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Estimating the lengths of crop growth stages to define the crop coefficient curves using growing degree days (GDD): Application of the revised FAO56 guidelines

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A R T I C L E I N F O

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A B S T R A C T

Growing Degree Days (GDD) are a fundamental tool for estimating crop growth stage lengths. Their importance in irrigated agriculture is major since the new FAO56rev guidelines have adopted GDD to estimate the length of the four crop growth stages of the crop coefficient curves, thus replacing the fixed time lengths. GDD are useful for supporting crop and water management by quantifying temperature accumulation over time. They can be used to estimate the dates of crop stages required for cropping operations and irrigation scheduling, as well as predict such dates in real time when appropriate tools are used. This study focuses on the defining the base and upper temperatures (T_{base} and T_{upper}) used to estimate the start and end of the crop growth stages. These values are crop specific and are herein tabulated for several vegetable, field, grass and woody fruit crops. Indicative cumulative GDD values, obtained from a literature review and from own computations, are provided for each crop growth stage of the FAO segmented crop coefficient curve, i.e. the initial, development, mid-season, and late season stages. Examples of application demonstrate their usage graphically and show how cumulative GDD results in different durations in different locations.

1. Introduction

The accurate estimation of crop irrigation requirements and water use has been for several decades, and still is, a major concern for farmers, researchers, technical irrigation personnel, water managers and planners. Related issues are becoming increasingly important as water scarcity is intensifying, particularly in areas marked by aridity, due to climate variability and change. It is predicted that the imbalance between water availability and demand will increase globally as a result of climate change, although its magnitude will vary between regions (Tanasijevic et al., 2014; IPCC, 2022; Lionello et al., 2023). Therefore, tools that allow more precise estimation of crop evapotranspiration (ET_c) and supporting the day-to-day irrigation management decision making, are required (Pereira et al., 2021). At the farm level, ET_c is commonly and operationally computed using the FAO K_c-ET_o approach (Allen et al., 1998; Pereira et al., 2025). ET_c is estimated as the product of the grass crop reference evapotranspiration (ET_o), which represents the evaporative demand of the atmosphere, and a crop coefficient (K_c), that represents the difference effects of the main crop characteristics that distinguish the evaporation potential of the crop under study from the reference grass crop (Allen et al., 1998; Pereira et al., 2025). K_c values change along the crop growth season as the crop develops, both daily and among the crop growth stages influenced by the crop characteristics such as crop height, leaf are index (LAI), and fraction of ground cover (Allen and Pereira, 2009, Pereira et al., 2021).

The FAO56rev guidelines (Pereira et al., 2025), like the original

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FAO56 (Allen et al., 1998), adopts the K_c segmented curve to represent crop water use throughout crop growth during four sequential stages, the initial, development, mid-season, and late season stages. The FAO K_c curve for a given crop is designed with the K_c values for the initial ($K_{c\ ini}$), mid-season ($K_{c\ mid}$) and end-season ($K_{c\ end}$) stages as described (Allen et al., 1998; Pereira et al., 2025). Thus, precision in defining the crop growth stages and their durations is required for an appropriate estimation of ET_c throughout the crop season. Due to the high interannual variability of weather conditions affecting crop growth, and to the adoption of diverse crop varieties, it is less advisable to use calendars representing fixed day-time durations of crop growth stages as provided in the original FAO56, rather than adopting calendars based on cumulated temperature requirements relative to the four crop growth stages.

Appropriate tools are therefore needed to assist in determining when each crop stage is coming to an end. The remote sensing (RS) of the vegetation using spectral vegetation indices (VI) is highly appropriate for the near real-time determination of the crop coefficients and allowing the duration of growth stages to be inferred (Allen et al., 2007a; Laipelt et al., 2021; Pôças et al., 2020). However, the availability of this type of information depends on the revisit time of the satellite used as well as on the cloudiness conditions (Doherty et al., 2022); in addition, for operational purposes it requires expert technicians able to well manage and interpret the images information.

For irrigation water management and irrigation scheduling, the tabulated K_c in the FAO56rev guidelines (Pereira et al., 2025) or in appropriate literature, desirably when adjusted to weather conditions, are commonly used in soil water balance models (Pereira et al., 2020), crop growth models such as AquaCrop (Raes et al., 2023; Salman et al., 2025), APSIM (Keating, 2024), STICS (Beaudoin et al., 2023) and WOFOST (De Wit et al., 2019), or models from the DSSAT-CSM group (Hoogenboom et al., 2019; Khan et al., 2024). However, model tools require calibration and parameterization, which is generally difficult and demanding in terms of agronomic data acquisition. Therefore, there is a need to develop easy-to-use tools that can effectively predict the dates of crop growth stages and, thus, supporting decision making, especially considering climate change and variability.

The linear or near-linear relationship between air temperature and plants growth, i.e., the time required for a plant to complete a certain physiological stage (Réaumur, 1735), has been the focus of many studies focusing on a great number of crops and their growth stages as reviewed in the companion article (Paredes et al., 2025). It is therefore possible to follow and estimate crop growth under non-limiting conditions based on temperature accumulation (McMaster and Wilhelm, 1997; Bonhomme, 2000). The latter is computed above the crop specific base temperature (T_{base}) and up to a ceiling or upper limit (T_{upper}) and is referred to as the growing degree days (GDD) required for the completion of a given crop stage or the season.

The main objectives of this study are, therefore, the following: 1) to provide consolidated T_{base} and T_{upper} values for a set of 117 crops to be used for the estimation of the time length (L) of the FAO four crop growth stages based on the findings of the companion article; 2) to provide and tabulate the GDD required to complete each of the four crop growth stages for a set of crops based on observations performed under near-pristine conditions; and 3) discuss an example of application of the GDD to obtain the time length of crop growth stages according to the FAO56rev Guidelines (Pereira et al., 2025). The overall objective is to support users of the FAO56rev Guidelines by improving and easing the calculation and accurate use of crop coefficients in crop and water management under climate variability and change.

