WEATHER-BASED MATHEMATICAL MODELS FOR ESTIMATING DEVELOPMENT AND RIPENING OF CROPS

by

G.W. Robertson

CAGM Rapporteur on Application of Models and Forecasting of Development and Ripening of Crops
WMO

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- To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
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PREFACE

One of the terms of reference of the rapporteur was to survey literature pertaining to research carried out on modelling/forecasting of crop development and ripening and to prepare a bibliographical list of existing literature of models for predicting the ripening dates of commercial crops.

To determine the present state of the art of weather-based crop development models, the rapporteur prepared and distributed a questionnaire to all countries, with the help of the WMO Secretariat. The bibliography accompanying this report was prepared from the replies received from some 63 countries, supplemented by the rapporteur's correspondence with researchers in this field and a literature search carried out by him.

The replies to the questionnaire revealed that most of the research on crop-development models had been undertaken by researchers in the developed countries and are mainly confined to the temperate climatic zone.

Many developing countries, particularly in equatorial areas, indicated that their scientists needed training in the preparation of crop-development models and their applications. This report is prepared primarily with this requirement in mind: attempting to present the material in a logical manner to take some of the mathematical mystery out of crop-development models and to present sufficient basic material which will serve as a background for teaching purposes, particularly for agrometeorologists (WMO Class I and Class II levels) and also for agronomists who have an occasion to use crop-development models in their agricultural activities.

Many replies to the questionnaire listed bibliographic items pertaining to weather-based crop-yield models. This topic is not covered in this report, because the WMO Task Force on Crop-weather Models has amply covered this topic and its report has been published as a World Climate Programme Report (Guidelines on Crop-weather Models: WCP-50).

Lastly, a list of the addresses of the agencies (with the names of researchers) which replied to the questionnaire is included. These have been supplemented with the names of a number of additional agencies which are known to be actively engaged in crop-weather modelling research and development. The list, however, is not exhaustive.

G. W. Robertson
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Weather and climate play an important role in crop production. Advance information on crop prospects is vital for economic planning and for the distribution of food products. It provides lead time for various agricultural operations, including fertilizing, pest and disease control, harvesting and transportation of agricultural produce.

The WMO Commission for Agricultural Meteorology, recognizing the need for intensive and continuing study of the relationship between weather and crop production, published a Technical Note on crop-weather models (WMO Technical Note No. 151) reviewing the techniques available for simulating and analysing crop responses to weather, with special emphasis on the operational use of empirical statistical yield models.

As a further step in this direction the Commission, at its seventh session (Sofia (Bulgaria), 1979), appointed a rapporteur, Mr. G. W. Robertson (Canada), to review the literature on weather-based models of crop development and ripening. The present Technical Note is based on the report of the rapporteur.

This Technical Note, I am sure, will be of great interest to agrometeorologists, research workers in agriculture, planners, and all those concerned with agricultural production and the distribution of agricultural products.

It is with great pleasure that I take this opportunity of extending to Mr. Robertson the appreciation of the World Meteorological Organization for the time and effort he has devoted to the preparation of this Technical Note.

A. C. Wiin-Nielsen
Secretary-General
SUMMARY

The development of plants is controlled, biologically, by a number of hormones which regulate the various morphological changes which progressively take place within plant cells. The production of these hormones, both promoting and inhibiting, is a genetic characteristic of each plant species and variety. Their production or destruction is strongly influenced by the external environment.

The predominating influence is by temperature which controls the rate of chemical reactions which produce the hormones. This effect of temperature on the production of hormones may vary from one genotype to another. High temperatures may destroy certain hormones.

The production, conversion, or distribution of several hormones is sensitive to the duration of very weak light as well as to the duration of the dark period. Thus, many plants have a characteristic response to photoperiod. The production of hormones within the plant is also controlled to a lesser degree by plant nutrition and therefore may be influenced both by water stress and by available soil nutrients.

Because of the regulatory effects of hormones on plant development and their dependence on the external environment it is possible to formulate models which relate the rate of crop development to certain environmental factors, mainly temperature and photoperiod.

Many models have been developed for estimating the effect of weather on the rate of crop development and on the time of maturity. The more widely applicable of these models involve the interaction of temperature and photoperiod and assume non-linear relationships. It has been shown that different species, different varieties and different phenological periods during the crop's development respond differently to temperature and photoperiod. A single model with variations in certain characteristic coefficients may be applicable to all phenological periods of all varieties of all species. The calibration of such a model, i.e. the determination for each genotype under a wide range of environmental conditions, is required.

Crop-development models have a wide range of applications in agricultural activities. These include crop zonation, land-use planning, management and operation of the production and processing of perishable crops, characterizing genotype response to the environment, and use as a biological time-scale sub-model in weather-based systems for monitoring crop conditions and forecasting crop yield and production.
RESUME

Le développement des plantes est contrôlé, biologiquement, par un certain nombre d'hormones qui régissent les diverses transformations morphologiques qui se succèdent au sein des cellules de la plante. La production de ces hormones, qui agissent à la fois comme accélérateurs et comme freins, est une caractéristique génétique de chaque espèce et variété végétale. Leur production ou leur destruction est fortement influencée par l'environnement extérieur.

L'influence prédominante est celle de la température, qui détermine la vitesse des réactions chimiques qui produisent les hormones. L'effet de la température sur la production d'hormones peut varier d'un type génétique à l'autre. Des températures élevées peuvent détruire certaines hormones.

La production, la conversion ou la répartition de plusieurs hormones sont sensibles à la durée des périodes de très faible luminosité aussi bien qu'à la durée de la période d'obscurité. De nombreuses plantes réагissent par conséquent de manière caractéristique à la période de photosynthèse. La production d'hormones à l'intérieur de la plante est également contrôlée, à un moindre degré, par la nutrition de la plante et peut, par conséquent, être influencée à la fois par la tension hydrique et par les substances nutritives présentes dans le sol.

En raison des effets régulateurs des hormones sur le développement de la plante et du fait que les hormones dépendent de l'environnement extérieur, il est possible de formuler des modèles exprimant le rapport existant entre la vitesse de croissance d'une culture et certains facteurs mésologiques, principalement la température et la période de photosynthèse.

De nombreux modèles ont été mis au point pour estimer l'incidence des conditions météorologiques sur la croissance des cultures et sur l'époque de la maturité. Les modèles qui présentent les plus larges possibilités d'application sont fondés sur l'interaction de la température et de la période de photosynthèse et supposent des relations non linéaires. Il a été démontré que, durant le développement de la culture, différentes espèces, différentes variétés et différentes périodes phénologiques réagissent différemment à la température et à la période de photosynthèse. Un seul modèle, avec des variations de certains coefficients caractéristiques, peut s'appliquer à toutes les périodes phénologiques, pour toutes les variétés de toutes les espèces. Il est nécessaire d'étalonner un tel modèle, c'est-à-dire de déterminer les caractéristiques de chaque type génétique en fonction d'une vaste gamme de conditions d'environnement.

Les modèles de développement d'une culture ont un large éventail d'applications aux activités agricoles. On peut relever notamment le zonage des cultures, la planification de l'emploi des terres, la gestion et les opérations de production et de traitement des cultures périsposables, la détermination des caractéristiques de réaction de chaque type génétique à l'environnement; ces modèles peuvent également servir de modèle secondaire à l'échelle temporelle biologique, pour les besoins des systèmes de surveillance des cultures et de prévision du rendement et de la production agricole en fonction des conditions météorologiques.
РЕЗЮМЕ

Развитие растений биологически контролируется рядом гормонов, которые регулируют различные морфологические изменения, происходящие постепенно в клетках растений. Выработка этих гормонов как способствующих росту, так и задерживающих его, является генетической характеристикой каждого конкретного растения и вида растения. Внешняя окружающая среда оказывает сильное воздействие на их выработку или разрушение.

