrees. For crops sown in the fall, the formula containing the biological threshold in the calculation mode is considered acceptable for thermal time because the temperature values in the fall–winter–spring months have a balanced weight. For crops sown in the spring, high temperature values were observed that contributed to the calculated value but did not contribute to plant biomass accumulation. These temperatures are considered supra–optimal as they slow down plant–specific metabolic processes.

To mitigate this effect, an upper temperature threshold was introduced. For corn, an upper threshold of 30 °C was introduced (*Cross H.Z. and Zuber M.S.,1972*), and one of 25 °C for wheat (*McMaster G.S. and Smika D.E., 1988*). Thus, the sum of effective temperature degrees is calculated only for those values within the temperature range limited by the minimum biological threshold and the upper threshold. This calculation method has become the most widespread and is used by several researchers (*Nield R.E. and Seeley W.M., 1977; Davidson H.R. and Campbell C.A.,1983*). With the advent of meteorological stations capable of recording atmospheric parameter values at a sampling rate of one hour or a few minutes, the possibility of increasing the accuracy of thermal time determination was analyzed. By increasing the sampling rate, the frequent fluctuations in temperature are taken into account, which normally cannot be covered by only the minimum and maximum daily temperatures.

Considering that biochemical reactions are correlated with temperature through a polynomial function that follows a bell–shaped trend, this study proposes using a nonlinear function to calculate the sum of effective degrees.

MATERIALS AND METHODS

In the experiment, barley, triticale, and oats were sown on an area of 200 square meters each on March 14, 2023, after preparing the seedbed through fall plowing and spring disking. Weekly, biometric determinations were carried out from March 27 to July 27, including plant height, plant mass, plant moisture, and phenological stage. Ten plants from each cultivated species were analyzed at each time interval. Atmospheric temperature data were collected from the local station at an hourly sampling rate.

The average plant height was determined by measuring the highest point of the plants from the soil surface. Plant moisture was determined using a thermobalance (Partner MAC50/NH) at 115 °C after three consecutive identical readings, and the BBCH scale determination was performed according to the specific scale for cereals (*Witzenberger A. et al., 1989; Lancashire P.D. et al., 1991*).

The calculation of the sum of useful degrees was performed using the classical (linear) method (2):

$$GDD = \sum\{[(T_{MAX}+T_{MIN})/2]-T_{BASE}\} \qquad (2)$$

where T_{BASE} for barley / two–rowed barley is 2°C and 5°C for oat, and the nonlinear method (3):

$$GDD = \sum[(a*T4+bT3+cT2+dT+e)*T/100]/24 \qquad (3)$$

where *a, b, c, d,* and *e* are the coefficients of the polynomial, and *T* is the atmospheric temperature.

For barley, triticale, and oats, the polynomial equations for determining the percentage of thermal comfort of atmospheric temperature are presented in Table 1.

Table1. The polynomial equations for determining the percentage of thermal comfort of atmospheric temperature

Species	non–linear equation GDD=∑
Barley – *Hordeum vulgare* L.	$[(0.00078*T^4 - 0.05985*T^3 + 1.15634*T^2 - 0.19557*T - 6.67968)*T/100]/24$
Two–rowed barley – *Hordeum distichon* L.	$[(0.00078*T^4 - 0.05985*T^3 + 1.15634*T^2 - 0.19557*T - 6.67968)*T/100]/24$
Oat – *Avena sativa* L.	$[(0.0047*T^4 - 0.33412*T^3 + 7.52267*T^2 - 56.67688*T + 135.4783)*T/100]/24$

RESULTS

The growth of plants in height during the experimental period followed a trend similar to climatic evolution (Figure 1).

