Impact of Crop Heat Units on Growth and Developmental Physiology of Future Crop Production: A Review

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Impact of Crop Heat Units on Growth and Developmental Physiology of Future Crop Production: A Review

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Abstract

Plant development depends on temperature and requires a specific amount of heat to develop from one point in their lifecycle to another, such as from seeding to the harvest stage. Temperature is a key factor for the timing of biological processes, and hence the growth and development of plants. Crop heat unit (CHU) or thermal time or growing degree days is a temperature response of development that differs between day and night. Growing degree days is a way of assigning a heat value to each day. Heat units are involved in several physiological processes like specific amount of heat units required for the plant at each stage from its germination to harvest of the crop would vary and the important processes are growth and development, growth parameters, metabolism, biomass, physiological maturity and yield. Growing degree days are used to assess the suitability of a region for production of a particular crop, determine the growth stages of crops, assess the best timing of fertilizer, herbicide and plant growth regulators application, estimate heat stress accumulation on crops, predict physiological maturity and harvest dates and ideal weather unit in constructing crop weather models.

Keywords: *Heat unit, degree days, nitrification, photoperiod, phyllochron, thermal time*

Abbreviations: *CHU–Crop heat unit; GDD–Growing degree days; HTU–Helio thermal units; PTU–Photo thermal units*

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INTRODUCTION

Temperature is a key factor for the timing of biological processes, and hence the growth and development of living biota. All the physical and physiological processes are temperature dependent. The heat unit system or growing degree days (GDDs) assumes that in general there is a direct and linear relationship between growth of plant and temperature. The crop heat unit (CHU) system suggests that the temperature response of development differs between the day and the night, but there is no physiological basis for the difference in response between day and night. Despite this flaw, the CHU system works well and is recognized around the world as one of the best heat unit systems to quantify the effect of temperature on crop development [1].

HEAT ACCUMULATION CONCEPTS

Temperature controls the developmental rate of many organisms. Plants require a certain amount of heat to develop from one point in their life cycles to another. This measure of accumulated heat is known as physiological time. Theoretically, physiological time provides a common reference for the development of organisms. The amount of heat required to complete a given organism's development does not vary; the combination of temperature (between thresholds) and time will always be the same. Physiological time is often expressed and approximated on hourly or daily time scales using units of degree-hour (°hr) or degree-day (°D).

Importance of Heat Units in Crop Production

The amount of heat energy an organism accumulates over a period of time is often expressed as a "growing degree-day" (GDD). The growth rate of many organisms is controlled by temperature. Growers use a concept related to degree-days called growing degree-days (GDDs), sometimes called heat units. GDDs are used to relate plant growth, development, and maturity to air temperature.

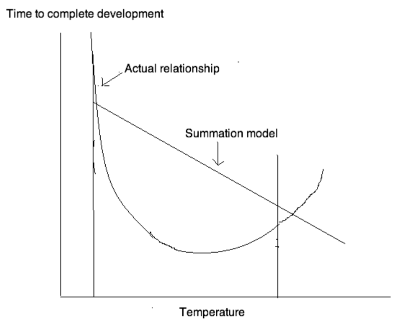
Applications of HU in Crop Production

(i) Assess the suitability of a region for production of a particular crop; (ii) Determine the growth-stages of crops; (iii) Predict best timing of fertilizer or herbicide and plant growth regulator application; (iv) Estimate the heat stress on crops; (v) Predict the maturity (physiological) and harvest dates; (vi) Tool for managing growth regulators or harvest aids; (vii) Ideal unit in crop weather model.

CROP HEAT UNIT/GROWING DEGREE DAY/THERMAL TIME

Crop heat unit is an energy term calculated for each day and accumulated from planting to the harvest date. The growth is dependent on the total amount of heat to which it is subjected during its lifetime. The French scientist Rene A. F. de Réaumur introduced the GDD idea almost 300 years ago, in 1700.