2. The GDD method: strengths and limitations

As in case of many methods, the GDD method offers several advantages that significantly improve agricultural management practices in the day-to-day practice. In contrast to fixed-length methods that assume constant growth rates, the GDD method considers different temperature conditions that affect plant growth allowing for more accurate predictions, thus contributing to improve the precision of crop management decisions (McMaster and Wilhelm, 1997; Purcell, 2003). GDD is closely related to the biological processes of plants which allow for a better management of critical growth stages, mainly flowering (Derieux and Bonhomme 1982a, b; Orlandi et al., 2005), fruiting or harvest timing (Gilmore and Rogers, 1958; Black et al., 2006; Campos et al., 2010; Elnesr et al., 2013; Yang et al., 2020; Garcia et al., 2025a,b). In addition, it is used to predict the potential productivity of crops (e.g. Steduto et al., 2012; Holzworth et al., 2018; Beaudoin et al., 2023). The use of GDD has proven to be a useful tool in practice, allowing the timing of agricultural interventions to be determined, leading to more efficient use of resources. GDD enables precise irrigation scheduling based on actual growth stages, so contributing to improve crop yields, efficient use of water (Huntington and Allen, 2009; Huntington et al., 2015) and water saving. A major advantage of using GDD to define crop growth stages is that the cumulative GDD required to complete a given crop growth stage is relatively constant contrarily to the number of days required to achieve the same growth due to its dependency on climate (Monteith, 1981; Purcell, 2003).

GDD also provides essential insights in delineating suitable agricultural regions (agro-climatic zoning, Dethier and Vittum, 1967) and identifying optimal crop varieties suitable for these specific areas (Boote et al., 1998; Kakabouki et al., 2021; Hachisuca et al., 2023), furthermore, it provides a more resilient framework for predicting crop development and improving yield predictions under changing climate scenarios (Saadi et al., 2015; Zhang et al., 2020; Soares et al., 2025; Belli et al., 2025).

However, the method also presents several limitations that impact GDD accuracy and reliability. A major limitation is the assumption of a linear relationship between temperature and plant development rate, which oversimplifies the non-linear responses of plants to temperature variations (Bonhomme, 2000). This linearity often only applies within a limited temperature range, and different developmental stages may respond differently to the same temperature (Bonhomme, 2000; Normand and Léchaudel, 2004; Pessotto et al., 2023). Furthermore, extreme temperatures, both high and low, can cause physiological stress or damage to plants, that may not be captured by simple GDD accumulation (Rasul et al., 2011).

As discussed by several authors, one of the most pointed out limitation of the use of GDD to estimate development stages is that temperature is not the only variable contributing to crop development (e.g. Wang, 1960; Ritchie and Nesmith, 1991; Bonhomme, 2000). Among other variables, photoperiod and water availability highly constraints crop development and must be taken into consideration for accurately predicting crop development and optimizing agricultural practices. Photoperiod regulates key processes such as flowering, seed germination, and vegetative growth. Short-day plants require longer nights to flower, while long-day plants flower with shorter nights. Therefore, the interaction between photoperiod and GDD is essential, namely in regions with significant seasonal variations in day length (Ritchie and Nesmith, 1991).

Water availability has significant impacts on crop development, hence on the effectiveness of accumulated thermal time. Water stress can limit the growth and development of plants, even when temperature conditions are optimal (Bonhomme, 2000).

Integrating GDD with photoperiod and water availability into crop models provides a more comprehensive understanding of crop phenology. Such approaches are often used in crop growth modelling such as those already quoted in the Introduction section.

The simplified GDD method has proven useful to meet practical requirements, rather than its precision or theoretical accuracy for scientists, crop consultants, and producers in predicting plant development rate and growth (Wang, 1960, Domínguez et al., 2012; Garcia et al., 2025).

As reviewed in the companion article (Paredes et al., 2025), there are different methods for calculating GDD, with different advantages and limitations. Nevertheless, only the simplified method is presented herein as it is the one that served as the basis for the FAO56rev computations. Although GDD simplifies the complex temperature response of plants and does not consider various other environmental factors that influence plant growth, it is widely used (Ruml et al., 2010) because it meets a practical need. The simplified GDD method has proven useful to meet practical requirements (Marin et al., 1995; Maynard and Hochmuth, 2007; Fresco et al., 2021) rather than its precision or theoretical accuracy.

The straightforward method proposed in FAO56rev computes GDD by estimating the difference between the average daily temperature and the base temperature (T_{base}). The latter is the lowest temperature (≥ 0 °C) allowing that growth initiates. The daily temperature cannot however exceed the upper temperature, which consists of a maximum temperature threshold (T_{upper}), often called ceiling temperature, that expresses the limit of the daily heat accumulation. GDD are, therefore, estimated as:

$$GDD = \begin{cases} 0, & T_{avg} < T_{base} \\ T_{avg} - T_{base}, & T_{base} < T_{avg} < T_{upper} \\ T_{upper} - T_{base}, & T_{avg} > T_{upper} \end{cases} \quad (1)$$

where T_{max} (°C), T_{min} (°C) and T_{avg} (°C) are, respectively, the maximum, minimum and average air temperature, T_{base} is the base temperature, and T_{upper} is the upper air threshold temperature that limits crop growth. T_{avg} is the average temperature between T_{max} and T_{min}.

Several modeling tools use this simplified approach, namely the FAO AquaCrop model (Steduto et al., 2012) and the updated version of SIMDualKc (Rosa et al., 2012), as well as the updated FAO56rev.