Преобладающее воздействие оказывает температура, которая определяет скорость химических реакций, в результате которых вырабатываются гормоны. Это влияние температуры на выработку гормонов может различаться в зависимости от генотипа. Некоторые гормоны могут разрушаться под действием высокой температуры.

Производство, превращение или распределение некоторых видов гормонов чувствительны к продолжительности периодов слабой освещенности и продолжительности периодов темноты. Таким образом многие растения обладают характерной реакцией в отношении фотоперiodа. Производство гормонов внутри растения в меньшей степени также определяется питанием растения, и, таким образом, на него может оказывать влияние как водный стресс, так и имеющиеся в почве питательные вещества.

Вследствие регулирующего влияния гормонов на развитие растений и их зависимости от существующей внешней среды имеется возможность создать модели, которые соотносят скорость развития культуры с определенными факторами внешней среды, а именно, температуры и фотоперiodа.

Были созданы многочисленные модели для оценки влияния погоды на скорость развития культуры и время созревания. Более широкое применение этих моделей связано с взаимодействием температуры и фотоперiodа и предполагает нелинейные зависимости. Было показано, что различные растения, различные виды и различные фенологические периоды во время роста культуры по-разному реагируют на температуру и фотоперiod. Для всех фенологических периодов всех видов растений может быть применена единственная модель при изменении некоторых характеристических коэффициентов. Необходима калибровка такой модели, т.е. выбор параметров для каждого генотипа в широком диапазоне условий окружающей среды.

Модели развития сельскохозяйственных культур имеют широкий диапазон применения в деятельности, связанной с сельским хозяйством. Сюда включается зонирование сельскохозяйственных культур, планирование землепользования, управление и производство продукции, обработка скоропортящихся культур, характеризующихся реакцией генотипа на окружающую среду, а также биологическая субмодель во временном масштабе, которая используется в системах, основанных на погоде, для мониторинга состояния сельскохозяйственных культур и прогнозирования урожайности культуры и производства.
RESUMEN

Desde el punto de vista biológico, el desarrollo de las plantas está controlado por una serie de hormonas que regulan los diversos cambios morfológicos que se van produciendo progresivamente en las células vegetales. La producción de estas hormonas, activadoras e inhibidoras, constituye una característica genética de cada especie variedad vegetal. Su producción o destrucción se hallan estrechamente ligadas al medio ambiente externo.

El factor predominante es la temperatura que determina la velocidad de las reacciones químicas mediante las que se producen las hormonas. El efecto de la temperatura sobre la producción de hormonas puede variar según los genotipos. Las temperaturas altas pueden destruir determinadas hormonas.

La duración de los períodos de muy escasa luminosidad y la duración de los períodos de obscurecimiento tienen influencia en la producción, conversión o distribución de varias hormonas. Así, pues, un gran número de plantas presentan una respuesta característica al período de fotosíntesis. La producción de hormonas en la planta está influída también, aunque en menor grado, por la nutrición y, por consiguiente, puede también resultar influenciada por la tensión del agua y por los nutrientes existentes en el suelo.

A causa del efecto regulador que ejercen las hormonas sobre el desarrollo de las plantas y su dependencia respecto al medio externo es posible elaborar modelos en los que se pongan en relación la velocidad de crecimiento de las plantas y determinados factores medioambientales, especialmente la temperatura y el período de fotosíntesis.

Se han elaborado muchos modelos para evaluar el efecto de las condiciones meteorológicas sobre el crecimiento de las plantas y sobre el momento de su maduración. Los modelos que presentan más posibilidades de aplicación se fundan en la interacción de la temperatura y el período de fotosíntesis y se basan en relaciones no lineales. Ha quedado demostrado que, durante el desarrollo de los cultivos, las diferentes especies variedades y períodos fenológicos reaccionan de manera diferente a la temperatura y al período de fotosíntesis. Un modelo único, con variaciones de determinados coeficientes característicos, puede aplicarse a todos los períodos fenológicos de todas las diferentes variedades y especies. Es necesario calibrar ese modelo, es decir que habrá que determinar las características de cada uno de los genotipos en función de una amplia gama de condiciones medioambientales.

Los modelos de crecimiento de las plantas tienen una amplia variedad de aplicaciones en la esfera de la agricultura. Entre éstas pueden citarse la zonación de cultivos, la planificación de la explotación de las tierras, la gestión y las operaciones de producción y tratamiento de los cultivos perenne, la determinación de las características reactivas de cada genotipo al medio ambiente, y también pueden servir de modelos secundarios a escala temporal biológica para las necesidades de los sistemas de vigilancia de los cultivos y de previsión del rendimiento y de la producción agrícola en función de las condiciones meteorológicas.
CHAPTER 1

INTRODUCTION

1.1 Importance

Certain agricultural activities often require advanced information on the dates of specific stages of crop development. An early forecast of ripening dates of many crops has considerable economic advantage. It provides a lead time for organizing such operations as the harvesting, packaging and transporting of the produce as well as for planning the time of harvest to coincide with market requirements (Lomas et al., 1970; Edey, 1977). For controlling diseases and insect pests of apples and other fruits it is advantageous to have a forecast of the early appearance of foliage and buds (Pearce and Preston, 1954; Primault, 1970; Theiler, 1980; Blackburn et al., 1982). In experimental and plant-breeding work it is necessary to have a good understanding of the effect of environmental factors on the behaviour of crop growth and development (Goyne et al., 1977; Brown, 1978; Clarkson and Russell, 1979). In many activities regarding land-use planning and crop zonation the length of time from sowing to harvest relative to the length of the wet period or to the freeze-free period is a very important consideration (Williams, 1969; Robertson, 1973; Bunting, 1975). Again, information on the rate of development and the date of various phenological stages is useful as input into models used for crop-weather surveillance systems (Baier, 1973) and for agricultural economics analyses (Baier, 1971).

Because of its importance in a number of agricultural areas of activity, the necessity for an understanding of the physiological process of development and how the rate of development is affected by certain environmental factors is indicated.

1.2 Development versus growth

Development of a crop is its progress from seed germination through floral bud differentiation to flowering and fruit formation and eventually to fruit maturity. It must be distinguished from growth, which is the accumulation of dry matter or material of the photosynthetic process. The process of development is often independent of the growth process and the two processes frequently proceed at different rates under the same environmental conditions.

The independence of development and growth is spectacularly illustrated by data gathered in experimental plots at Ottawa (Robertson, 1955a, 1955b). Millet crops were sown at six different dates at about fortnightly intervals during the spring and early summer. Among the crop observations taken were the dates of heading (earing) and the height at heading. The reciprocal of the age at heading is a measure of the average daily rate of development from sowing to heading, while the height at heading divided by the age at heading is a measure of the average daily rate of increase in crop height (growth). For the six dates of sowing experiments the rates of development and of growth were almost unrelated (Table 1.1). Similar results were found for Marquis wheat sown at different stations throughout Canada (Ripley, 1959).
CHAPTER 1

TABLE 1.1

The average rates of development and of growth for six crops of millet sown at Ottawa at six different times during the spring and early summer of 1955 (Data from Robertson, 1955b)

<table>
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<th>Dates of:</th>
<th>At heading:</th>
<th>Rates of:</th>
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<tr>
<td></td>
<td>Sowing</td>
<td>Heading</td>
<td>Age Height</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(days) (cm)</td>
</tr>
<tr>
<td>1</td>
<td>5 May</td>
<td>23 June</td>
<td>39 39</td>
</tr>
<tr>
<td>2</td>
<td>27 May</td>
<td>12 July</td>
<td>46 71</td>
</tr>
<tr>
<td>3</td>
<td>8 June</td>
<td>21 July</td>
<td>43 47</td>
</tr>
<tr>
<td>4</td>
<td>25 June</td>
<td>28 July</td>
<td>33 31</td>
</tr>
<tr>
<td>5</td>
<td>15 July</td>
<td>25 Aug.</td>
<td>41 73</td>
</tr>
<tr>
<td>6</td>
<td>27 July</td>
<td>22 Sept.</td>
<td>57 70</td>
</tr>
</tbody>
</table>

The main reason for this difference between the rate of development and the rate of growth is physiological. Development is influenced mainly by temperature and day length (photoperiod) while the rate of growth is influenced mainly by water stress in the plant tissue, temperature and light intensity. Furthermore, temperature may influence the rate of development differently than it influences the rate of growth. For example, high temperature may, in some crops, favour rapid development but suppress the rate of growth and final yield (Figure 1.1).

