THE USE OF HEAT UNITS IN MAIZE PRODUCTION
PART I LITERATURE REVIEW

(Met opsomming in Afrikaans)

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Abstract

The relationship between temperature and plant growth and plant development was recognised long ago. The expression of this relationship in a simple formula like the remainder index

$$\frac{\text{maximum} + \text{minimum temperature}}{2} - \text{base temperature}$$

to calculate the effective heat units available for growth and development has been criticised. However, no other system has been found which can adequately replace it.

The practical application of the heat unit system in the USA and in Canada and the possible use of it in South African maize production are discussed.

Introduction

The effect of temperature on the growth and development of plants was noticed in the early days of agriculture, when man started cultivating land to obtain food.

Observations were made but no measurements could be taken until in the 18th century when Fahrenheit, Celsius and Reaumur designed the first temperature scales. Reaumur was especially interested in biology and made a quantitative study of temperature relationships (Wang, 1960). He was the first scientist to express the developmental stages of plant life in terms of thermal units and maintained that the amount of heat required for a plant to reach a given stage of maturity was a constant.

Since Reaumur many articles have been published dealing with the applicability of the theory of thermal constants to plant life in general (reviewed by Nuttonson, 1953, Tsotsis, 1958 and Wang, 1960).

Early workers calculated the heat requirements for a given stage in the development of a plant by adding the average daily temperatures expressed in degrees of one of the thermometer scales, over the number of days taken to complete this developmental stage. All temperatures below 0°C were disregarded. Each degree on the thermometer scale was called a 'heat unit' or 'degree-day' or 'thermal unit.'

In the 19th century it was realized that below a certain temperature, depending on species and even on varieties within species, no growth and development can take place. Gasparin (1844), adopted 5°C as the 'effective temperature' and began the computations of the temperature summations on the first day this temperature was attained (Nuttonson, 1953).

Over the years many systems to express the relationship between the development of plants and the environmental conditions, have been proposed by research workers. The only system which will be dealt with in this paper is the remainder index system as it has met with the greatest approval due to its simplicity and to the satisfactory results obtained in practice.

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Remainder index

In this system, introduced by Adanson in 1750, a minimum temperature (physiological zero, threshold value, base temperature) is deducted from the average daily temperature to arrive at the number of effective heat units per day. The assumption is made that plant growth and development are directly proportional to changes in temperature above the base temperature.

This system was criticised by Went (1950, 1957) and Wang (1960). According to Went (1957) the fact that heat sums prove so constant is amazing as in most plants growth is not a straight line function of temperature. Moreover Went disagrees with the summation of heat as if it were a quantity.

"Heat cannot be used by any plant for growth; the energy used is all chemical energy present in the stored food. Heat can only control the rate at which this chemical energy can be made available and the efficiency with which it is used, or it can influence the rate of photosynthesis. Therefore as heat is not a form of available energy for plants and only modifies other processes, it is logically impermissible to talk about — or even calculate — heat sums".

Arnold (1959) in a discussion of Went's criticism contends that although the value obtained from the remainder index formula is mathematically equal to the summation of mean daily effective temperatures, it is also a relative measure of the accumulated morphological and biochemical changes through which a plant has passed in going from one developmental stage to another. The development, which is dependent on temperature, could be expressed in 'developmental units'. The total number of developmental units would be equal to the developmental units per day per degree of effective temperature times the mean effective temperature times the number of days

$$\text{development} = \text{dev/day/°te} \times \text{xte} \times \text{days}.$$

In the heat unit system an arbitrary value of 1 is selected for the effect of temperature on the rate of development per day (dev/day/°te). Consequently a heat unit is equivalent to a developmental unit, which in a linear system is measured by the difference between the amount of development taking place per unit of time at a certain mean effective temperature and one which is one degree higher.

A heat summation thus becomes equivalent to the total number of developmental units occurring between stages of development (Arnold, 1959).

The main criticisms offered by Wang (1960) are that plants respond differently to the same environmental factor during various stages of their life cycle and upper and lower threshold values change with the advancing age of the plant. In addition no attention is paid to other factors influencing plant growth and development, such as soil moisture, vapor pressure deficit, etc. According to Wang the heat unit system has been widely adopted because of its value in satisfying practical needs rather than for its accuracy or its theoretical soundness. Because no other system has been found which can adequately replace it, it continues to enjoy widespread popularity.

Method of calculation

The calculation of the heat unit sum is based on the mean daily temperature and a base temperature.