3. Consolidated T_{base} and T_{upper} proposed as support to FAO56rev

Based on the literature review in the companion article (Paredes et al., 2025) provided for selecting the T_{base} and T_{upper} values presented in the following. Despite the high variability of the T_{base} and T_{upper} values available in literature (see the Supplemental Information in Paredes et al., 2025), an approach considering the known physiological and field characteristics of the crops, and their most common sowing/initiation periods, and experts' knowledge has allowed the selection of their most appropriate values. Due to this approach, the selected T_{base} and T_{upper} values intentionally vary in a much small range than the values shown in the reviewed literature (Paredes et al., 2025). The selected, consolidated values are presented in Tables 1 through 3 respectively for vegetable and herbs and spice crops, field and forage crops, and woody fruit crops.

3.1. Vegetable crops, herbs and spices

Vegetable crops, like other crops, can be classified as cool or warm season crops (i.e. according to the temperature tolerance). Among those grouped as roots, tubers, bulbs and stems, the cool season refers to asparagus, carrot, celery, garlic, potato, onion, radish, turnip, and table beets, while the warm season vegetable crops include cassava and yam, also known as taro, both native from tropical and subtropical regions, as well as sweet potatoes.

Within cool-season vegetables (Table 1), the T_{base} values range from 2 °C for potatoes to 6 °C for carrots, but most crops are in the 4 °C to 4.5 °C range. T_{upper} values are generally around 30 °C to 35 °C, however with a lower value of 24 °C for celery. The warm season crops have T_{base} values in the 10 °C to 12 °C range, and T_{upper} from 30 °C to 40 °C. Results show that the range of values for both T_{base} and T_{upper} is quite narrow when crops are considered as cool or warm season crops.

Leaves and flowers vegetable crops in the current study may be considered as cold season crops, having T_{base} in the range 4 °C to 5 °C

Table 1
Consolidated base and upper temperature thresholds (T_{base} and T_{upper}) required for the computation of the growing degree days (GDD) for selected vegetable crops.

Crop	T_{base} (°C)	T_{upper} (°C)
Roots, tubers, bulbs and steams vegetable crops		
Asparagus (*Asparagus officinalis*)	4.5	35
Carrots (*Daucus carota*)	6	30
Cassava (*Manihot esculenta*)	10	40
Celery (*Apium graveolens*)	4	24
Garlic (*Allium sativum*)	4	30
Onions (*Allium cepa*)	4.5	35
Potato (*Solanum tuberosum*)	2	30
Radish (*Raphanus sativus*)	4.5	30
Sweet potato (*Ipomoea batatas*)	12	30
Table beets (*Beta vulgaris*)	4.5	30
Turnip (*Brassica rapa*)	4	35
Yam, Taro (*Colocasia esculenta*)	10	35
Leaves and flowers vegetable crops		
Artichoke (*Cynara scolymus*)	5	32
Broccoli (*Brassica oleracea* var. italica)	4.5	30
Brussel sprouts (*B. oleracea* cv. gemmifera)	4.5	30
Cabbage (*B. oleracea*)	4.5	30
Cauliflower (*B. oleracea* cv. botrytis)	4.5	30
Lettuce (*Latuca sativa*)	4	28
Spinach (*Spinacia oleracea*)	4	25
Fruit vegetable crops		
Banana (*Musa accuminata*)	14	37
Bell & Chili pepper (*Capsicum annuum*)	10	35
Cucumber (*Cucumis sativus*)	10	32
Eggplant (*Solanum melongena*)	10	35
Melon (*Cucumis melo*)	10	38
Melon, cantaloupe (*Cucumis melo*)	10	38
Okra (*Abelmoschus esculentus*)	10	35
Pineaple (*Ananas comosus*)	13	25
Pumpkin (*Cucurbita argyrosperma*)	10	32
Squash, Zucchini (*Cucurbita pepo*)	10	32
Strawberries (*Fragaria × ananassa*)	3	30
Tomato (*Solanum lycopersicum*)	7	28
Watermelon (*Citrullus lanatus*)	10	35
Herbs and spices		
Basil (*Ocimum basilicum*)	10	30
Black cumin (*Nigella sativa*)	5	30
Black pepper (*Piper nigrum*)	10	40
Coriander (*Coriandrum sativum*)	4	30
Fenugreek (*Trigonella foenum-graecum*)	4	35
Lemon balm (*Melissa officinalis*)	5	35
Mint (*Mentha spicata*)	0	35
Oregano (*Origanum vulgare*)	5	30
Parsley (*Petroselinum crispum*)	4	27
Saffron (*Crocus sativus*)	10	30

but the latter corresponds to only one crop, asparagus. The upper threshold varies from 25 °C to 32 °C but the extreme values refer to only one crop, spinach for the lower and asparagus having the higher.

Most of the fruit vegetable crops in Table 1 are warm season crops. Their T_{base} was set at 10 °C (Table 1) for all them, excepting tomato, banana, and pineapple, whose T_{base} are 7 °C, 14 °C, and 13 °C, respectively, with the higher values for banana and pineapple, because they are originated in tropical areas, thus susceptible to cold. Also originating from tropical and subtropical regions, okra has a T_{base} also set at 10 °C. Differently, a lower T_{base} of 3 °C was set for strawberry, behaving as a cold season crop. The T_{upper} values show a relatively large difference among all fruit vegetable crops; therefore, values were set in a wide range, with higher values for melon and banana (38 °C and 37 °C, respectively) and lower values for tomato and strawberry (28 °C and 30 °C, respectively). These results indicate that both tomato and strawberry are susceptible to warm weather, e.g. heat waves.

The herb and spice crops show a wide range of T_{base} values (Table 1). Those behaving as cold season crops have T_{base} values ranging from 0 °C to 5 °C, with the lower value for mint, while T_{upper} ranges 27 °C to 35 °C, with the lower value for parsley. The warm season crops, which include basil, black pepper, and saffron, have a common T_{base} of 10 °C, and a

T_{upper} of 30 °C to 40 °C, with the highest value for black pepper. The source of information for herbs and spice crops was, however, reduced, which increases the uncertainty of the temperature limits for these crops.