![Figure 1.1](image)

Figure 1.1 - A comparison of the effect of maximum temperature during the period from jointing to heading on the relative rate of development and of growth (yield) of spring wheat (Adapted from Robertson, 1968, 1974)
1.3 Development periods

The life cycle of a plant or crop from seed germination, or primordia initiation in the case of perennial crops, to seed maturity can be divided into a number of homogeneous developmental periods. The end of each period and the beginning of another is marked by a more or less distinct stage. For example, in cereals it is common to speak of periods between stages such as sowing to emergence, emergence to jointing or the beginning of internode elongation, jointing to heading, heading to anthesis, anthesis to milk stage, and milk stage to maturity. During each period the plant undergoes certain morphological changes in its development from one stage to another. Thus, for example, during the period from sowing to emergence the seed is germinating and during the period from milk stage to maturity nutrients are transferred into the seed and transformed into products which can be stored until the seed is ready to use them when the life cycle starts over again.

1.3.1 Germination

Germination of the seed of annual plants, or the initiation and expansion of the primordia in perennial plants, is the first step in crop development.

The prime requisite for seed germination is the imbibition of water to break its dormant or rest period. Following this the early development of the seedling is affected chiefly by temperature, which controls the rate of conversion of stored food in the seed to readily available sugars and other nutrients required by the growing seedling before the latter is capable of providing its own nutrients through the photosynthesis process.

In some plants adequate moisture is not sufficient to cause germination. The seed must be subjected to a certain period of cold temperature. This characteristic of some plants is a natural method for preventing germination of seeds immediately after maturity and running the risk of the seedlings being destroyed by a harsh winter or a long period of drought.

In other plants, particularly those adapted to survival in arid areas, germination cannot take place until the seeds have been flooded with water. This removes a certain growth-inhibiting substance which prevents early germination. (The inhibiting substance protects the seeds from germinating after a light rainfall, which would be insufficient to support growth after germination.) The seeds will germinate only after a heavy rainfall which will provide sufficient stored soil water to meet the plants' requirements until new seeds develop or until further rains arrive.

The whole subject of seed dormancy and germination is very complex and varies greatly from species to species. The controlling factors appear to be the balance between growth-inhibiting and promoting hormones. The production of these is controlled by a number of factors which vary in importance from plant species to plant species. These factors include, besides temperature and moisture, light intensity, the spectral composition of light, photoperiod, and heat stress (Leopold and Kriedemann, 1975).

1.3.2 Bud dormancy

The dormancy of buds in perennial plants and plants having cyclical vegetative and flowering periods is also controlled by various hormones much
the same as in seeds. The purpose of dormancy, of course, is to provide the plant with protection during cold periods or periods of drought when growth and reproduction could not take place. Bud dormancy is usually broken by temperature and moisture although light intensity and photoperiod are often controlling factors in certain species.

1.3.3 Floral bud initiation

After germination some plants require a period of cool or cold temperature to initiate the floral bud or to speed the onset of flowering. This requirement is called vernalization and is characteristic of most winter wheats and other autumn-sown temperature-zone crops. One explanation for the action of this effect is that the cool temperature slows vegetative growth and allows the plant to initiate the floral organs. With the return of warmer temperatures the floral bud continues to develop.

In a large number of plant species the initiation of the floral primordia takes place sometime after germination and early shoot growth. Some process within the plant must change vegetative buds to floral buds.

Physiologically speaking, development, involving morphological and other changes in the plant, appears to be controlled by certain regulating substances or hormones such as auxins and gibberellins which are manufactured within the plant. The production of these biochemicals is controlled primarily by both temperature and photoperiod. According to some scientists the production of photosyntheate also regulates development or at least the initiation of the flowering stage, in certain plants. Photosynthesis, of course, is affected by, among other things, water stress, light intensity and temperature. The onset of flowering in many apparently day-neutral (non-photoperiodically responsive), humid tropical plants appears to be initiated by high water stress during dry spells (Williams and Joseph, 1970).

Photoperiodism in plants was first described by Garner and Allard (1920). Since then the phenomenon has been studied intensively and many plants have been classified as to their photoperiodic requirements: long day, short day (or long night), or day neutral. In many cases day-neutral plants may be insensitive in certain geographical areas where day length undergoes little variation, such as near the Equator (Figure 2.5), but when they are moved to areas with greater day-length variation they are found to be photoperiodically sensitive. Other plants may be very sensitive to the slightest variation in day length, such as certain varieties of rice in tropical areas (Robertson, 1975).

The photoperiodic influence takes place even with very weak light intensity. The threshold light intensity for this influence is about that occurring shortly before sunrise or just after sunset (Robertson, 1966). Thus, the photoperiod of a site is usually considered to be the length of the period from astronomical sunrise to sunset.

The photoperiodic phenomenon in plants is associated with certain light-absorbing pigments called photochromes. The effect is reversible under different light qualities. For example, red light of about 660 nm sensitizes one form of the pigment, P(fr), so that it can absorb far-red light intensity of about 730 nm. On the other hand, far-red light sensitizes another form of the pigment, P(r), to absorption of red light. The P(r) form may be sensitized slowly in darkness and its formation is temperature-sensitive. Thus
there is a complex relationship of the ratio of the amounts of \( P(r)/P(fr) \) to day length, night length and temperature. A high ratio causes floral bud initiation in long-night (short-day) plants and a low ratio causes floral bud initiation in long-day plants. The phenomenon is quite complex and varies from species to species due to confounding by light intensity and water stress. For a more detailed discussion the reader is referred to Withrow (1959).

Although many domesticated crops can be classified as to their response to photoperiod and other factors affecting floral bud initiation and development, there may be variations in these responses due to selection and breeding.

The following list, therefore, must be considered as only approximate:

<table>
<thead>
<tr>
<th>Long day</th>
<th>Short day</th>
<th>Day neutral</th>
<th>High water stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Rice (Indica)</td>
<td>Pineapple</td>
<td>Cocoa</td>
</tr>
<tr>
<td>Barley</td>
<td>Soybean</td>
<td>Rice (Japonica)</td>
<td>Coconut</td>
</tr>
<tr>
<td>Oats</td>
<td>Sugar cane</td>
<td></td>
<td>Coconut</td>
</tr>
<tr>
<td>Onion (bulb)</td>
<td>Coffee</td>
<td></td>
<td>Oil palm</td>
</tr>
<tr>
<td>Sunflower (tuber)</td>
<td>Tropical yam</td>
<td>Potato (tuber)</td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.3.4 Other morphological and phenological changes

Aside from primordia initiation and floral bud differentiation, other changes take place within the plant during the early period of development. One such change is the formation of tillers or side shoots in cereals and grasses. Again the initiation of these is controlled by growth hormones, water stress, temperature, photoperiod and light intensity. Sexual differentiation of the floral bud in oil palm and other monoecious species is also controlled by hormones, the production of which is influenced by variations in environmental factors.

Anthesis and pollination are other very important but complex stages in the development of crops. These processes are controlled by several growth-promoting and growth-inhibiting substances, most of which are either temperature- or light-sensitive.