A generalized relationship between temperature and length of time is required for completing development. The curve indicates temperature below which the plant will not grow. Also, other is the intermediate optimum temperature that permits the most rapid development. Above the optimum, adverse temperature causes a lengthening of the time required for development. The actual response of the plant to temperature is curvilinear while the temperature summation concept assumes a linear relationship.



Relationship between development time and mean temperature for the period is compared with the temperature summation model for the relationship [2]. Each developmental stage of an organism has its own total heat requirement. The fifth-leaf stage of wheat occurs either at an average of 21 calendar days after germination or 350 degree days after germination.

Calculation of GDD

"Growing degree days" (abbreviated GDD or DD) is a way of assigning a heat value to each day. Growing degree days are calculated in each day using the maximum daily temperature (Tmax), the minimum daily temperature (Tmin), and a base temperature (Tbase).

$$GDD = \frac{(T\,max + T\,min)}{2} - T\,base \text{ (Threshold Temperature)}$$

T base – The base temperature or threshold temperature – is the temperature below which no growth takes place. This varies with different crops. Generally, the threshold temperatures are higher values for tropical crops and lower values for temperate crops.

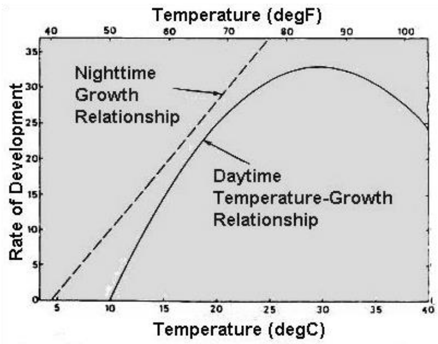


Fig. 1: *Corn Development Rate with Temperature.*

Table 1: *Threshold Temperature of Agricultural Crops* [3].

Crops	Temperature (°C)
Wheat, barley	4.4
Potato, oats, sugar beet	5.0
Sorghum, maize, groundnut	8.0–10.0
Rice	10.0–12.0
Tobacco	13.0–14.0

HEAT UNITS ON PHYSIOLOGICAL PROCESS

The heat units or thermal time are involved in the physiological process of plants. The specific amount of heat units required for the plant at each stage from its germination to harvest of the crop would vary and the important processes are listed below:

1. Growth and development
2. Growth parameters
3. Nitrification
4. Biomass
5. Physiological maturity
6. Yield

Growth

Phenology

Periodic occurrence of different stages of development in the life cycle of a plant in relation to environmental conditions is called phenology. The plants in higher temperature environment during floral induction would produce higher primodia with same initiation rate and duration of induction on an average with one leaf every 4 °C temperature range of 15 to 32 °C. Thermal time to tasseling is not constant in photosensitive genotypes [4].

Table 2: *Cumulative GDD or Thermal Time Requirement for Different Development Stages.*

Stages	Corn	Pearl millet
Emergence – Coleoptiles	0	0
2 leaves fully emerged	213	251
4 leaves fully emerged	345	457
6 leaves fully emerged	476	659
8 leaves fully emerged	608	853
10 leaves fully emerged	739	-
12 leaves fully emerged	871	-
14 leaves fully emerged	1003	-
16 leaves fully emerged	1134	1013
Silking/Anthesis/Boot leaf	1397	1043
Kernal in blister stage/half bloom	1661	-
Kernal in dough stage	1924	-
Kernal begins to dent	2187	1262
Kernal fully dented	2450	
Physiological maturity	2713	1661

Seedling Emergence to Terminal Spikelet Initiation

(i) Leaf Appearance: The rate of leaf emergence is affected by temperature. An increase in temperature speeds up leaf emergence.