3.2. Field crops and grasses

A large variety of field crops are considered (Table 2). The cool season grain legumes, which include chickpea, fava bean, pea and lentil, have a T_{base} of 5 °C, but lentil that has a lower value of 2 °C. The remaining crops are of warm season and have a T_{base} ranging from 8 °C to 10 °C, with the lower value for mungbean. T_{upper} values range from 27 °C to 35 °C for cool season grain legumes, with the lower value for pea, and from 32 °C to 40 °C for the warm season crops, with soybean having one of the highest upper thresholds.

Within the fibre crops (Table 2), cotton and sisal are warm season crops and therefore have T_{base} of 10 °C and 12.5 °C, respectively. Flax (or linseed), a cool season crop, has a T_{base} of 0 °C. The T_{upper} values are similar for all fiber crops, close to 35 °C. Among the sugar crops (Table 2), sugar beet is a cool season crop, with a low T_{base} threshold of 5 °C and T_{upper} of 30 °C. Differently, the sugar cane is a warm season crop and therefore has a higher T_{base} of 10 °C and a rather high T_{upper} of 45 °C, showing its ability to adapt when facing high temperatures.

Cool season oil crops (Table 2) include camelina, canola, mustard, safflower, and sesame, having T_{base} ranging from 0 °C to 5 °C, with camelina and canola having the lower values. Their T_{upper} ranges from 30 °C to 40 °C, with the highest value for mustard. The T_{base} for warm season oil crops is around 10 °C, except for sunflower with T_{base} of 8 °C and guar of 15 °C. T_{upper} values range from 30 °C to 40 °C, with the higher value in case of guar, mustard and sesame.

The cool season cereals and pseudo cereals (barley, oats, quinoa, rye, bread and durum wheat) have a T_{base} of 0 °C to 4 °C, with the cereal crops having a T_{base} of 0 °C but rye that has a value of 4 °C. Their T_{upper} is in a short range of 30 °C to 35 °C. Quinoa, originaire of the Andes, has T_{base} of 2 °C and a small T_{upper} of 25 °C. The warm season cereals have a T_{base} of 10 °C but rice that has the highest T_{base}, 12 °C. T_{upper} values range widely, from 30 °C to 40 °C, with maize having 32 °C and rice 35 °C. The pseudocereals amaranthus and teff have T_{base} of 7 °C and 12 °C, and T_{upper} of 40 °C and 30 °C, respectively, showing a behaviour distinct from cereals.

Table 2 also includes grasses and forages. The warm-season grasses and forages include Bermuda grass, Elephant grass, Guinea grass and Sudan grass, which have a T_{base} ranging from 10 °C to 15 °C, while the cool-season grasses and forages have a much smaller T_{base}, ranging from 0 °C, as for alfalfa, to 6 °C for the Persian clover. The T_{upper} values are 25–30 °C for the cool season grasses, and range higher, from 30 °C to 40 °C, for the warm season grasses, with the higher value for elephant and Guinea grasses.

For vegetable, field and grass crops (Tables 1 and 2), the T_{base} and T_{upper} values relative to diverse crops of the same botanical family show generally great similarity, thus evidencing a physiological coherence of these thresholds. In addition, as expected, when crops are grouped according to cool or warm seasons, show temperature thresholds reasonably consistent, often with T_{base} values of 0–5 °C for the cool season and 7–12 °C for the warm season. The upper limits have a wider range, with T_{upper} at 25–35 °C and 35–45 °C for cool and warm season crops, respectively, indicating greater uncertainty, as already noted in the companion review paper by Paredes et al. (2025).

Table 2
Consolidated base (T_{base}) and upper (T_{upper}) temperature thresholds required for the computation of the growing degree days (GDD) for field crops and grasses.

Crop	T_{base} (°C)	T_{upper} (°C)
Grain legumes		
Bean (*Phaseolus vulgaris*)	10	32
Mungbean (*Vigna radiata*)	8	40
Black and green gram (*Vigna mungo*)	10	40
Chickpea (garbanzo) (*Cicer arietinum*)	5	32
Cowpea (*Vigna unguiculata*)	10	35
Fava bean (*Vicia faba*)	5	30
Groundnut (peanut) (*Arachis hypogaea*)	10	35
Lentil (*Lens culinaris*)	2	35
Pea (*Pisum sativum*)	5	27
Soybean (*Glycine max*)	10	40
Fiber crops		
Cotton (*Gossypium hirsutum*)	12.5	35
Flax (Linseed) (*Linum usitatissimum*)	0	36
Sisal (*Agave sisalana*)	10	35
Sugar crops		
Sugar beet (*Beta vulgaris*)	5	30
Sugar cane (*Saccharum officinarum*)	10	45
Oil crops		
Camelina (*Camelina sativa*)	4	30
Canola (*Brassica napus*)	2	30
Castorbean (*Ricinus communis*)	10	30
Guar (*Cyamopsis tetragonoloba*)	15	40
Mustard (*Brassica juncea*)	5	40
Safflower (*Carthamus tinctorius*)	5	35
Sesame (*Sesamum indicum*)	10	40
Sunflower (*Helianthus annuus*)	8	30
Cereals and pseudocereals		
Amaranth grain (*Amaranthus* sp.)	7	40
Barley (*Hordeum vulgare*)	0	30
Maize (*Zea mays*)	10	32
Oats (*Avena sativa*)	0	30
Pearl Millet (*Pennisetum glaucum*)	10	40
Quinoa (*Chenopodium quinoa*)	2	25
Rye (*Secale cereale*)	4	35
Sorghum (*Sorghum bicolor*)	10	30
Teff (*Eragrostis tef*)	10	30
Wheat, common (*Triticum aestivum*)	0	35
Wheat, durum (*Triticum durum*)	0	35
Rice (*Oryza sativa*)	12	35
Grasses		
Alfalfa (*Medicago sativa*)	0	30
Bermuda (*Cynodon dactylon*)	10	30
Berseem clover (*Trifolium alexandrinum*)	4	30
Common vetch (*Vicia sativa*)	0	30
Elephant grass (*Pennisetum* sp.)	15	40
Grass pastures	4	30
Guinea grass (*Panicum maximum*)	14	40
Hairy vetch (*Vicia villosa*)	2	25
Italian ryegrass (*Lolium multiflorum*)	2	25
Persian clover (*Trifolium resupinatum*)	6	35
Sudan grass (*Sorghum × drummondii*)	10	35