1.4 Development between stages

Finally, there is the development which takes place between the distinct phenological or morphological stages. It appears that plants require a certain minimum length of time to pass from one stage to another. The filling and ripening of grain and fruit including tubers, leaves (tobacco), and stalks of plants (sugarcane), for example, involves the translocation of nutrients from leaves and other photosynthesizing areas to the harvestable plant part where they are converted to complex sugars, starch, oils and proteins. These processes are dependent on growth-promoting and inhibiting substances such as auxins, gibberellins, cytokinins and other hormones which control many biochemical changes, all of which are, more or less, temperature-
sensitive and influenced by light through photoreceptors in the plant. In particular, raising or lowering the temperature within limits will, respectively, decrease or increase the length of time from one stage to another. The effect of day length on the length of time to pass from one stage to another is more complex and depends on the photoperiodic responses of the species as noted previously. Development rate may also be influenced by growth rate, which depends also on temperature as well as on water stress, light intensity and the availability of nutrients. Here the distinction between development and growth becomes indistinct. However, the difference still exists: growth is the amount of photosynthetic photosynthate produced, translocated, transformed and stored, while development is the length of time for the processes to take place.

This period of time between stages is quite variable as is indicated by the data on oats in Table 1.2.

**TABLE 1.2**

<table>
<thead>
<tr>
<th>Station N Latitude:</th>
<th>Sowing date</th>
<th>Number of days from previous stage to:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Emergence</td>
</tr>
<tr>
<td>Harrow 42°02'</td>
<td>2 April</td>
<td>10</td>
</tr>
<tr>
<td>Ottawa 45°24'</td>
<td>5 May</td>
<td>8</td>
</tr>
<tr>
<td>Ottawa 45°24'</td>
<td>27 May</td>
<td>4</td>
</tr>
<tr>
<td>Normandin 48°51'</td>
<td>27 May</td>
<td>9</td>
</tr>
<tr>
<td>Swift Current 50°16'</td>
<td>19 May</td>
<td>8</td>
</tr>
<tr>
<td>Lacombe 52°28'</td>
<td>11 May</td>
<td>9</td>
</tr>
<tr>
<td>Beaverlodge 55°11'</td>
<td>4 May</td>
<td>15</td>
</tr>
<tr>
<td>Fort Vermilion 58°23'</td>
<td>17 May</td>
<td>9</td>
</tr>
<tr>
<td>Fort Simpson 61°52'</td>
<td>18 May</td>
<td>10</td>
</tr>
</tbody>
</table>
1.5 References


CHAPTER 2

MODEL FORMULATION

Mathematical models for relating crop development to climatological or meteorological factors have several purposes: (a) to be able to estimate (forecast) the date of maturity or of other phenological stages for certain planning and operational purposes; (b) to be able to interpret the influence of certain meteorological factors on crop development; and (c) to estimate the reaction of crop development to specific climatological factors.

Most models involve temperature relationships in one form or another (Lindsey and Newman, 1956; Holmes and Robertson, 1959; Bassett et al., 1961; Brown, 1963; Franquin, 1968; Edey, 1969, 1977; Williams and Joseph, 1970; Blackburn et al., 1982). Some models incorporate both temperature and day length in an attempt to overcome the problems encountered when using temperature alone (Nuttonson, 1948; Robertson, 1968; and Williams, 1974a, 1974b; Coligado and Brown, 1975a, 1975b; Major et al., 1975). A few models combine solar energy with temperature in an attempt to account for both day length and the effect of sunlight on heating the plant tissue above ambient air temperature (Amores-Vergara, 1973; Caprio, 1971a, 1971b and 1974). In other models duration of bright sunshine data are used along with temperature to account for the effect of the duration of light as well as its intensity (Primault, 1969a, 1969b; Varga-Haszonits, 1971). Still another model makes use of net radiation alone; this being considered to be the heat available to the crop for development purposes (Newman et al., 1967). The techniques used for model development and testing are quite varied but, for the most part, are of the statistical type since crop development does not readily lend itself to mechanistic-type modelling such as is sometimes used in crop yield/weather modelling.

The modelling of the effect of weather on crop development, nevertheless, can be rationalized by giving consideration to certain fundamental biological aspects of the problem.

2.1 Constant rate of development model

First, it is convenient to consider development, not as a total process, but as a "rate" taking place from day to day (Robertson, 1968, 1973; Major et al., 1975; Clarkson and Russell, 1979). Since this daily rate usually cannot be measured directly, it is determined as an average of the total development over short time intervals during which a fairly homogeneous developmental process takes place. The rate is the reciprocal of the length of this time interval. For example, Beaver oats at Harrow (Table 2.1) took 20 days to develop from the emergence stage to the heading stage in 1955. The average rate of development during the period, therefore, would be $1/20 = 0.05$ per day. This is sometimes called the daily fractional increment of development (Clarkson and Russell, 1979).

The simplest crop development model, therefore, is one in which it is assumed that the average rate of development towards maturity or the end of the phenological period under consideration, $\frac{dM}{dt}$, is a constant, $C$, from one phenological stage to another, thus:
\[ \frac{dM}{dt} \frac{1}{N} = C \quad (2.1) \]

or

\[ dM = \frac{dt}{N} \]

which, upon integration over a phenological period from the stage \( S_1 \) to another stage \( S_2 \) becomes

\[ M = \int_{S_1}^{S_2} dM = \int_{0}^{N} \frac{dt}{N} = \frac{N}{N} = 1 \quad (2.2) \]

where \( M \) stands for maturity, at least for the phenological period under consideration. Infinite summation from this can be written as:

\[ M = \sum_{S_1}^{S_2} \frac{1}{N} = 1 \quad (2.3) \]

where \( \sum \) signifies summation.

Stated simply, this means that, by summing the daily fractional development over a given phenological period, the total will be unity at the end of the period.

2.2 Temperature remainder index model (TRIM)

The daily rate of development is seldom a constant but varies because of a number of environmental factors (mainly temperature and day length) which, theoretically at least, influence the biochemical rate of production of certain hormones in the plant, which in turn controls its rate of development. The relationship can be expressed as a differential equation:

\[ \frac{dM}{dt} = R = F(W) \quad (2.4) \]

where \( M \) is development towards maturity;
\( R \) is the rate of development; and
\( F(W) \) is a function of a number of daily weather factors.

The values of \( M \) and \( R \) cannot readily be observed but they can be evaluated by integrating Eq. 2.4 with respect to time over the interval of the phenological period, i.e. from phenological stage \( S_1 \) to stage \( S_2 \) as was
MODEL FORMULATION

\[ M = \int_{S_1}^{S_2} R dt = \int_{S_1}^{S_2} F(W) dt = 1 \quad (2.5) \]

It is assumed that development progresses from zero to one during a single homogeneous phenological period. Thus the integral in Eq. 2.5 is set to unity for the degree of development of maturity at time \( S_2 \). The choice of value of \( M = 1 \) at the end of a phenological period is purely arbitrary. In a somewhat similar approach Varga-Haszonits (1971) suggested a value of 1 000. Brown (1960) and Bassett et al. (1961) used a value of 10 000 while Arnold (1959) suggested a value of 100 which expresses the rate of development in terms of percentage, 100 per cent being the value of development at the end of a phenological period.

Since there may be several homogeneous phenological periods during the total developmental span of a crop, the total value of \( M \) at maturity may be a multiple of one. For spring wheat, for example, total development passes from sowing through emergence, jointing, heading, soft dough and hard dough, a total of five phenological periods making, at maturity, the total value of \( M = 5 \). This was the basis for the development of the biometeorological time scale (BMTS) by Robertson (1968).

The function \( F(W) \) may be a function of any number of weather elements taken in any combination to provide a realistic model which may be related to the rate of development, \( R \). In the case where a linear function of temperature is assumed to be the only influence on development, Eq. 2.4 becomes:

\[ R = a + bT_m \quad (2.6) \]

\[ = b(T_m + a/b) \quad (2.7) \]

Here \( R \) is the daily rate of development and \( T_m \) is the daily mean temperature.