An accurate way to calculate the mean daily temperature is by averaging the 24 hourly readings. As this is a laborious operation, the summation of maximum and minimum temperature divided by two is generally considered to be a good enough approximation.

No general agreement exists on the temperature to be used as a base below which physiological activity stops.

Most authors accept 10°C (50°F) as the base temperature for maize, sweet corn as well as seed maize (Phillips, 1950; Lana & Haber, 1951; Seaton, 1955; Andrew, Stronmen & Ferwerda, 1956; Gilmore & Rogers, 1958; Tsotsis, 1958; Newman, Blair, Dale, Smith, Stirm & School, 1968), 4.4°C (40°F) for peas (Phillips, 1950; Katz, 1952; Seaton, 1955), 7.2°C (45°F) for sunflowers (Robinson, Bernat, Geise, Johnson, Kinman, Mader, Oswalt, Putt, Swallers & Williams, 1967), 0°C (32°F) to 4.4°C (40°F) for wheat, barley and rye (Nuttonson, 1956), and 4.4°C (40°F) for oats (Wiggans, 1956).

As it has been shown that varieties within crops differ as far as base temperature is concerned, the selection of a certain base temperature for all the varieties may lead to considerable error in the determination of heat requirements (van Dobben, 1953; Becker, 1954; Dijkhuis, 1956; Arnold, 1959). If the base temperature is taken too high, the heat unit sum will be too low as effective temperatures below the selected, but above the actual base, are disregarded. Selection of a base temperature which is too low will lead to a heat unit sum which is higher than it should be as it includes ineffective temperatures above the selected but below the actual base.

Methods which have been proposed for the determination of the base temperature have been designed to give that particular base that would result in (a) the minimum variability in heat unit summations or (b) a zero change in the summations when related mathematically to the mean temperatures involved (Arnold, 1959).

Heat unit summations from a series of plantings in one season or in a number of seasons can be calculated on a number of selected base temperatures and the base giving the least variation can be found. By using a great number of base temperatures this method will give a fairly accurate indication of the actual base temperature. According to Arnold (1959), the coefficient of variation is the best statistic to use as a measure of variability.

Another method to determine the base temperature, which can be used in conjunction with the previous method, makes use of the mean temperature and the mean rate of development of the plant (Arnold, 1959). If a plant requires 80 days to develop from planting to flowering the mean rate of development for that period is

$$\frac{100}{80} = 1.25\%$$

The mean daily temperature for the same period is determined and when these two values are worked out for a number of plantings a regression equation can be calculated in which the mean temperature, x, is the independent variable and the mean rate of development, y, the dependent variable. For $y = o$, the solution of the equation gives a value for x which is the base temperature. Using this method Arnold (1959) found the base temperature for maize to be 6.7°C (44°F).

Modifications of the remainder index system

1 The relationship between temperature and rate of growth and development is not linear over the whole range of growing temperatures. Lehenbauer (1914) in a classical study of the growth of maize seedlings in relation to temperature presented curves with a minimum below 12°C (53.6°F), an optimum at 31-32°C (87.8°-89.6°F) and a maximum over 43°C (109.4°F). Loomis (1934) found the daily growth of maize to be stimulated by increasing temperatures in the range from 5°C to 35°C.

However, the part of the curves between minimum and optimum temperature is very nearly linear. (Lehenbauer, 1914; Arnold, 1959; Ferguson, 1958). As stated above Lehenbauer (1914) found the optimum temperature for the growth of maize seedlings to be at 31°-32°C (87.8°-89.6°F) while Went (1957) pointed out that development of plants still takes place at temperatures which are too high for growth.

Gilmore et al, (1956), determined the coefficients of variation for the heat units obtained for a number of maize hybrids from planting to silking in a planting date experiment, when calculating the heat sum in 15 different ways. The lowest coefficient of variation (1.63%) was found when all temperatures below 50°F and above 86°F were disregarded.

The effect of temperatures above the optimum on the development of plants will depend largely on the frequency with which these temperatures occur and on the length of time. Moreover, in periods of drought stress the optimum temperatures become lower.

In the system set up for maize recommendations in Ontario, day and night temperatures are treated separately in arriving at a final heat sum. The relationship used is as follows (Brown, 1963),

Daily heat units =

$$(T\ min - 40°F) + (4.39\ T\ max - 0.0256\ T\ max^2 - 155.8)$$

A threshold value of 40°F is assumed for night temperatures, based on work reported by Went (1957) showing that night time temperature requirements for most plants are lower than day time requirements. A unit linear response per degree above 40°F is assumed. The maximum temperature relationship is a parabola with a base of 50°F and optimum of 86°F, based on previous work by Brown (1960) with soyabeans.