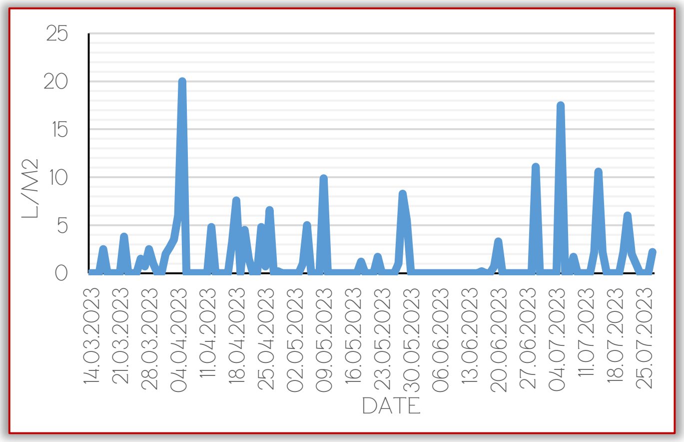

Figure 1 – Rainfall amount during the experimental period

In Figure 2 is presented the dynamics of height growth of plants where it can be observed that the majority of collected sample had increasing values, except for three determinations out of the 18. In the first month from sowing, all three species had the same height. Throughout the growth period, it was observed that two–rowed barley and oat had a more accelerated height growth compared to barley. This difference in growth may be due to genetic characteristics defining the species or adaptability to drought.

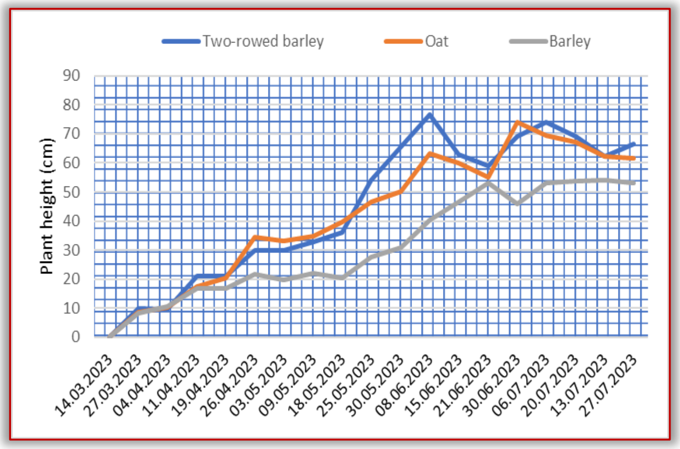

Figure 2. – The height growth dynamics of barley, oats, and two–rowed barley

Correlations between the sum of growing degrees calculated by the two methods (Figure 3 and Figure 4) and the dynamics of height growth had regression coefficient (R^2) values ranging between 0.94 and 0.96, demonstrating that plant height can be mathematically approximated using atmospheric temperature values. Due to the very close values of the regression coefficients, it can be concluded that there are no significant differences between the two methods regarding the physico–mathematical determination of plant height.

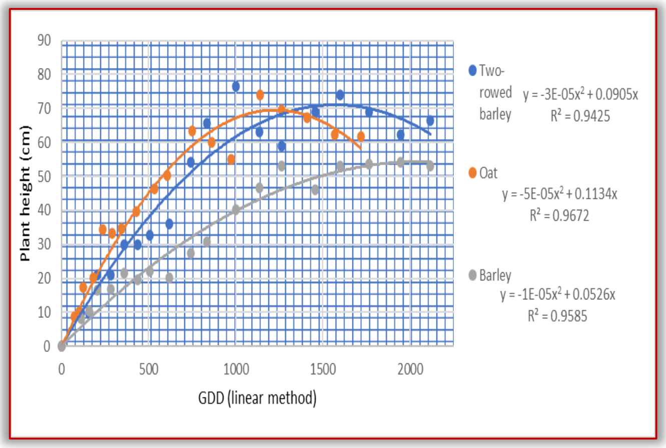

Figure 3. – The correlation between plant height and GDD (classical linear–method)

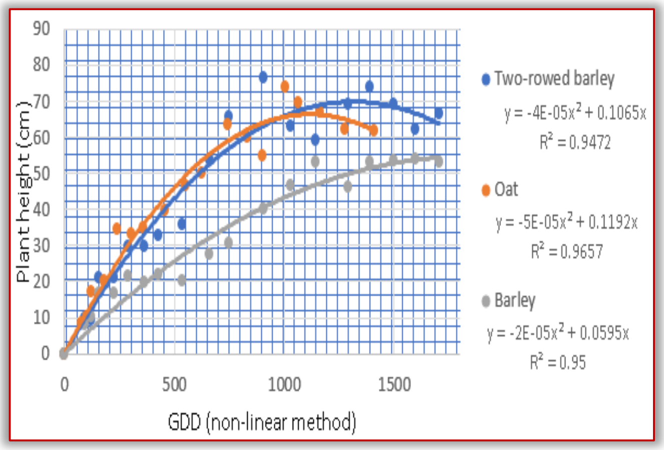

Figure 4. – The correlation between plant height and GDD (non–linear method)