Crop	Phyllochron (day °C)
Sorghum	54.0
Cotton	20.0
Soybean	18.9
Pearl millet	75.0–98.0
Maize	38.0–45.5

In terms of the temperature summation index, the development of one leaf requires about 100 degree days before the initiation of panicle primodia and about 170 degree days thereafter. When the rice plant is grown at 25 °C, leaves emerge every 5 days (100 degree days/20 °C = 5 days). When it is grown at 25 °C, they emerge every 4 days before panicle primodia initiation. Thermal time or GDD required for each leaf to appear is called Phyllochron. The interval of thermal time between leaf tip appearance is known as phint. The crops, which require different thermal duration for the phyllochrone, are listed below [4].

(ii) Initiation to Flowering: The exposure to low temperature is a requirement for formation of spikelets called vernalization. It is effective in between 0 and 7/8 °C but less effective between 7/8 °C and 18 °C. Winter wheat is more sensitive to vernalization, whereas spring wheat shows little sensitivity.

(iii) Terminal Spikelet Initiation: The terminal spikelet initiation is strongly influenced by temperature and needs about three phyllochrons in wheat. The thermal time for pearl millet was 370 °C.

(iv) End of Leaf Growth: The end of leaf growth is influenced by temperature, vernalization and photo period. The development of leaves stop in this stage and takes duration of thermal time of two phyllochrons.

(v) End of Ear Growth to Beginning of Grain: This ear growth is dependent on temperature and photoperiod. The total biomass stored from stem and roots is translocated to kernels.

(vi) Grain Filling: It is an important phenological stage to set grain size. The thermal time varied with different genotypes. The thermal time requirement for genotypes is 500 day °C after flowering or 20 day °C after anthesis to maturity at which a rapid increase in grain weight takes place.

Development

Comparison of growth chamber (dark) and field (light). Thermal time requirements of various developmental stages for the Pisum sativum cultivar puget using growth chamber determined cardinal temperatures [5].

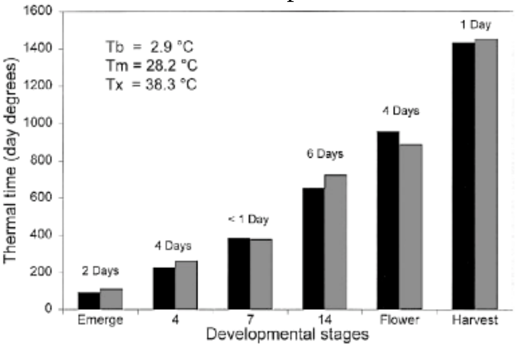


Fig. 2: *GDD requirement for Pisum sp. at different stages of growth.*

Apical Development

The time course of apical development of wheat varieties in degree-days by two successive linear phases of primordial initiation, the second that was faster than the first.

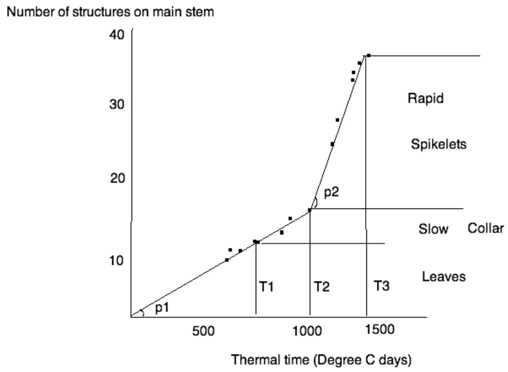


Fig. 3: *GDD effect on linear model of primordial initiation in rice.*

A two-stage linear model of primordial initiation indicating rates and associated phases of leaf, collar and spikelet initiation. P1 and P2 are the rates of initiation of primodia during slow and rapid phases. T2 is the rate at which the rate of initiation changed, T1 is the date of initiation of collar (start of reproductive development), and T3 is the date of terminal spikelet.

