

EVALUATION OF DEGREE-DAYS FOR SPRING CROPS, CONSIDERING UPPER TEMPERATURE THRESHOLDS AND CUT-OFF TECHNIQUES

VALUTAZIONE DEI GRADI-GIORNO PER COLTURE PRIMAVERILI, CONSIDERANDO SOGLIE DI TEMPERATURA SUPERIORI E TECNICHE DI CUT-OFF

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Abstract

Variations in temperature trends connected to climate change have considerable consequences on plants' phenological development, being temperature its major driving force. Several modeling approaches exist, to simulate the phenological development through the calculation of GDDs, all of them having in common the consideration that the plant starts to cumulate heat units above a minimum temperature threshold (base temperature), required to develop from one stage to another, and slows down, or stops, when a maximum temperature threshold is reached.

Aim of the present work was to compare different upper threshold cut-off techniques, applied to the single triangle method, in order to assess which of them could give the best results in terms of GDDs calculation for summer crops in the climate change scenario in the North of Italy. For this purpose, a historical series of phenological data was used, comparing "standard years" and years in which high temperatures conditions were recorded.

Parole chiave

Calcolo dei GDD, fenologia, cambiamenti climatici, tecniche di cut-off, soglie termiche

Keywords

GDDs calculation, phenology, climate change, cut-off techniques, thermal thresholds

Introduction

Variations in temperature trends connected to climate change have considerable consequences on plants' phenological development, being temperature its major driving force. This connection is expressed in growing degree days (GDDs), defined as the "heat units" (useful for the progression of the life cycle) accumulated during a day (24 h), as reported in Poggi et al. (2022).

Several modeling approaches exist, to simulate the phenological development through the calculation of GDDs, all of them having in common the consideration that the plant starts to cumulate heat units above a minimum temperature threshold (base temperature), required to develop from one stage to another in its life cycle.

The simplest way to calculate GDDs is represented by the so-called "rectangle method" (Arnold 1960). This is an averaging method, calculating GDDs starting from daily maximum and minimum air temperature.

This model assumes that the useful heat cumulated in the 24 hours for the phenological development can be approximated to the difference between mean daily temperature and crop base temperature.

However, it now has been extensively demonstrated how this approach presents several weaknesses, due to its excessive simplification.

First of all, it assumes that the relationship between the whole range of temperature and GDDs is linear, despite the

recognized evidence that the response of biological organisms to temperature is nonlinear (Maiorano 2012).

The nonlinear approach considers that plants development rate increases linearly with temperature only between the base temperature and the optimal temperature for the crop development. Once temperature exceeds the optimal, developmental rate starts decreasing, till it becomes zero when temperature reaches the so-called "maximum cardinal temperature".

Secondly, averaging method does not take into account daily temperature fluctuation, while developmental rates at constant or variable temperatures are deeply diverse.

To solve both problems, the most refined models make use of the beta-distribution function method. The equation takes into account T_{base} , $T_{optimal}$ and T_{max} of plant development. Thermal time is considered to be zero if $T < T_{base}$ or if $T > T_{max}$, and to be maximum if $T = T_{optimal}$. The equation models the decrease of the developmental rate as temperature exceeds $T_{optimal}$ and approaches to T_{max} . Moreover, using hourly temperature data as input, it considers daily temperature fluctuation (Zhou and Wang 2018).

At an intermediate level of complication, between the too simple "rectangle method" and the highly refined "beta-distribution function method", other methods have been proposed for estimating GDDs cumulation, and are frequently employed in field-operational contexts, having

the advantage of being easy-to-use, using as input minimum and maximum daily temperature instead of hourly temperature.

These methods aim to take into account daily temperature fluctuation, assuming that daily temperature profile can be represented by a geometrical shape, such as the single triangle method (Snyder et al. 1999).

In a climate characterized by high temperatures, these methods can be refined with “cut-off” techniques (horizontal, vertical, intermediate), in order to consider the detrimental effect of temperatures higher than $T_{optimal}$. In these cut-off methods, degree-day calculation area is modified in relation to an upper threshold temperature, above which developmental rate starts to decrease, or stops, depending on the cut-off strategy used (University of California Davis,

www.ipm.ucdavis.edu/WEATHER/ddconcepts.html).

Given all these considerations, GDDs calculation method, which do not consider an upper threshold temperature, and thus do not take into consideration negative effects of high temperatures on plants’ development, can be successfully applied under “standard” climate conditions, but could be inadequate under climate change conditions, characterized by increasing frequency of heat waves, leading to interpretations of climate effects not consistent with the real phenological response to temperature.

In this context, aim of the present work was to compare different upper threshold cut-off techniques, applied to the single triangle method, in order to assess which of them could give the best results in terms of GDDs calculation for summer crops in the climate change scenario in the North of Italy. For this purpose, a historical series of phenological data was used, comparing “standard years” and “warm years” (years in which high temperatures conditions were recorded).