Substituting Eq. 2.7 in Eq. 2.4 and integrating with respect to time or, on a finite basis, summing daily over the span of the phenological period from stage \( S_1 \) to stage \( S_2 \) gives:

\[ \Sigma_{S_1}^{S_2} R = \Sigma_{S_1}^{S_2} b(T_m + a/b) = M = 1 \quad (2.8) \]

Upon dividing by \( b \) (and omitting the summation limits) this becomes:
\[ \Sigma (T_m + a/b) = l/b = k \quad \text{(2.9)} \]

or

\[ \Sigma (T_m - T_0) = k \quad \text{(2.10)} \]

This is the well-known heat-unit or growing degree-day equation used by vegetable growers and food processors for estimating the date of maturity of certain vegetable crops (Holmes and Robertson, 1959, and Edey, 1977).

The term "heat-unit" equation or model is a misnomer as no quantity of heat, in the physical sense, is involved (Went, 1957). Nowhere in the equation is temperature multiplied by specific heat to give a quantity of heat. Temperature is involved directly in that it influences the rate of certain biochemical reactions which in turn control the rate of development. The term "growing" degree-day model or equation is also not correct for the purposes of this publication, which deals with development, not growth, as influenced by temperature and other meteorological factors.

The equation is sometimes referred to as the temperature-remainder index model (TRIM). This name circumvents the objections to "heat" and "growth" and will therefore be used throughout this report when referring to this model (Eq. 2.9). The daily temperature index will be referred to as TRI and the sum of the daily values as TRIS.

The value of \( T_0 = -a/b \) is the "apparent" threshold temperature at which development begins to take place. Arnold (1959) and Goyne et al. (1977) point out that this apparent threshold or base temperature may not necessarily coincide with the true physiological threshold temperature. The difference between them depends on the method used for determining the threshold value and the assumptions made concerning the influence of weather factors on the rate of development. Where temperature is considered to be the sole influence on rate of development and where a linear response is assumed, the error between the apparent threshold and the physiological threshold may be quite large. With this understanding, the term "threshold" in this report will be considered to be the "apparent" threshold temperature which may or may not coincide with the true physiological threshold.

The value \( l/b = k \) in Eq. 2.9 is the value of the summation constant (TRIS), the number of degree days, or the sum of the daily temperature-remainder indices (TRI) required for the crop to pass through the phenological phase in question.

The coefficients, \( a \) and \( b \), may be evaluated by regression analysis using a modification of Eq. 2.9. This provides a unique solution to the problem of evaluating both the threshold temperature and the summation constant simultaneously (Arnold, 1959).

Dividing by \( N \), multiplying by \( b \), and omitting the limits of summation, the equation becomes:

\[ \frac{\sum T_m}{N} + \frac{\sum a}{N} = \frac{1}{N} \quad \text{(2.11)} \]
which is

\[ bT_a + a = R_a \]  

2.12

where

\[ T_a = \frac{T_m}{N} \]  

2.13

\( T_a \) is the average of the daily mean temperatures during the phenological period in question and \( R_a = 1/N \) is the average daily rate of development during the period.

To accomplish the regression analysis it is necessary to have a number of sets of daily data from which a series of pairs of values of \( T_m \) and \( 1/N = R_a \) can be calculated for use in the regression analysis. An example of such a set of data and an analysis is shown in Table 2.1 and Figures 2.1 and 2.2.

**TABLE 2.1**

Average duration of the period from heading to maturity, the calculated average rate of development during the period and the average of the daily mean temperatures during the period for Marquis wheat grown at eight stations throughout Canada. Results are based on five years of observations (1952-1957) (Ripley, 1959)

<table>
<thead>
<tr>
<th>Station</th>
<th>Duration (days)</th>
<th>Average rate of development (1/day)</th>
<th>Average of the daily mean temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harrow (42°02')</td>
<td>31</td>
<td>0.0323</td>
<td>21.1</td>
</tr>
<tr>
<td>Ottawa (45°24')</td>
<td>29</td>
<td>0.0345</td>
<td>20.6</td>
</tr>
<tr>
<td>Normandin (48°51')</td>
<td>54</td>
<td>0.0185</td>
<td>15.0</td>
</tr>
<tr>
<td>Swift Current (50°16')</td>
<td>41</td>
<td>0.0244</td>
<td>18.1</td>
</tr>
<tr>
<td>Lacombe (52°28')</td>
<td>59</td>
<td>0.0169</td>
<td>14.7</td>
</tr>
<tr>
<td>Beaverlodge (55°28')</td>
<td>54</td>
<td>0.0185</td>
<td>13.9</td>
</tr>
<tr>
<td>Fort Vermilion (58°23')</td>
<td>48</td>
<td>0.0208</td>
<td>15.3</td>
</tr>
<tr>
<td>Fort Simpson (61°52')</td>
<td>38</td>
<td>0.0263</td>
<td>16.4</td>
</tr>
</tbody>
</table>

A plot of the number of days to maturity, \( N \), against temperature, \( T_a \), indicates an almost linear negative relationship (Figure 2.1). It is tempting to take the direct approach and do a regression analysis of \( N \) against \( T_a \) to obtain the following relationship:
\[ N = a + bT_a \] (2.14)

or

\[ = b(T_a + a/b) \] (2.15)

The regression or least-squares analysis produces the following values for the coefficients:

- \( a = 107.65 \)
- \( b = -3.75 \)
- \( a/b = -28.7 \)

so that Eq. 2.15 becomes

\[ N = -3.75(T_a - 28.7) \] (2.16)

This regression line is shown in Figure 2.1.

The value of \( a/b \) indicates that a temperature of 28.7°C is optimum, resulting in maximum development by reducing the duration from heading to maturity to zero! This is physiologically impossible. Furthermore, the equation gives no hint as to the minimum threshold value of temperature although if a value of 0°C is substituted for \( T_a \) in Eq. 2.16 the calculated value for the duration of the period from heading to maturity, \( N \), becomes 108 days — not a very likely value at the freezing point! Thus it is quite evident that such a model or mathematical relationship will give unrealistic results and must be used with a great deal of caution outside the range of the experimental data used for evaluating the coefficients.

A careful study of the plotted data in Figure 2.1 suggests that the relationship between \( N \) and \( T_a \) is curvilinear (hyperbolic) and that the relationship might be linearized by using the reciprocal of \( N \), the average rate of development, \( R_a \), as suggested in Eq. 2.12. This relationship is shown in Figure 2.2. Regression analysis yields the following equation:

\[ R_a = 1/N = 0.00228(T_a - 6.34) \] (2.17)

or in terms of the TRIM (Eq. 2.10):

\[ \Sigma(T_m - 6.34) = 439 \] (2.18)

This relationship is much more realistic. The threshold temperature of 6.34°C is close to field and growth-room observations. At this temperature the rate of development, \( 1/N \), is zero and the time to maturity would be infinite. At higher temperatures the rate of maturity increases until at 40°C the value of \( 1/N \) is 0.0767, indicating that the duration from heading to maturity is 13 days, not an impossible value (although such a high temperature might result in poor grain quality). It appears, therefore, that the equation embodying rate of development and temperature (Eq. 2.12 or 2.17) is superior to the equation for the direct relationship involving the duration of the period and temperature (Eq. 2.14) in that it provides more realistic estimates for extreme temperatures and it is physiologically more sound, taking into account one of the cardinal points of the temperature-development relationship.
Figure 2.1 - Number of days from heading to maturity of wheat plotted against the average of the daily mean temperatures showing a curvilinear relationship (Data from Table 2.1)

The simple linear relationship (Eq. 1.12 or 2.17) assumed by TRIM will not always give good results, however, as indicated by the plot of average development against the average of the daily mean temperatures from emergence to heading for Marquis wheat for some 53 station-years of data observed in different areas of Canada (Figure 2.3).