The biomass accumulation of the three species followed a normal growth trend for plants, reaching values of 34.69 g per plant for two–rowed barley, 32.15 g for oats, and 28.6 g for barley. In Figure 5, the dynamics of plant biomass accumulation are presented, highlighting that the majority of collected biometric samples were useful for mathematical analysis.

Mathematical correlations between the sum of temperature degrees and plant mass (Figure 6 and Figure 7) had regression coefficient (R^2) values ranging between 0.77 and 0.83. The correlation coefficient values of plant mass and GDD are lower than those of plant height and GDD, by both methods. One possible explanation could be the lack of the uniformity of the collected samples.

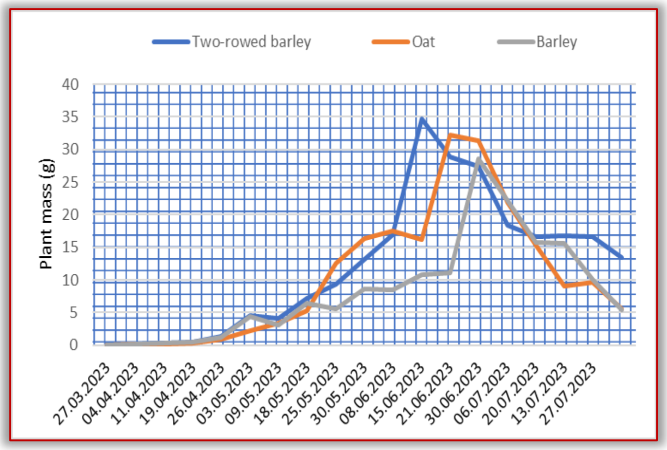

Figure 5. – Biomass accumulation dynamics of barley, oats, and two–rowed–barley

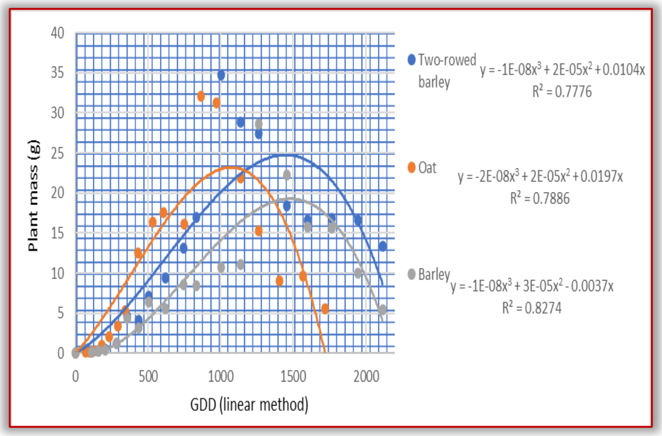

Figure 6. – The correlation between plant mass and GDD (classical linear–method)

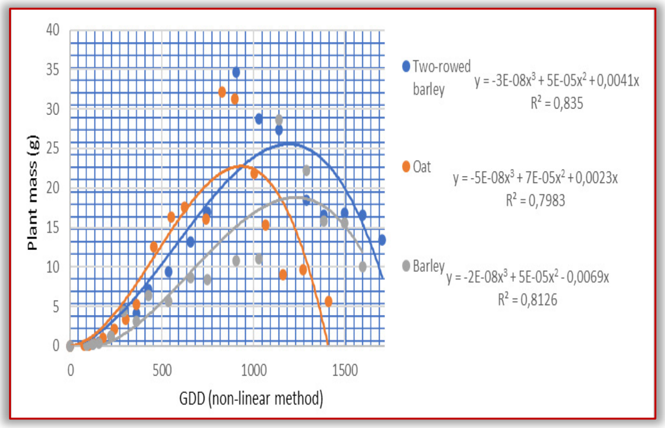

Figure 7. – The correlation between plant mass and GDD (nonlinear method)

The water content of the plants (Figure 8) reached values close to 85–90% during the period from germination to the halfway point of inflorescence emergence (BBCH 55), after which it began to decrease progressively to 10%, indicating the optimal harvest time.