Plant Development

Table 3: *Growing Degree Days on Maturity of Plants.*

Crop	Processes
Corn	1360 GDD to crop maturity
Sugar beet	130 GDD to emergence and 1400–1500 GDD to maturity
Barley	130 GDD to emergence and 1400–1500 GDD to maturity
Wheat	143–178 GDD to emergence and 1550–1680 GDD to maturity
Dry beans	1100–1300 GDD to maturity depending on cultivar and soil condition
Grapes white variety	1064 GDD 50% of final berry weight was reached
Grapes red variety	1340 GDD 50% of final berry weight was reached earlier

Table 4: *Growing Degree Days on Flowering of Plants.*

Red maple	Begins flowering at 1–27 GDD
Beach plum	Full bloom at 80–110 GDD
White ash	Begins flowering at 30–50 GDD
Sugar maple	Begin flowering at 1–27 GDD
Crabapple	Begins flowering at 50–80 GDD

Nitrification

Nitrification process will be initiated according to the degree-day accumulation. It is assumed that the moisture is correct. By the time 1000 growing degree-days have accumulated, 90% of the applied nitrogen has been converted to the nitrate form.
Regulation of growth in photosensitive crops (varieties) regulated by temperature is based on:

i) A rise in temperature increases the rate at which leaves emerge.
ii) The number of developed leaves on main culm before heading is fairly constant for a given variety.
iii) Because of the above two process, the number of days from sowing to heading is fairly constant under a given temperature regime.
iv) A rise in temperature increases the rate of grain filling after flowering.

Impact of Excess or Deficit of Heat Units on Crop

The temperature pattern (slow accumulation in May and above normal in July and August) results in a diminishing corn yield.

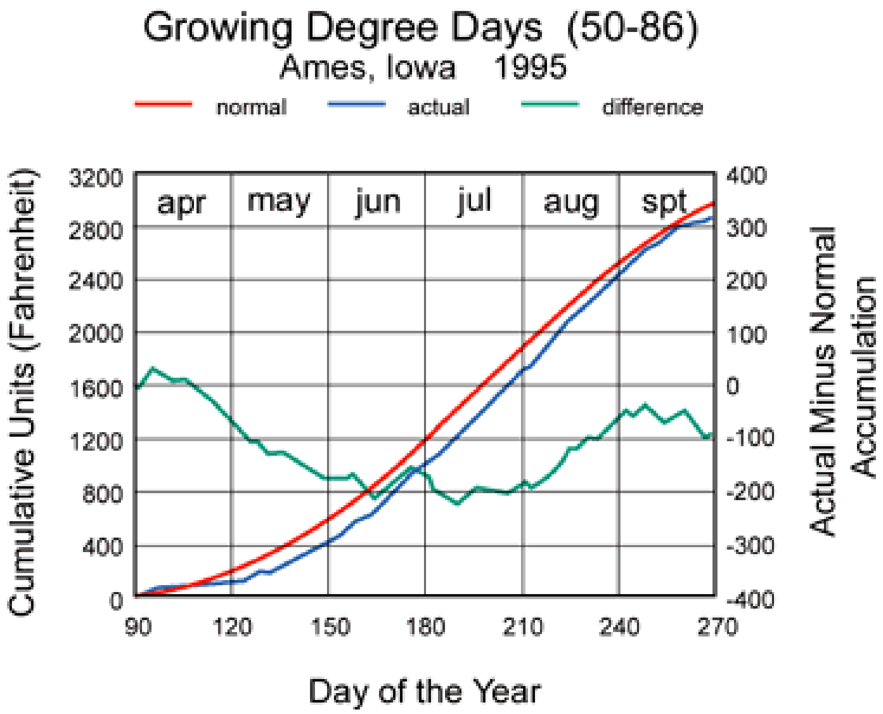


Fig. 4: *Daily GDD unit accumulation deviation through out the year*

The growing degree-day pattern throughout the season is associated with a yield response in most years. Daily GDD unit accumulation deviation from average (green line – right axis), actual accumulation (blue line) and normal accumulation (red line – left axis) growing seasons.