Possible reasons for lack of a relationship here include the following:

(a) The temperature relationship may be curvilinear;

(b) Photoperiod may be an important factor as well as the consideration of a threshold photoperiod;

(c) The length of the phenological period may be too long, covering more than one homogeneous phenological period. In fact the period from emergence to heading spans at least two periods: emergence to jointing and jointing to heading. Each period may have different responses to temperature and photoperiod;

(d) Daily mean temperature may not be a good function of temperature to use in a crop-weather development model. There may be separate and different developmental responses to day and to night temperatures;

(e) Other factors such as vernalization, light intensity and water stress might have some influence on the rate of development.
Figure 2.2 - Average rate of development of wheat from heading to maturity plotted against the average of the mean daily temperatures showing a linear relationship. Figures on right show the corresponding duration of the period in days (Data from Table 2.1)

Figure 2.3 - Scatter diagram of the average rate of development \((1/N)\) for the period from emergence to heading against the average of the daily mean temperature for the same period using regression data for 1953-1957, showing the inability of TRIM to account for influence of temperature on rate of development (After Robertson, 1968)
2.3 Curvilinear temperature models

Many biological responses to temperature follow a typical curvilinear pattern consisting of five parts (see Figure 2.4). Moving from lower temperatures to higher, these are:

(a) A threshold temperature at which biological activity begins;
(b) A nearly exponential increase of activity with increasing temperatures over a small range of temperature;
(c) A levelling off of biological activity at some optimum value;
(d) A rapid decrease in biological activity with a further increase in temperature;
(e) Finally, an upper limit is reached at which temperature is lethal to biological processes and at which activity ceases.

Lehnenbauer (1914) first noticed this relationship in connexion with the growth of roots of germinating maize seedlings. Livingston (1916) used the concept in connexion with his physiological index for estimating the influence of temperature on crop maturity.

Several researchers have since used a quadratic equation as an expression for relating the non-linear rate of development to the daily mean temperature (Brown, 1960; Robertson, 1968; Williams, 1974a; Holt et al., 1975; Major et al., 1975; and Clarkson and Russell, 1979). The general form of this relationship (see Eqs. 2.4 and 2.6) is:

\[ R = F(W) = a_0 + a_1 T_m + a_2 T_m^2 \]  (2.19)

and in the form similar to Eq. 2.12 where phenological-period averages are used:

\[ R_a = a_0 + a_1 T_a + a_2 T_a^2 \]  (2.20)

where the coefficients \( a_0, a_1 \) and \( a_2 \) can be evaluated by regression analysis.

Eq. 2.19 can be written in a temperature remainder form similar to the linear form (Eq. 2.7):

\[ R = a_1 (T_m - T_0) + a_2 (T_m - T_0)^2 \]  (2.21)

where the threshold temperature, \( T_0 \), is given by:

\[ T_0 = \frac{-a_1 - (a_1^2 - 4a_0 a_2)^{1/2}}{2a_2} \]  (2.22)
and the optimum temperature is:

\[ T_{op} = \frac{-a_1}{2a_2} \]  
(2.23)

Finally, Eq. 2.21 can be written in the form of a summation similar to TRIM (Eq. 2.10):

\[ \Sigma \left[ a_1 (T_m - T_0) + a_2 (T_m - T_0)^2 \right] = k_2 \]  
(2.24)

A weakness of the quadratic relationship is the indicated rapid increase in development rate for temperatures immediately above the threshold and the indicated slower decrease in development rate following the optimum temperature.

Figure 2.4 - Schematic diagram showing the general relationship of the influence of temperature on biological activities and the three cardinal points: (1) threshold, (2) optimum, and (3) the upper limit.

Several investigators (Holt et al., 1975; Sierra and Murphy, 1977; Primault, 1980) recognized the importance of the physiological form of the relation (Fig. 2.4). Foong (1980) used this form in his work on oil palm and proposed a unique equation, which he called the exponential quadratic, for the relationship:

\[ Y = a_0 + a_1 C^T + a_2 C^{2T} \]  
(2.25)
The cardinal points \( (T_0, T_{op}, \text{ and } T_{ul}, \text{ for temperature threshold, optimum and upper limit, respectively}) \) are related by:

\[
\frac{T_{op}}{2C} = \frac{T_0}{C} + \frac{T_{ul}}{C}
\]

(2.26)

where the optimum temperature is:

\[
T_{op} = \ln \left( \frac{T_0 + T_{ul}}{2} \right) \frac{1}{\ln C}
\]

(2.27)

the threshold temperature is:

\[
T_0 = \frac{\ln \left( 2C_{op} - C_{ul} \right)}{\ln C}
\]

(2.28)

and the upper limit is:

\[
T_{ul} = \frac{\ln \left( 2C_{op} - C_0 \right)}{\ln C}
\]

(2.29)

Here \( Y \) is the rate of the biological activity which could be the rate of development. \( C \) is a constant which is raised to the power of the temperatures, \( T \). With the proper choice of the coefficients the shape of the curve can be made to fit that shown in Figure 2.4. In Poong's research he determined by trial and error that \( C = 1.15 \). The value is not critical. The other coefficients were determined by least-squares (regression) analysis using field observations.

2.4 The temperature-day-length model

Nuttonson (1948) demonstrated the weakness of TRIM to explain adequately the duration of the period from emergence to maturity for wheat grown at sites between Mexico and northern Canada where a wide range of day lengths were experienced (Figure 2.5). He attempted to overcome this by introducing the average photoperiod (day length) during the period. His photo-thermal model, a modification of Eq. 2.10, can be written in the form:

\[
\Sigma (T_m - T_o) L_a = K
\]

(2.30)

where \( L_a \) is the average day length during the phenological period and \( K \) is the photothermal summation constant.

Nuttonson found that the variability from station to station of his summation constant, \( K \), was less than the variability of the summation constant, \( k \), in the TRIM but still there was room for improvement.
Figure 2.5 - Monthly trend in day length at the Equator and northward at latitudes 20°, 40°, and 60°

Eq. 2.30 is suitable for long-day crops under certain circumstances. For short-day crops the equation should be changed to use the length, D, of the dark period instead of L, the length of the light period, thus:

\[ \sum (T_m - T_0)D_a = K_d \]  (2.31)

2.5 Threshold photoperiod in models

Robertson (1953) reported on a simple model similar to TRIM but using day length and a day-length threshold to explain differences in the length of the period from emergence to heading of Redman wheat (a long-day crop) and crown proso millet (a short-day crop). Six dates of sowing were made for each crop throughout the growing season at Ottawa in 1952. Although the data were meagre the results were spectacular. The early sowings of wheat had a shorter interval to heading while the earlier sowings of millet took longer to head out. As the season progressed and days became shorter, after 21 June, the wheat took longer to head out while millet headed faster. TRIM calculations did not explain this difference but the accumulation of hours of daylight above a threshold for wheat and of hours of darkness above a threshold of dark hours for millet did explain the changes in length of the period with advancing season and also the differences in the rate of development between wheat and millet.
The equations used for this purpose were:

\[ \Sigma (L - 10.7) = 194 \quad (2.32) \]

\[ \Sigma (D - 5.7) = 151 \quad (2.33) \]

where \( \Sigma \) is summation from emergence to heading;
\( L \) is the daily day length;
\( D \) is the daily night length or duration of the dark period.

If day length instead of night length had been used for millet the equation would have been

\[ \Sigma (L - 18.3) = -147 \quad (2.34) \]

The negative summation value arises from the fact that the threshold day length is greater than the actual day lengths at Ottawa (and, in this case, below-threshold values were not discounted). Although this equation works equally well as Eq. 2.33, the latter is physiologically more realistic and avoids negative values.

This concept of a threshold photoperiod was used in the tri-quadratic model described in the next section.