2 The use of soil temperatures as the basis for the computation of heat units for the period from planting to emergence has been suggested by Fletcher (1950) and Dijkhuis (1956). Hortik & Arnold (1965) used soil temperatures from planting to the fourth leaf stage, as they found that at that stage the food reserves of the seed were depleted and the plants were completely dependent on the function of the above-ground parts for the first time.

3 Nuttonson (1948) attempted to improve the results obtained with the remainder index system by incorporating the effect of photoperiod into the heat summation. In a study of the phenology of a few varieties of wheat and flax and of Alaska peas grown over a wide range of latitudes in North America, Nuttonson (1948) found that a multiple of the average length of day and the summation of day degrees, photothermal units, provided a less variable unit of the interval between phenological events than the use of day degrees alone.

Ferwerda (1953) found that the same maize hybrid or inbred required the same number of photothermal units in Spain as in the Netherlands at locations which are 11 degrees latitude apart. Unfortunately no comparison with heat units (thermal units) was made.

Tsotsis (1958) compared the thermal and photothermal units accumulated during the period from planting to silking for a number of hybrids over three seasons. No purpose was served by the introduction of the photoperiod. This was not surprising as the experiments were all carried out at one location. Consequently the heat units were multiplied by a constant.

Allison (1963) determined the thermal and photothermal requirements of eight maize varieties for the periods from planting to pollen shedding and silking over a wide area (34°S to 14°S) in southern Africa. Over the whole period of experimentation the day length varied from 14.0 hours (at 34°S) to 12.8 hours (at 14°S). The results showed that the variability of sums of day degrees x day length was only slightly lower than that of day degree sums for tasselling and higher for silking.

Van Dobben (1953) points out that the formula used by Nuttonson can only be accepted if there is a direct relationship between the photoperiodic reaction of the plant and the length of day, which does not exist.

Conclusion

The inclusion in the remainder index formula of a factor covering the effect of temperatures above the optimum will be of importance for areas where these temperatures occur during a substantial period in the growing season.

The use of soil temperatures for the period from planting to emergence would require special equipment and extra work, which may only be warranted in areas where the seed is planted deep. Under these conditions there would be a marked difference between air and soil temperatures.

The introduction of day length into the formula has been done rather indiscriminately. More research work regarding the period of influence of day length on the development of maize is needed.

In the USA and Canada the remainder index formula

$$\frac{\text{maximum} + \text{minimum temperature}}{2} - \text{base temperature}$$

is modified in such a way that temperatures above the optimum and below the minimum for plant growth are disregarded (Holmes & Robertson, 1959). In the case of maize this means that temperatures above 30°C are taken as 30°C and below 10°C are taken as 10°C (Gilmore & Rogers, 1958).

Practical application of heat summations

Until the 1920's the study of the influence of temperature on the rate of development of plants was of an academic nature. From then onwards, however, research workers in different agricultural spheres started to realize that the heat unit sum, notwithstanding its shortcomings, gave a less variable expression of the different developmental stages of plants than the number of days. Heat unit summations have become established practice in the USA and in Canada in the following cases

1 Canning industry; scheduling of plantings of canning crops (sweetcorn, peas).
2 Maize production; as a measure of the adaptability of maize hybrids to different areas.
3 To a lesser degree maize breeders make use of the concept in order to effect synchronization of the flowering of inbred lines for crossing purposes.

Canning industry

The steady flow of produce to the factory is of great importance, consequently the scheduling of plantings of the crops should be as accurate as possible. The expression of the length of the period from planting to the canning stage in number of days, which had been used in the past, led to considerable confusion, as the length of this period would be dependent on weather conditions and especially temperature.

When the average number of heat units required by a variety of a crop to reach canning ripeness over a number of years is known, growers may plant such an acreage on one day that the factory can be kept going for one day, and delay successive plantings until approximately the same number of heat units have accumulated as are recorded on average on a single day during the harvest season (Phillips, 1950; Katz, 1951). Although the heat unit summations for a variety of a crop are subject to seasonal variations due to factors other than temperature (moisture conditions, fertility levels, soil type, depth of planting etc) the method proved to be of such value, especially in the case of peas and sweetcorn, that most canning companies now make use of it.