- Flowering performance
- Biomass accumulation variation
- Yield performance

Flowering Performance

The GDDs are must for the development of crop growth. The excess or deficit GDD accumulation causes delay in flowering, or early flowering, in some crops failure of flowering, yield loss, reduction in biomass occur.

Flowering

Accumulation of HU or GDD to estimate the expected time of flowering. The deficit growing degree days or heat unit accumulation at the time of flowering leads to early flowering. The excess GDD accumulation at flowering causes delayed flowering.
Planting date effect on GDD and flowering date of sorghum crop.

Table 5: *Cumulative GDD on flowering at different sowing dates* [6]

Date Of Sowing	GDD at flowering	Days to flowering
19 Mar	1880	82
16 Apr	1976	77
14 May	1889	63
18 June	1958	61
2 July	1874	57
16 July	1816	56
30 July	1686	52

Rice Heading Stage

In rice where the temperature drops from 24 °C to 21 °C a sharp decrease in days to heading occur. A temperature drop by 1 °C leads to 13-day delay in heading. When the temperature increases above 24 °C, days to heading decreases to 91 days at 27 °C and to 86 days at 30 °C. A temperature raise of 1 °C above 24 °C shortens the number of days to heading by less than 2 days.

Yield Reduction in Soybean

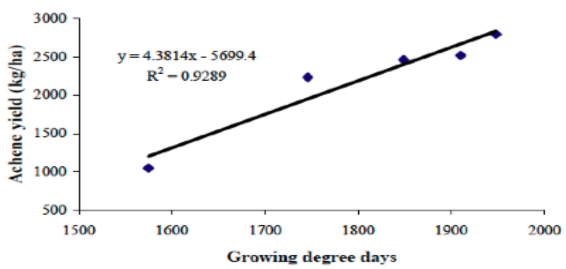
The study of HUE versus seed and stover yield showed that the HUE increased with advancement of the age of crop. The results also showed that the HUE of overall growth period was found more in II (normal GDD) and III (low GDD) as compared to I (high GDD) in seed yield. It was reverse in the case of stover yield. Early sown crop produced more dry matter and also resulted in higher yield of both seed and stover than the late sown crop as they had accumulated more growing degree days.

Table 6: *Cumulative GDD effect on yield of soybean.*

Treatments	Acc. GDD (°C day)	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	HUE of seed with GDD (kg ha^{-1} °C day^{-1})	HUE of Stover yield with GDD (kg ha^{-1} °C day^{-1})
I-High GDD	6157	1817.3	5148.2	0.29	0.83
II-Normal GDD	2286	1784.7	5894.6	0.78	2.57
III-Low GDD	1510	1033.6	4078.6	0.68	2.70

Sunflower Yield Variation Depends on GDD

Comparing the two seasons of sunflower planting, the accumulation of GDD is very less in spring than in the autumn season. Low to high accumulation of GDD is compared with the yield and yield components. The reduced achene yield was due to low GDD accumulation.



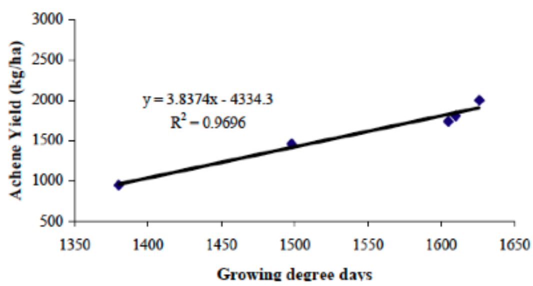


Fig. 5: *GDD, Yield and Yield Components of Sunflower Hybrids during Spring; GDD, Yield and Yield Components of Sunflower Hybrids during Autumn.* [7].

Effect of Planting Date on Potato

Accumulated growing degree days and calendar days to emergence, full flower, and harvest per planting date–Spring 2004.