2.6 Tri-quadratic model

In order to improve on TRIM and the photothermal model, Robertson (1968) proposed a tri-quadratic model involving quadratic functions of daytime and night-time temperatures and of photoperiod as well as shorter phenological periods as suggested in the list in section 2.4 above. The form of his model followed that of Eqs. 2.4 and 2.5 where \( P(W) \) became the product of the three quadratic functions

\[ \int_{S_1}^{S_2} F_1(T_1, T_2) \cdot F_2(L) \, dt = 1 \quad (2.35) \]

or, more specifically, using finite summation and omitting the summation limits:

\[ \Sigma \left[ a_1 (L-a_0)^2 + a_2 (L-a_0)(T_1-b_0)^2 + b_2 (T_1-b_0)^2 + b_3 (T_2-b_0)^2 + b_4 (T_2-b_0)^2 \right] = 1 \quad (2.36) \]

where \( \Sigma \) is the summation of daily values;
\( L \) is the daily duration of daylight in hours from astronomical sunrise to sunset;
\( T_1 \) and \( T_2 \) are daily maximum and minimum temperatures, respectively;
a_0 and \( b_0 \) are threshold values of photoperiod and temperature, respectively;
a_1, a_2, b_2, b_3, b_4 are coefficients.
Summation of the product is carried out daily from the beginning of one phenological period to the end of the period.

The daily summation produces, at the end of each day, an accumulated total which is a fraction of the total development for the phenological period under consideration. This accumulated total is similar to a scale of development indicating the progress towards maturity. This scale produced by the tri-quadratic model has become known as the biometeorological time scale or BMTS. For one phenological period the scale runs from 0.0 to 1.0. For wheat five phenological periods were considered and, adding these together, this gives a BMTS running from 0.0 at time of sowing to 5.0 at time of maturity. The BMTS can be compared to the biological time scale on a one to one basis (see Figure 2.7).

Besides the obvious advantages of this equation, there is an important inherent one. Since the equation involves the product of daily values of the environmental factors, daily extremes of temperature are not masked by the averaging process as is the case in models where all factors are added such as in multiple regression models. This effectively widens the range of environmental factors available for coefficient evaluation in the tri-quadratic model.

One weakness of the model is that it is mathematically necessary to restrict the lower threshold temperature to a common value for both maximum and minimum temperatures. Apparently no one has ever evaluated the seriousness of this assumption that both thresholds are equal. There is biological evidence that they may not be so.

The coefficients in the equation have been evaluated for five different phenological periods for two crops, spring wheat (Robertson, 1968) and barley (Williams, 1974a) using crop data for five years (1953-1957) from eight stations across Canada (Table 1.2). Meteorological data consisted of daily values of day length and of maximum and minimum temperatures. The latter were assumed to be representative of the effective day-time and night-time temperatures of the crop. The evaluation of the coefficients in Eq. 2.36 was undertaken by an iterative least-squares technique developed by Robertson (1968) and elaborated by Amores-Vergara (1973) and by Williams (1974a). A similar model, using only daily mean temperatures, was used by Major et al. (1975) to calculate the development of soybeans.

The results of the evaluation of the coefficients for Marquis wheat can be summarized graphically in a set of characteristic response curves, showing the influence of photoperiod, maximum temperature and minimum temperature during each of the five phenological periods (Figure 2.6).

In some instances the curvilinear relationship is evident. In several cases, however, only a linear relationship was established. This was because the range of observational data did not include a great enough range of values to cover the curvilinear part of the response. The iterative programme for evaluating the coefficients was designed to calculate coefficients for a linear relationship if a curvilinear one was not statistically significant. Had a larger range of experimental data been available, more of the relation-
Figure 2.6- Characteristic response curves for Marquis wheat based on the regression coefficients calculated by an iterative technique using the tri-quadratic model (Eq. 2.36). The dotted portions of the curves are beyond the range of observed data. (The range of the observed data is indicated by the bar at the base of each graph). The ordinates are relative values of the daily contribution of the three environmental factors to the daily rate of development (After Robertson, 1968).

The calculated coefficients provide data from which some of the cardinal points for various phenological periods can be evaluated for Marquis wheat and Olli barley (Table 2.2).

There are some similarities and several differences in the response characteristics of barley and wheat (both spring cereal crops) as indicated by the table of cardinal points. It should be noted that, for mathematical reasons, the lower threshold temperature for both maximum and minimum temperatures had to be set equal (Eq. 2.36). The negative temperature threshold for wheat for the phenological period emergence to jointing appears low but this variety of wheat (Marquis) is very hardy to freezing temperatures just after emergence and this negative threshold may reflect this genetic characteristic (Robertson, 1968).
TABLE 2.2

Values of the cardinal points for various phenological periods for Marquis wheat (after Robertson, 1968) and for Olli barley (after Williams, 1974a) as determined by the tri-quadratic model

<table>
<thead>
<tr>
<th>Phenological period</th>
<th>Crop</th>
<th>Maximum temp.</th>
<th>Cardinal points</th>
<th>Minimum temp.</th>
<th>Photoperiod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowing to emergence</td>
<td>Marquis</td>
<td>6.9 20.4 33.9</td>
<td>6.9 18.8 30.7</td>
<td>No response</td>
<td>No response</td>
</tr>
<tr>
<td></td>
<td>Olli</td>
<td>4.3 19.7 35.1</td>
<td>4.3 19.1 33.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergence to jointing</td>
<td>Marquis</td>
<td>-4.6 14.8 34.2</td>
<td>-4.6 19.1 **</td>
<td>8.4 Linear</td>
<td>6.1 Linear</td>
</tr>
<tr>
<td></td>
<td>Olli</td>
<td>10.1 19.9 29.8</td>
<td>10.1 30.6 **</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jointing to heading</td>
<td>Marquis</td>
<td>5.9 Linear</td>
<td>5.9 Linear</td>
<td>10.9 18.6 **</td>
<td>11.0 17.9 **</td>
</tr>
<tr>
<td></td>
<td>Olli</td>
<td>-1.4 23.8 **</td>
<td>-1.4 Nearly linear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heading to soft dough</td>
<td>Marquis</td>
<td>5.7 Linear</td>
<td>5.7 Linear</td>
<td>10.9 19.4 **</td>
<td>2.1 Linear</td>
</tr>
<tr>
<td></td>
<td>Olli</td>
<td>15.9 24.8 40.8*</td>
<td>15.9 18.4 20.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft dough to maturity</td>
<td>Marquis</td>
<td>3.2 Linear</td>
<td>3.2 Linear</td>
<td>24.4 Linear</td>
<td>24.7 Linear</td>
</tr>
<tr>
<td></td>
<td>Olli</td>
<td>No response</td>
<td>4.1 14.9 25.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Cardinal points (see Figure 2.2): Min. – minimum or lower threshold; Opt. – optimum point; Max. – maximum or upper threshold; * – extrapolation beyond the range of observed values; ** – value beyond reasonable range of extrapolation.
The threshold values for photoperiod, in the phenological period soft dough to maturity, which are greater than 24 hours can be interpreted as positive dark-period responses with positive dark-period thresholds equal to the indicated photoperiod thresholds minus 24 hours.

Two important facts arise from these values of the cardinal points and the characteristic response curves in Figure 2.4:

(a) Each phenological period of a crop may have distinct environmental response characteristics (cardinal points and contribution to development rate);

(b) Each species (and possibly each variety or genotype) may also have distinct environmental response characteristics.

It follows from the above that any model in which the same coefficients are used throughout the life cycle of a crop for estimating the time of maturity or duration of development may be subject to inherent errors.

To test the validity and superiority of the tri-quadratic model, Robertson (1968) used a second set of independent data from across Canada for the years 1958-1962 and an entirely independent set of data (same variety of wheat) obtained from Argentina for the years 1961-1965.

Four models were evaluated:

Model No. 1 was based on the assumption that the best estimate of the age of the crop at various phenological stages could be obtained from the average ages at the various stages of the set of regression data (Eq. 2.3).

Model No. 2 was based on TRIM (Eq. 2.10).

Model No. 3 was based on the simple photo-thermal equation proposed by Nuttonson (Eq. 2.30).

Model No. 4 was the tri-quadratic model (Eq. 2.36).