3.3. Fruit trees, vines and shrubs

The fruit tree crops (Table 3) have T_{base} values related to the climatic characteristics of the locations where they are grown. The T_{base} values for subtropical and tropical crops are in the range of 10–15 °C, while T_{upper} is around 35 °C for most of these crops. Woody crops with T_{base} values in the same range include grapes, citrus, and pistachios. All other crops have T_{base} values between 4 °C and 7 °C and T_{upper} generally between 25 °C and 35 °C. Woody fruit crops have relatively small number of studies, which may increase the uncertainty risk of the tabulated values.

4. Examples of tabulated GDD values for the K_c curves of FAO56rev

The definition of crop growth stages proposed in FAO56rev (Pereira et al., 2025), namely the initial, development, mid-season and late season stages, is based on the GDD accumulation. Therefore, the GDD_{ini} corresponds to the accumulation GDD during the initial crop growth stage computed using Eq. 1 and the T_{base} and T_{upper} in Tables 1–3. The initial stage spans from the sowing or planting date up to approximately 10 % of ground covered by the crop in the annual crops while for the perennial crops, it spans from the time when the initiation of new leaves occurs, or when the dormancy phase of the sprout buds ends up to 10 %

Table 3
Consolidated base (T_{base}) and upper (T_{upper}) temperature thresholds required for the computation of the growing degree days (GDD) for woody fruit crops.

Crop	T_{base} (°C)	T_{upper} (°C)
Mediterranean climate fruit trees and vines		
Olive (*Olea europaea*)	7	35
Wine and table grapes (*Vitis vinifera*)	10	35
Citrus (*Citrus* sp.)	13	30
Warm temperate trees and shrubs		
Avocado (*Persea americana*)	6	33
Loquat (*Eriobotrya japonica)*	4	42
Temperate climate trees		
Pomme fruit trees		
Apple (*Malus domestica*)	4	35
Pear (*Pyrus communis*)	4	35
Stone fruit trees		
Apricot (*Prunus armeniaca*)	7	25
Cherry (*Prunus avium*)	4.5	30
Peach and nectarine (*Prunus persica*)	7	35
Plum (*P. domestica* and *P. salicina*)	4.5	25
Nut fruit trees		
Almond (*Prunus dulcis*)	4.5	35
Pistachio (*Pistacia vera*)	9	35
Walnut (*Juglans regia*)	4.5	30
Other temperate vines and shrubs		
Kiwifruit (*Actinidia deliciosa*)	6	30
Hop (*Humulus lupulus*)	5	30
Berries (*Vaccinium* sp.)	6	30
Sub–tropical and tropical orchards and plantations		
Passionfruit *(Passiflora edulis)*	10	35
Pomegranate (*Punica granatum*)	10	35
Sub–tropical and tropical evergreen orchards and plantations		
Coffee (*Coffea arabica*)	10	32
Guava (*Psidium guajava*)	12	35
Lychee (*Litchi chinensis*)	10	30
Mango (*Mangifera indica*)	12	32
Papaya (*Carica papaya*)	15	35
Palm plantations		
Date palm (*Phoenix dactylifera*)	10	35
Oil palm (*Elaeis guineensis*)	15	40

ground cover. The GDD_{dev} represents the accumulation of GDD during the development stage, i.e., from 10 % of ground cover up to effective full cover or maximum cover is achieved, which in some anual crops correspond to the initiation of flowering. GDD_{mid} corresponds to the accumulation of temperature during the mid-season stage i.e., from full ground cover up to the start of senescesce or maturity. The GDD_{late} corresponds to the cumulative GDD during the late season stage which corresponds to the period from start of senescence or maturity to harvest.

The observed data for these diverse crop stages were retrieved from multiple studies as detailed in Table 4. The selected studies were primarily based on field observations, often conducted in farmers managed fields where crops were well irrigated and properly managed, thus avoiding water stress and other growth constraints.

Although several studies found in the literature provide for cumulative GDD, namely those reviewed in the companion article (Paredes et al., 2025), they were not used in the current study due to various limitations:

- Inconsistent T_{base} values: The T_{base} used in these studies were larger or smaller than the tabulated values proposed in the current study (Tables 1, 2 and 3);
- Lack of/or inconsistent T_{upper} values: studies that did not account for threshold T_{upper}, and/or used threshold values different from those proposed;
- Non-comparable crop growth stages: The crop stages defined in several studies were not consistent with the FAO56 stages (i.e., initial, crop development, mid-season, and late season); and
- Suboptimal growing conditions: Several of those studies were performed when the crops were subject to water stress, nutrient deficiencies, salinity, or other environmental constraints that could bias the reported GDD values.

Table 4
Selected studies used to develop the tabulated GDD for the four FAO crop growth stages.