Materials e Methods

Twenty-one years of phenological data were used in this study (2003 – 2023), obtained from the phenological bulletin, released weekly by the Department of Agricultural and Food Sciences (DISTAL), University of Bologna. The bulletin publishes data of the phenological surveys carried out in accordance with the Phenagri protocol (Pasquini 2006), at the agro-phenological station experimental plots sited in Cadriano (BO) (44° 33' 03" N, 11° 24' 36" E). Phenology was analyzed according to the internationally recognized BBCH scale (Biologische Bundesanstalt, Bundessortenamt, and Chemical industry), encoding plants’ development stages using a double-digit code, going from sowing (00) to harvest (99), thus consisting of 10 principal stages (0–9), with 10 secondary stages (0–9) for each principal one (Meier 1997).

For GDDs calculation, to be coupled to phenological data, weather data (daily maximum and minimum temperature) were provided by DISTAL agrometeorological station, sited next to the DISTAL agro-phenological station.

To evaluate high temperature regimes effects on GDDs calculation for summer crops, the aforementioned 21 years

were divided in “standard years” and “warm years”, following the procedure of Fornaciari et al. (2023); “standard” and “warm” years were defined as years in which average temperature in the trimester June – August was respectively above and below the median value of the 21-years period.

First of all CGDD (Cumulated Growing Degree Days) for the reaching of BBCH stage 65 (full flowering) and 89 (full maturity) were calculated, using the single triangle method with no cut-off techniques for “standard years”, in order to define thermal requirements for two crop species used in this study, for the reaching of BBCH stages 65 and 89. The two chosen crops are particularly relevant summer crops for the area of the Po Plain, in the north of Italy: corn (*Zea mays*, L.) and sorghum (*Sorghum vulgare* Pers.).

Then, in order to understand which upper threshold cut-off technique for GDDs calculation could give the best results in the climate change context, with respect to the use of single triangle method with no cut-off strategies, both single triangle method with no cut-off and with cut-off techniques (horizontal, vertical and intermediate), respectively, were used in “warm years” to simulate the DAS (Days After Sowing) at which thermal requirements for BBCH 65 and BBCH 89 were reached.

DAS for the reaching of BBCH 65 and BBCH 89 observed in the field in warm years (obtained from phenological bulletin) were thus compared with DAS for the reaching of BBCH 65 and BBCH 89 predicted with the different aforementioned strategies, using Root Mean Square Error (RMSE)

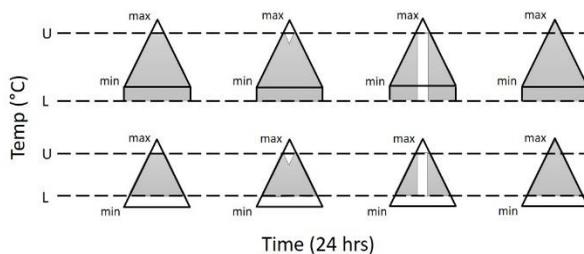


Fig. 1: Possibili relazioni tra il ciclo termico giornaliero e le soglie termiche superiore e inferiore.

(max= temperatura massima giornaliera, min= temperatura minima giornaliera, U= soglia termica superiore, L= soglia termica inferiore)

Fig. 1: Possible relationships between the daily temperature cycle and the upper and lower thresholds.

(max= maximum daily temperature, min= minimum daily temperature, U= upper threshold temperature, L= lower threshold temperature)

The different cut-off techniques are presented in Figure 1. Briefly, the horizontal cut-off method considers that development continues at a constant rate when temperature exceeds the upper threshold. The intermediate cut-off method assumes that development slows (but does not stop) at temperatures above the upper threshold. The vertical cut-off method considers that development totally stops over the upper threshold temperature. Considering the

conceptualization of the different cut-off techniques, the upper threshold was chosen equal to crop T optimal (temperature over which developmental rate starts decreasing) for horizontal and intermediate strategies, while it was chosen equal to crop T max (temperature over which developmental rate totally stops) for vertical cut-off. For corn T base, T optimal and T max adopted were 8°C, 30°C and 40 °C, respectively (Zhou and Wang 2018; Raes et al. 2018). For sorghum, 8°C, 30°C and 42 °C were used (Singh et al. 2017; Raes et al. 2018).

Results and discussion

The two groups of standard and warm years are presented in Table 1.

Tabella 1: Anni standard e anni caldi nel periodo considerato di 21 anni, in base alla temperatura media nel trimestre giugno – agosto. Il valore mediano di riferimento, calcolato sull'intero dataset, è 24,4°C.