Maize production

The different varieties and hybrids of maize vary widely in their heat requirements from planting to maturity. In order to be able to assess which varieties or hybrids can be grown in a certain area, it is necessary to determine how many heat units can be accumulated during the normal growing season in that area. The length of the growing season may be determined by different climatic factors, mainly temperature and rainfall. In countries with severe winters, planting can only take place when, in spring, the soil has warmed sufficiently to allow germination of the seed. The end of the growing season is determined by the occurrence of the first frost.

In areas with less severe but dry winters, the beginning of the growing season depends on the spring rains, while the end is again determined by the occurrence of the first frost.

In other areas again, rainfall may be the only factor influencing the length of the growing season.

Boughner & Kendall (1959) compiled a list of accumulated degree-day totals (heat units) above 42°F for 1957 and 1958 for 146 Canadian stations and designed charts showing the aereal distribution for this parameter for Canada. The data used were daily temperature records.

Brown (1963) divided southern Ontario (Canada) into 'iso heat units' areas based on the accumulation of heat units from the date of occurrence of a mean temperature of 55°F until the day before the first killing frosts in nine years out of ten. At the same time heat units were accumulated over the period planting to maturity (35% kernel moisture) for all the hybrids in the Ontario Corn Trials at four locations for five years. The heat unit sums proved considerably less variable (CV 2.6%) than the number of days (CV 7.2%). As a result it was decided to define the corn hybrids that are recommended for production in Ontario on the basis of heat units, using maturity data collected in the Ontario Corn Trials.

In the USA the effect of temperature on maize production is expressed by means of heat units, with a base temperature of 55°F. The farmers appear to be fully conversant with the meaning of heat units as shown by the fact that the popular agricultural press refers to it as matter of fact.

A similar system has been suggested for South Africa (Dijkhuis, 1968). In this country because of the regular occurrence of mid-summer droughts, it will be more important to determine the heat requirement of different hybrids from planting to flowering than from planting to maturity. As dry weather conditions around the time of flowering are particularly harmful to yield, hybrids should be planted at such a time that they flower before or after the dry period. Optimum planting dates differ according to area, but the deciding factor is the first sufficient rainfall in spring (50 mm or more).

It would be necessary to determine the heat unit sum available in the different maize-growing areas in South Africa from the average date of the occurrence of planting rains to the average date on which the mid-summer drought starts.

Furthermore the seasonal heat unit sum for the different areas should be known. Depending on the time when the mid-summer drought occurs, it might be advisable to plant hybrids which would flower after the dry period. It would then be necessary to know how many heat units are still in hand for the completion of the period from flowering to maturity.

Synchronisation of flowering

Ferwerda (1953) suggested the use of the 'temperature sum' to obtain synchronization of flowering of inbred lines, hybrids and varieties of maize, which have to be crossed with each other in a maize-breeding programme.

In general the difference in number of days from planting to flowering of two crossing partners is determined and the later flowering is planted first, followed by the earlier flowering after a certain number of days.

The inaccuracy of this method is well known to maize breeders and seed producers. Alternative methods, including clipping of maize plants to retard reproductive development and the use of growth regulating chemicals, have been tried but never generally used. Singleton (1948) recommended modifying the 'number-of-days' method by sowing the latest inbred first and then waiting until the plants were up so that the rows were clearly visible before planting the earlier line. "The reason for this procedure, rather than waiting a specified number of days, is that weather conditions play a large part in hastening and retarding the emergence of young seedlings. Since differences in growth of the plant is the thing desired, it is best to let the plants themselves determine this difference."

It may be an improvement, but it is still an inaccurate method.

The use of heat units seems to be indicated and it is surprising that in South Africa so little use is being made of this method.

Opsomming

DIE GEBRUIK VAN WARMTE-EENHEDE IN MIELIEVERBOUING DEEL 1 LITERATUUROORSIG

Die verband tussen die temperatuur en die groei en ontwikkeling van plante is lank gelede al erken. Die uitdrukking van die verband in 'n eenvoudige formule soos die ,remainder index':

$$\frac{\textit{maximum} + \textit{minimum temperatuur}}{2} - \textit{basis temperatuur}$$

vir die berekening van effektiewe warmte-eenhede wat beskikbaar is vir groei en ontwikkeling, is gekritiseer, maar geen ander stelsel, wat dit doeltreffend kan vervang, is gevind nie.

Die praktiese toepassing van die warmte-eenhede stelsel in die VSA en in Kanada en die moontlike gebruik daarvan in die Suid-Afrikaanse mielieverbouing is bespreek.

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