The mathematical determination of water content dynamics throughout all phenological stages, according to the analysis of correlation coefficient values, can be accurately performed regardless of the method used to calculate the sum of degree days. In Figures 9 and 10, correlation coefficient values ranging between 0.90 and 0.97 are presented. The linear method of calculating the sum of degree days had regression coefficient values higher than those of the nonlinear method, but statistically non–significant.

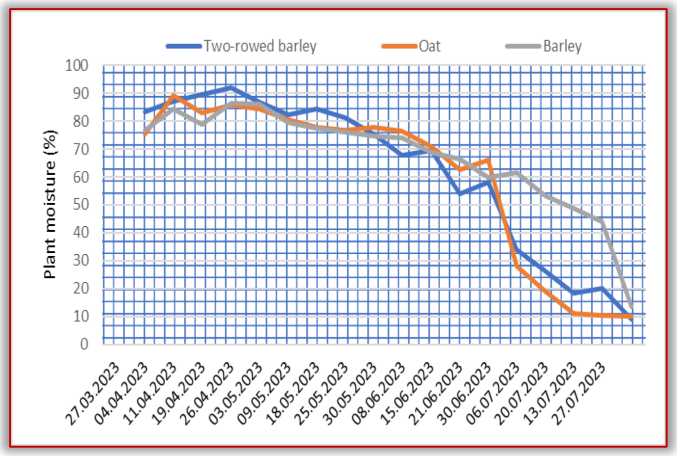

Figure 8. – The plants water content variation during the 2023 growing season

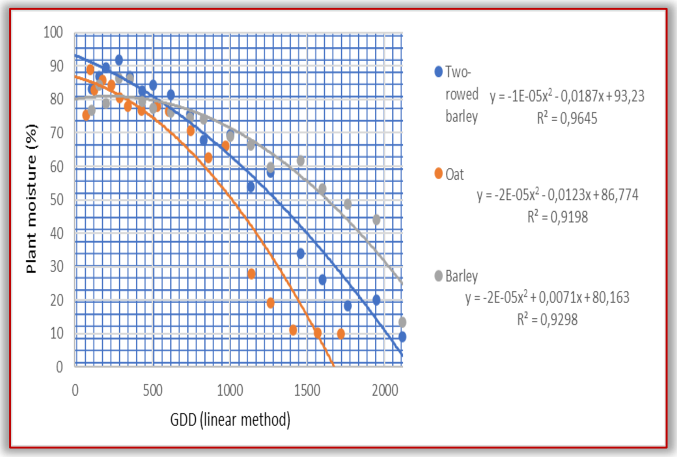

Figure 9. – Water content and GDD correlation (classical linear–method)

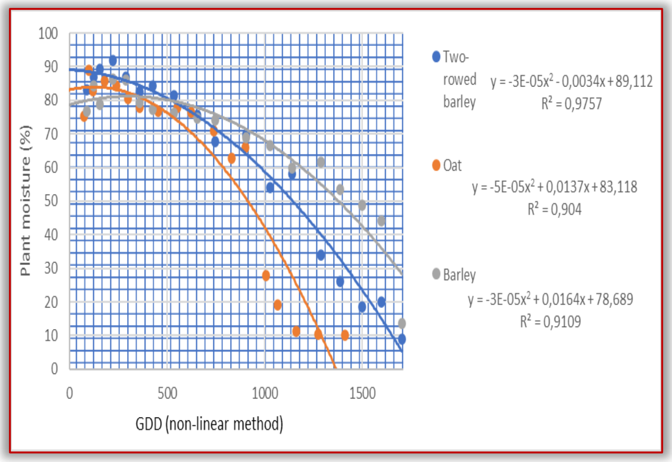

Figure 10. – Water content and GDD correlation (nonlinear method)

The analysis of the cumulative growing day degree values for the phenological ripening phase of grains highlighted that, using the linear method (Figure 11), higher accumulated heat values are obtained compared to the nonlinear method (Figure 12). Thus, barley and two–rowed barley crops reached the phenological stage of ripening at a value of 1457 degree days using the linear method and at 1290 using the nonlinear method. Both values fall within the range reported in the literature, specifying for these crops a range between 1193 and 1438 days–degree (*Miller P. et al., 2001*). The oat crop reached the phenological ripening stage at 1139 days degree using the classical calculation method and at 1007 days degree using the nonlinear method.