Table 1: Standard and warm years in the 21-years considered period, based on average temperature in the trimester June – August. The reference median value, calculated on the whole dataset, is 24.4°C.

standard years	average T in June - August	warm years	average T in June – August
2004	23.5 °C	2003	26.8 °C
2005	22.8 °C	2009	24.5 °C
2006	22.4 °C	2012	25.9 °C
2007	23.7 °C	2015	25.1 °C
2008	24.0 °C	2017	26.1 °C
2010	24.0 °C	2018	24.9 °C
2011	24.4 °C	2019	26.0 °C
2013	23.8 °C	2021	24.9 °C
2014	23.0 °C	2022	25.6 °C
2016	23.9 °C	2023	24.9 °C
2020	24.2 °C		

CGDD for the reaching of BBCH stage 65 and 89 were calculated using the single triangle method with no cut-off techniques for “standard years”. For corn, these two thermal thresholds corresponded to 837 and 1757 CGDD, while for sorghum they resulted equal to 949 and 1680 CGDD, respectively.

These thermal thresholds were used to simulate DAS necessary to reach full flowering and full maturity in warm years, with single triangle method both with and without cut-off techniques. The predicted DAS obtained with the different strategies were compared with the DAS observed (from phenological bulletins). RMSE between observed and predicted DAS for both phenological stages of both crops are presented in Table 2.

With regard to the flowering phase, for both crops, it was observed that, looking at RMSE values, the application of the cut-off strategies resulted in modest improvements, compared to the single triangle method without the use of

upper thresholds. In the considered “warm years”, full flowering was, on average, reached on 25th June and 4th July for corn and sorghum, respectively. Thus, the phenophase was reached before summer high thermal regime resulted in a large lag between the CGDDs calculated with and without the consideration of an upper threshold temperature. In particular, vertical cut-off method did not show any improvement compared to the single triangle method, as the considered upper threshold temperature adopted (40 °C and 42 °C) was never reached. For the same reason, the prediction of the DAS for the reaching of BBCH 89, with vertical cut-off and single triangle method showed the same RMSE. On the contrary, other cut-off strategies resulted in a reduction of the RMSE compared to the single triangle method for the modelling of the DAS for the reaching of BBCH 89. As reported in Table 2, in particular, intermediate cut-off technique showed the best results for both crops. These results are not surprising. In fact, as previously observed by Maiorano (2012), in the modelling of GDDs cumulation for poikilothermic organisms, vertical cut-off does not consider any slowdown of GDDs cumulation above T optimal, until the maximum temperature is reached. Horizontal cut-off is notoriously more imprecise respect to intermediate cut-off. In fact, the first one is incorrect for temperatures higher than optimal, assuming that development continues at a constant rate above the upper threshold, thus not considering the detrimental effect of excessive temperatures on plant development. The second, on the contrary, can be considered a better approximation of the physiological response of the crop, considering that plant development slows at temperatures above the upper threshold (fixed equal to T optimal).

Comparing the two crops of this case study, modelling solution adopted showed better results for corn than for sorghum. “Standard” years were used for the identification of the thermal thresholds for the reaching of BBCH 65 and BBCH 89. For corn, these two phenophases in the “standard” years respectively showed a standard deviation of 49 and 118 CGDD, respectively. For sorghum, these two standard deviations were 105 and 149 CGDD, respectively. Higher standard deviations observed in sorghum could at least partially explain the phenomenon. In the case of corn, RMSE values of 6.13 and 6.43 obtained with intermediate cut-off strategy for BBCH 65 and BBCH 89 modelling can be considered particularly satisfying, as seven days correspond to the experimental error (the used dataset is, in fact, derived from phenological observations of weekly released bulletins).

Conclusions

Aim of the present work was to compare different upper threshold cut-off techniques, applied to the single triangle method, in order to assess which of them could give the best results in terms of GDDs calculation for summer crops in the climate change scenario in the North of Italy. In fact, these techniques are frequently employed in field-operational contexts, having the advantage of being easy-to-use, using as input minimum and maximum daily temperature instead of

hourly temperature. However, these approximation methods require specific validation, as their performance can deeply vary in function of the time of the year, the geographical location and the biology of the crop under consideration. For these reasons, case study such the one here presented are precious source of information about the possibility of successfully employ cut-off techniques for the modelling of GDDs cumulation in a specific area.

Tabella 2: Errore quadratico medio (RMSE) dei giorni dalla semina (DAS) osservato – previsto, per il raggiungimento di BBCH 65 e BBCH 89, per mais e sorgo.

Table 2: Observed - predicted DAS RMSE for the reaching of BBCH 65 and BBCH 89, for corn and sorghum.

Corn		Sorghum	
BBCH 65		BBCH 65	
GDDs calculation method	RMSE (d)	GDDs calculation method	RMSE (d)
Single Triangle	6.43	Single Triangle	10.67
Vertical cut-off	6.43	Vertical cut-off	10.67
Horizontal cut-off	6.13	Horizontal cut-off	10.40
Intermediate cut-off	6.13	Intermediate cut-off	10.04
BBCH 89		BBCH 89	
GDDs calculation method	RMSE (d)	GDDs calculation method	RMSE (d)
Single Triangle	9.56	Single Triangle	12.85
Vertical cut-off	9.56	Vertical cut-off	12.85
Horizontal cut-off	8.14	Horizontal cut-off	12.00
Intermediate cut-off	6.43	Intermediate cut-off	10.45

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