Crop	References
Roots, tubers, bulbs vegetable crops	
Carrots (*Daucus carota*)	Chaterlán et al. (2011), Carvalho et al. (2014) and Léllis et al. (2017)
Garlic (*Allium sativum*)	Cortés et al. (2003), Chaterlán et al. (2011); Domínguez et al. (2012, 2017) and Martínez-López et al. (2022a)
Onions (*Allium cepa*)	López-Urrea et al. (2009), Chaterlán et al. (2011), Domínguez et al. (2012) and Ferreira et al. (2022)
Potato (*Solanum tuberosum*)	Paredes et al. (2018), Martínez-Romero et al. (2019), Montoya et al. (2019), López-Urrea et al. (2021) and Ferreira et al. (2022)
Leaves and flowers vegetable crops	
Broccoli (*Brassica oleracea* cv. italica)	López-Urrea et al. (2009) and Ferreira et al. (2022)
Lettuce (*Lactuca sativa*)	French et al. (2024)
Fruit vegetable crops	
Bell pepper (*Capsicum annuum*)	Chaterlán et al. (2011) and Allen et al. (2020)
Green bean (*Phaseolus vulgaris*)	Jadoski et al. (2000), Carlesso et al. (2007) and Oliveira et al. (2011)
Melon (*Cucumis melo*)	Leite et al. (2015) and Ferreira et al. (2022)
Tomato (*Solanum lycopersicum*)	Ferreira et al. (2022)
Grain legumes	
Pea, fresh (*Pisum sativum*)	Paredes et al. (2017) and Ferreira et al. (2022)
Soybean (*Glycine max*)	Wei et al. (2015), Giménez et al. (2017), Petry et al. (2024a)
Fiber crops	
Cotton (*Gossypium hirsutum*)	Allen et al. (2007b), Cholpankulov et al. (2008), Allen et al. (2020)
Oil crops	
Canola (*Brassica napus*)	Sánchez et al. (2014), López-Urrea et al. (2020)
Sunflower (*Helianthus annuus*)	López-Urrea et al. (2014), Miao et al. (2016), Ferreira et al. (2022)
Cereals	
Barley (*Hordeum vulgare*)	Pereira et al. (2015), González-Piqueras et al. (2019), López-Urrea et al. (2020), Pardo et al. (2022) and Martínez-López et al., (2022b)
Maize, grain (*Zea mays*)	Allen et al. (2007b), Domínguez et al. (2012), Martins et al. (2013), Paredes et al. (2014), González et al. (2015), Miao et al. (2016), Giménez et al. (2016), Allen et al. (2020), Ferreira et al. (2022)
Maize, silage (*Zea mays*)	Cameira et al. (2003), Allen et al. (2007b), Allen et al. (2020) and Ferreira et al. (2022)
Maize, sweet (*Zea mays*)	Allen et al. (2007b) and Allen et al. (2020)
Oats (*Avena sativa*)	Martínez-López et al. (2022a)
Wheat, Winter (*Triticum aestivum*)	Zhao et al. (2013), Zhang et al. (2013), Allen et al. (2007b) and Allen et al. (2020)
Wheat, Spring (*Triticum aestivum*)	Allen et al. (2007b), López-Urrea et al. (2009), Miao et al. (2016) and Allen et al. (2020)
Rice (*Oryza sativa)*	Ferreira et al. (2022) and Petry et al. (2024b)
Fruit trees and vines	
Olive (*Olea europaea*)	Gómez-del-Campo (2013), Paço et al. (2014) and Ramos et al. (2023)
Citrus (Oranges, clementines, mandarin)	Ramos et al. (2023)
Pomegranate (*Punica granatum*)	Ramos et al. (2023)
Wine grapes (*Vitis vinifera*)	López-Urrea et al. (2012)
Almond (*Prunus dulcis*)	Sánchez et al. (2021), Montoya et al. (2022), Mirás-Avalos et al. (2023) and Ramos et al. (2023)
Pistachio (*Pistacia vera*)	Memmi et al. (2016)

The retrieved data from the selected studies (Table 4) were analysed using Eq. 1, along with the tabulated T_{base} and T_{upper} values (Tables 1, 2 and 3), to estimate the cumulative GDD required for each crop growth stage. Tables 5 and 6 show the cumulative GDD that define the length of

Table 5
Cumulative GDD required by vegetable and field crops to complete each crop growth stage and the total crop season derived from field observations under non-stressed and well-managed conditions.

Crop	Type of season	Initial	Develop.	Mid-season	Harvest	Total GDD (°C)
		GDD_{ini} (°C)	GDD_{dev}(°C)	GDD_{mid}(°C)	GDD_{late}(°C)	
Roots, tubers and bulbs vegetable crops						
Carrots (*Daucus carota*)	Common	320	465	500	290	1575
Garlic (*Allium sativum*)	Short season	150	340	335	315	1140
	Long season	580	615	315	240	1750
Onions (*Allium cepa*)	Common	460	470	880	480	2290
Potato (*Solanum tuberosum*)	Short season	260	490	525	325	1600
	Long season	405	530	490	835	2260
Leaves and flowers vegetable crops						
Broccoli (*Brassica oleracea* cv. italica)	Short season	195	250	210	100	755
	Long season	295	350	525	110	1280
Lettuce (*Lactuca sativa*)	Short season	365	385	215	20	985
	Long season	360	455	455	20	1290
Fruit vegetable crops						
Bell pepper (*Capsicum annuum*)	Common	445	1180	745	45	2415
Melon (*Cucumis melo*)	Short season	185	520	315	155	1175
	Long season	140	545	460	455	1600
Tomato (*Solanum lycopersicum*)	Industry	280	520	880	220	1900
	Market	325	660	880	200	2065
Grain legumes						
Bean, seed (*Phaseolus vulgaris*)	Short season	160	260	360	180	960
	Long season	320	410	400	220	1350
Pea, fresh (*Pisum sativum*)	Industry	90	300	510	25	925
	Market	155	350	575	320	1400
Soybean (*Glycine max*)	Short season	300	350	650	350	1660
	Long season	310	410	680	560	1960
Fiber crop						
Cotton (*Gossypium hirsutum*)	Short season	280	520	800	350	1950
	Long season	345	905	615	285	2150
Oil crops						
Canola (*Brassica napus*)	Short season	330	310	450	595	1685
	Long season	460	555	905	595	2515
Sunflower (*Helianthus annuus*)	Short season	345	555	715	175	1790
	Long season	385	570	685	265	1905
Cereals						
Barley (*Hordeum vulgare*)	Short season	290	455	345	360	1450
	Long season	300	675	690	660	2330
Maize, grain (*Zea mays*)	Short season	200	380	500	340	1540
	Long season	295	420	775	465	1955
Maize, silage (*Zea mays*)	Short season	200	380	430	120	1155
	Long season	250	500	600	200	1550
Maize, sweet (*Zea mays*)	Short season	200	310	360	115	985
	Long season	355	500	430	200	1485
Oats (*Avena sativa*)	Common	450	595	550	255	1850
Wheat, Winter (*Triticum aestivum*)	Short season	395	445	440	365	1645
	Long season	560	405	730	410	2105
Wheat, Spring (*Triticum aestivum*)	Short season	360	480	590	190	1640
	Long season	360	680	720	540	2300
Rice (*Oryza sativa)*	Short season	235	465	665	295	1670
	Long season	255	490	740	320	1730
Sorghum (*Sorghum bicolor*)	Short season	280	300	570	230	1380
	Long season	280	310	650	280	1520