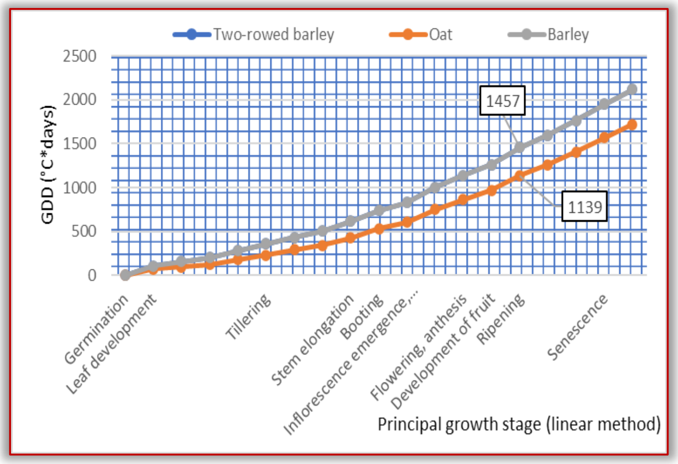

Figure 11. – The correlation between the phenological phase and GDD (classical linear–method)

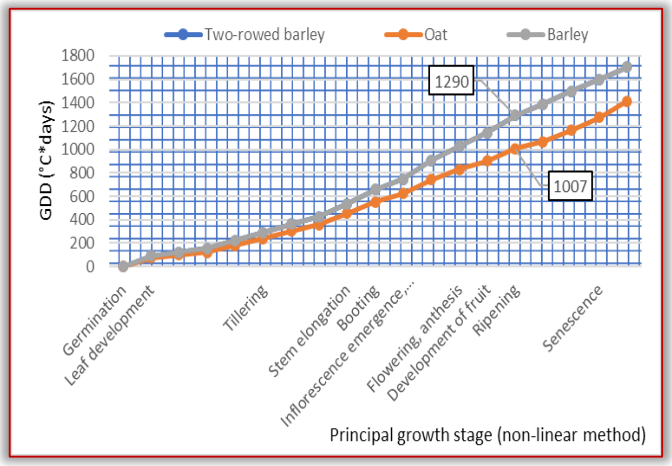

Figure 12. – The correlation between the phenological phase and GDD (nonlinear method)

Comparatively, the values obtained for the oat crop using both methods were lower than the known data range (1483–1738 degree–days) (*Miller P. et al., 2001*). One possible explanation for this could be the spring planting of crops and the low precipitation of 176 mm (Figure1) between March 14 and July 27, 2023, significantly lower than the 30–year average of 287.4 mm for the same period (*INS, 2007*).

The precipitation deficit also affected the production level, with two–rowed barley and oat crops yielding 1.5 and 1.2 tons/ha, respectively, compared to the multi–year average for fall–sown crops of 3.4 tons/ha. The precipitation deficit was more pronounced in the case of barley, with a production of only 270 kg/ha, significantly lower than the average of 1900 kg/ha.

CONCLUSIONS

Determining thermal time is crucial for planning specific agronomic activities at the farm level. By comparing calendar time to thermal time, assessments can be made regarding the progression and duration of the crop's vegetative cycle. Precise knowledge of the thermal constants for cultivated species and the theoretical cumulative growing degree days for the spring crop season enables farmers to decide whether to establish a barley, two–rowed barley or oat crop in place of failed fall–sown crops. Since the nonlinear method of calculating cumulative growing degree days generated lower values for phenological stages compared to the classical method, it can be concluded that this method leads to a better correlation with the phenological stage of the plant because it takes into account the fact that the temperatures above the upper biological threshold do not optimally contribute to biomass accumulation.

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