Table 7: *Effect of GDD on flowering and tuber yield of potato by different planting dates.*

Planting order	Date of planting	GDD to emergence	GDD to full flower	GDD to harvest	Total yield (t ha^{-1})	Marketable yield (t ha^{-1})
1	13 Jan	240	841	1493	28.3	24.1
2	27 Jan	226	806	1676	29.0	21.9
3	9 Feb	178	749	1951	33.8	27.6
4	23 Feb	218	820	2374	32.6	26.3
5	9 Mar	202	816	2490	26.8	18.7
6	24 Mar	211	792	2840	26.7	21.9

Accumulated GDD = growing degree days [(minT + maxT)/2–7 °C (45 °F)] [8].

GDD REQUIRMENT OF CROPS AND THEIR USES

Accurate prediction for crop stages can determine the growth progress of cereal crops in relation to temperature and moisture. It permits accurate comparisons of crop development in different years at widely separated locations. It predicts and determines when nutrient and irrigation scheduling can correspond to crop deficiencies. Fertilizers can be added during early growth stages to correct deficiencies and increase yields. Effective corrective measures can sometimes be taken at certain growth stages.

Heat Unit Requirement of Crops

Phenology calculations using 0 °C and 32 °F base temperatures are combined with the Universal Growth Staging Scale descriptive terms for crops – list of crops and the heat unit requirement for their particular developmental process in the growth stages.

Table 8: *Requirement of GDD for Different crops.*

Crop	GDD (°F)	GDD (°C)
Wheat	2800–3029	1537–1665
Barley	2280–2930	1248–1610
Oat	2701–3106	1482–1737
Mustard	2748–2930	1508–1610
Chickpea	3054–3277	1678–1802
Peanut	2843	1560
Sunflower	3236–3581	1780–1971
Cotton	4352	2200–2400
Corn	5072	2200–2800
Sorghum	2580	1415
Pearl millet	1661	905

Table 9: *Heat Unit Requirement and Development of Wheat* [9].

Stage	Purpose	GDD (°C)
Emergence	Leaf tip just emerging from above ground coleoptile.	125–160
Leaf development	Two leaves unfolded.	168–207
Tillering	First tiller visible (tillering of cereals may occur as early as stage)	368–420
Stem elongation	First node detectable	591–658
Anthesis	Anthesis – flowering commences; first anthers of cereals are visible.	**806–900**
Seed filling	Seed filling begins. Caryopsis of cereals watery ripe	1067-1773
Dough stage	Soft dough stage, grain contents soft but dry, fingernail impression does not hold.	1433–1555
Maturity complete	Grain is fully mature and dry down begins. Ready for harvest when dry.	1537–1665

Other Related Parameters that Contribute to Heat Units

Other environmental factors that are taken into account when comparing laws concerning the action of temperature on crop growth are:

- Photoperiod
- Vernalization
- Sunshine hours
- PTU (photo thermal units)
- HTU (helio thermal units)

Photoperiodic effects can be interpreted as vernalization effects on “long day” plants because the estimated temperature threshold can be very low for long days while photoperiodic thresholds are low [10].

Practical Applications of CHU

Prediction of harvest date in many of the crops, especially horticultural crops (physiological maturity and harvest maturity) predict best timing of fertilizer or herbicide and plant growth regulator application. Used in crop weather models, it involves prediction of flowering date and selection of suitable variety from the date of sowing. For example, delayed planting shortens the effective growing season for corn, increasing the risk of prior to grain maturation. Growers often must decide whether to switch to early maturity hybrids to minimize this risk.

CONCLUSIONS

Predictive accuracy of CHU in crop growth is 67–91% (vegetative phenostage) and 90–95% (reproductive phenostage). It is used to predict crop growth stages for agricultural practices and physiological response of the crop by the accumulation of temperature. Daytime GDD accumulation is a must for biomass production; night time is must for GDD accumulation on flower formation. Performance or suitability of the genotype or variety at different growing regions. Performance or suitability of genotype or variety at different planting dates in same growing field condition. Molecular aspect of heat unit accumulation response in flower induction.

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