Table 6
Cumulative GDD required by fruit trees and vines to complete each crop growth stage and the total crop season derived from field observations under non-stressed and well-managed conditions.

Crop	Type of season	Initial	Develop.	Mid-season	Harvest	Total GDD (°C)
		GDD_{ini} (°C)	GDD_{dev}(°C)	GDD_{mid}(°C)	GDD_{late}(°C)	
Olive (*Olea europaea*)	Early maturation	50	430	1385	800	2665
	Late maturation	380	350	2055	720	3505
Wine grapes (*Vitis vinifera*)	Early maturation	435	1225	505	160	2325
	Late maturation	465	1145	800	590	3000
Citrus (Orange, clementine, mandarin)	Common	35	220	1580	60	1895
Pomegranate (*Punica granatum*)	Common	95	185	1900	265	2445
Almond (*Prunus dulcis*)	Early maturation	250	300	2260	815	3625
	Late maturation	280	325	2730	475	3810
Pistachio (*Pistacia vera*)	Common	225	555	1130	210	2120

the FAO56 crop growth stages (Allen et al., 1998; Pereira et al., 2025) and of the full crop season for various annual and perennial crops. The tabulated GDD values could be considered as indicative standards, but as various crops have different cultivars with different cumulative GDD values, it is advisable to perform field observations to substantiate the choices of the tabulated GDD values. These cumulative GDD values (Tables 5 and 6) provide a reliable reference for defining the length of the four FAO crop growth stages and can be used as a guide for agronomic planning, crop modeling, and irrigation scheduling.

Further research is required to further consolidate the values presented in Tables 5 and 6 namely extending the data sets of field observations thus, allowing for further validation.

5. Examples of K_c curves estimated with GDD

Examples illustrating the differences in the duration of the FAO56 crop growth stages as a function of sowing dates and weather conditions are presented in Figs. 1 and 2. The standard K_c values tabulated in Pereira et al. (2021, 2025) were used in both figures. Fig. 1 shows an example of the use of GDD to estimate the dates of the FAO crop growth stages for short-season beans (Table 4) when sown at different dates and under contrasting weather conditions at the same location in Santa Maria, southern Brazil. Shifting the sowing date leads to a reduction in the total duration of the bean cycle as temperature tends to increase. The length of the different growth stages also changes.

Fig. 2 shows the different durations of the K_c curves when beans are grown in different regions, using the same year (2019) for comparison. In Hetao, Inner Mongolia (China), Coruche (Portugal) and Almeria (southern Spain), beans are sown from late March to early May, so 15 April was used for the estimates. In the case of Inner Mongolia, the

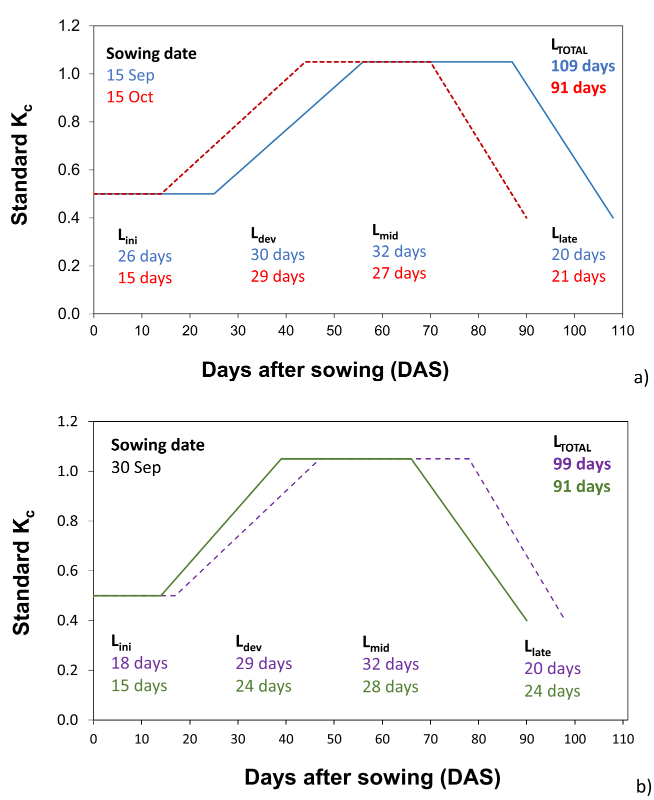

Fig. 1. Crop coefficient segmented curve for beans in Santa Maria, Rio Grande do Sul, Brazil when a) sown by 15 September (blue) and 15 October (red) in the same year, and b) sown by 30 September in the climate conditions of two seasons 2016/2017 (- -) and 2024/2025 (–) (L_{ini} – length of initial stage; L_{dev} – length of the growth stage; L_{mid} – length of the mid-season stage; L_{late} – length of the late season stage; L_{TOTAL} – length of the total crop cycle).

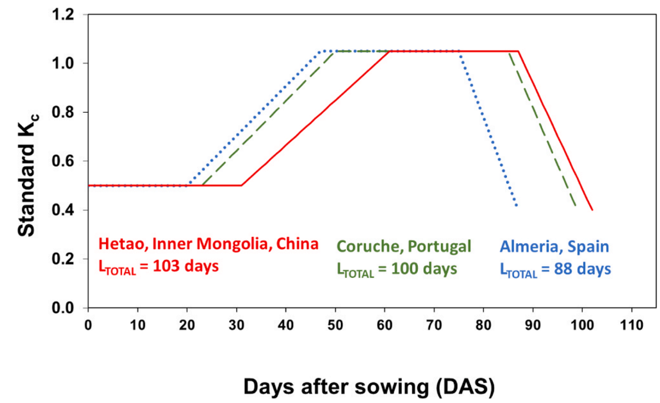

Fig. 2. Crop coefficient segmented curve for beans sown by 15 April of the same year (2019) in Hetao, Inner Mongolia, China (–), Coruche, central Portugal (–) and Almeria, southern Spain (•) (L_{TOTAL} – length of the total crop cycle).

average temperature during April up to mid-May was 14.6 °C leading to an average accumulation of 4.6 °C per day, but with 3 days without accumulation of temperature as $T_{mean}<T_{base}$, thus extending L_{ini} to 32 days, while in the locations of Portugal and Spain L_{ini} was 24 and 21 days respectively, with an average T_{mean} of 16.4 °C 17.3 °C. The behavior of L_{mid} was quite different, as in Inner Mongolia it lasted for 27 days, while in Portugal L_{ini} lasted 37 days and in Spain 29 days. These differences are related to the T_{mean} values, as in Inner Mongolia the average T_{mean} was 27 °C, while in Portugal it was 18.3 °C and in Spain 22.3 °C.

Few differences were observed during the late season stage with L_{late} of 15, 14 and 12 days respectively for Inner Mongolia, Portugal, and Spain, has the average T_{mean} was 22.8 °C, 22.1 °C and 26.0 °C. The results in Fig. 2 show that the stage duration depends on the temperature conditions and, therefore, needs to be estimated locally.

6. Conclusions and recommendations

This article underlines the central role of GDD in supporting decision-making in irrigated agriculture, particularly in estimating the FAO56 crop growth stages. By accurately defining these stages, GDD enables the optimization of water and crop management practices, thereby improving resource efficiency and agricultural productivity.

The article provides a comprehensive analysis of the principles of GDD calculation and identifies its strengths and limitations. One of the most frequently highlighted limitations is that GDD does not consider key environmental factors, such as photoperiod, nutrients and water availability, which have a significant impact on crop growth. Therefore, to achieve greater accuracy in predicting crop growth stages, more advanced modelling tools need to be used. These tools should integrate additional physiological and environmental variables to provide a more accurate and dynamic representation of crop growth beyond temperature-based accumulation alone.

The current study assumes that the simple average method offers adequate precision for practical applications, namely for defining crop growth stages, as proposed in FAO56rev. A key aspect is the need to carefully define the base and upper temperature thresholds, as these values are critical for accurate calculation of GDD and for ensuring reliable predictions of crop phenology. The indicative consolidated T_{base} and T_{upper} values are available for a wide range of crops and may be used for different stages of plant growth providing for valuable reference data for both researchers and practitioners, namely to support crop and water management strategies under climate variability and change. These consolidated values serve as guidance for improving crop growth forecasts, refining irrigation and agronomic management, and enhancing the application of FAO56-based methods. However, when crop varieties are much different their variability is a source of inaccuracy.

The current study highlights the need for further research to improve the application of GDD in agriculture. It is recommended that users actively monitor and record the dates of crop growth stages to estimate GDD and validate the approach under their specific growing conditions for many crops that do not yet have accurate T_{base} and T_{upper} and hence adequate GDD. Such developments can improve the accuracy of phenological predictions from T_{base} and T_{upper} conservative values and ensure that GDD-based models are consistent considering local environmental and management factors.

In addition, the use of technological advances, such as remote sensing and machine learning, offers new opportunities to improve the monitoring and prediction of crop growth stages. New research tools can improve the efficiency and accuracy of real-time agricultural management, thus enabling farmers and managers to make more informed decisions and better adapt to changing climatic conditions.

The set of tabulated GDD values provided for the FAO56 crop growth stages should be used under non-limiting water and light conditions and in the absence of pests and diseases that prevent full crop growth rates. Therefore, these values can be considered as guidelines, but need to be validated for different crop varieties and cultivars to ensure their applicability in different agricultural contexts. The T_{base} and T_{upper} values now tabulated, combined with the simple average method to compute GDD, provide a valuable tool to support the implementation of the FAO56 segmented curve, facilitating accurate crop growth predictions, and improved irrigation scheduling.

CRediT authorship contribution statement

Paula Paredes: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Ramón López-Urrea:** Writing – review & editing, Formal analysis, Data curation. **Ángel Martínez-Romero:** Writing – review & editing, Formal analysis, Data curation. **Mirta Petry:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Maria do Rosário Cameira:** Writing – review & editing, Formal analysis, Data curation. **Francisco Montoya:** Writing – review & editing, Formal analysis, Data curation. **Maher Salman:** Writing – review & editing, Formal analysis, Data curation. **Pereira Luis Santos:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Compliance with ethical standards

None.

Data availability

Data will be made available on request.

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