Three tests were used to compare the four models. Firstly, when the estimated age is plotted against the actual age for a set of data, the intercept of the regression line should be near zero, indicating that there is a minimum of bias in the estimated age. Secondly, the slope of the regression curve in such a plot should be near unity, indicating that any bias which does exist is uniform throughout the range of actual ages in the data set; and thirdly, the root-mean-square error between estimated and actual ages in the set should be a minimum.

The following comparisons of the four models (Tables 2.3, 2.4 and 2.5) indicate that the EMTS performs better under most tests excepting that for the intercept for the Argentine data.
CHAPTER 2

TABLE 2.3

The y-axis intercept for the regression of actual age (y) at different stages of development on calculated age (x) using various models and two independent data sources (After Robertson, 1968)

<table>
<thead>
<tr>
<th>Phenological stages</th>
<th>Test data source</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergence</td>
<td>Canada</td>
<td>9</td>
<td>2.5</td>
<td>3.0</td>
<td>-1.2*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>9</td>
<td>5.4</td>
<td>3.9</td>
<td>3.2*</td>
</tr>
<tr>
<td>Jointing</td>
<td>Canada</td>
<td>29</td>
<td>14.2</td>
<td>11.2</td>
<td>0.4*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>29</td>
<td>38.1</td>
<td>1.5*</td>
<td>13.2</td>
</tr>
<tr>
<td>Heading</td>
<td>Canada</td>
<td>55</td>
<td>20.5</td>
<td>14.5</td>
<td>1.2*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>55</td>
<td>-3.7*</td>
<td>8.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Soft dough</td>
<td>Canada</td>
<td>80</td>
<td>34.6</td>
<td>20.3</td>
<td>7.6*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>80</td>
<td>-20.9</td>
<td>-1.5*</td>
<td>10.6</td>
</tr>
<tr>
<td>Mature</td>
<td>Canada</td>
<td>95</td>
<td>58.4</td>
<td>60.5</td>
<td>17.3*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>95</td>
<td>-29.2</td>
<td>-10.4</td>
<td>1.9*</td>
</tr>
</tbody>
</table>

NOTE: * designates the model that best meets each of the three criteria above: i.e. near-zero intercept, near-unity slope, and minimum SEE.

TABLE 2.4

The slope for the regression of actual age at different stages of development on estimated age using various models and two sources of test data (See Table 2.2)

<table>
<thead>
<tr>
<th>Phenological stage</th>
<th>Test data source</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergence</td>
<td>Canada</td>
<td>0</td>
<td>0.73</td>
<td>0.66</td>
<td>1.15*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>0</td>
<td>0.73</td>
<td>0.64</td>
<td>1.07*</td>
</tr>
<tr>
<td>Jointing</td>
<td>Canada</td>
<td>0</td>
<td>0.51</td>
<td>0.60</td>
<td>1.00*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>0</td>
<td>1.09</td>
<td>1.41</td>
<td>0.98*</td>
</tr>
<tr>
<td>Heading</td>
<td>Canada</td>
<td>0</td>
<td>0.59</td>
<td>0.69</td>
<td>0.96*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>0</td>
<td>1.63</td>
<td>1.28</td>
<td>0.90*</td>
</tr>
<tr>
<td>Soft dough</td>
<td>Canada</td>
<td>0</td>
<td>0.58</td>
<td>0.76</td>
<td>0.92*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>0</td>
<td>1.66</td>
<td>1.19</td>
<td>0.91*</td>
</tr>
<tr>
<td>Mature</td>
<td>Canada</td>
<td>0</td>
<td>0.44</td>
<td>0.42</td>
<td>0.89*</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>0</td>
<td>1.65</td>
<td>1.24</td>
<td>0.99*</td>
</tr>
</tbody>
</table>

* See note to Table 2.3.
TABLE 2.5

The standard error of estimate (SEE) for the regression of actual age at different stages against estimated ages using various models and two independent sources of test data (See Tables 2.2 and 2.3)

<table>
<thead>
<tr>
<th>Phenological stage</th>
<th>Test data source</th>
<th>Model No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Emergence</td>
<td>Canada</td>
<td>5.7</td>
<td>1.6</td>
<td>1.7*</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>3.8</td>
<td>1.6</td>
<td>1.1*</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Jointing</td>
<td>Canada</td>
<td>7.5</td>
<td>6.1</td>
<td>5.5</td>
<td>5.3*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>18.0</td>
<td>15.9</td>
<td>8.0</td>
<td>6.6*</td>
<td></td>
</tr>
<tr>
<td>Heading</td>
<td>Canada</td>
<td>8.1</td>
<td>5.3</td>
<td>4.1</td>
<td>4.0*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>23.5</td>
<td>14.5</td>
<td>6.8</td>
<td>4.2*</td>
<td></td>
</tr>
<tr>
<td>Soft dough</td>
<td>Canada</td>
<td>11.1</td>
<td>7.9</td>
<td>6.6*</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>24.7</td>
<td>8.4</td>
<td>4.9</td>
<td>3.5*</td>
<td></td>
</tr>
<tr>
<td>Maturity</td>
<td>Canada</td>
<td>12.1</td>
<td>7.6</td>
<td>7.6</td>
<td>6.8*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>26.9</td>
<td>9.7</td>
<td>5.9</td>
<td>5.4*</td>
<td></td>
</tr>
</tbody>
</table>

* See note to Table 2.3.

In Argentina several sowings of Marquis spring wheat were made in their autumn season. For this reason the wheat had to remain over winter in semi-dormant condition when temperature and photoperiod were both below their respective thresholds for development. The effect of this overwintering on development and the ability of the tri-quadratic model to estimate the effect is well illustrated in Figure 2.7 overleaf. This ability of the model to perform well under adverse conditions is characteristic of a model which takes into consideration many of the environmental factors which affect development.

2.7 Vernalization model

Some crops require a cold treatment, called vernalization, during the period of early vegetative growth shortly after germination in order to reduce the length of time to flowering (see Section 1.3.3). Very few attempts have been made to express the vernalization process by a mathematical model.

While working with medicis Clarkson and Russell (1979) encountered a variety which required vernalization. They proposed that the rate of development towards flowering was a function of the minimum temperature. The development of the model is similar to Eqs. 2.2, 2.4, and 2.5. Since the rate of vernalization decreases with increasing temperature, they chose a function of the daily minimum temperature such that:

\[ F(T_2) = a_1 \exp(-a_2T_2) \]  

(2.37)
Figure 2.7 - The accumulated development of Marquis wheat at Buenos Aires, Argentina, 1965. BMTS is the calculated biometeorological time scale (Eq. 2.37). BTS is the actual biological time scale from P = planting (sowing) to E = emergence, J = jointing, H = heading, S = soft dough, and R = ripe or mature. The small circles are the dates of observed stages. The triangles are the average dates of stages as observed over five years in Canada. The curves are as follows: --- development calculated by TRIM; ------ development calculated by photo-thermal model; ------- development calculated by tri-quadratic model (After Robertson, 1968)

Integrating or summing this by days over the development period gave an indication of the maturity or completion of that period, thus:

\[ M = \sum a_i \exp(-a_2T_2) = 1 \]  

(2.38)

It was found by least-squares analysis that the values of \( a_1 = 0.265 \) and \( a_2 = 0.334 \) gave the best results.

Although this model gave substantial improvement in estimating the duration of the development period, one problem may be that they used daily minimum temperatures taken during the development period in question; whereas the vernalization effect is usually a result of a cold treatment during the dormant period after germination but prior to the floral bud development period. It appears, therefore, that the temperatures used in a vernalization model should be those for the period prior to the floral bud development period. The exact durations of the vernalization period and of the affected floral bud development period need to be better defined.
2.8 References


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CHAPTER 3

OPERATIONAL MODELS

3.1 Temperature remainder index model (TRIM)

3.1.1 General

TRIM is the most widely applied of those models using meteorological data for estimating the dates of phenological events, particularly the date of maturity. The equation for the model (see Eq. 2.10) is usually written in the form:

\[ \frac{S_2}{S_1} \sum (T - T_0) = k \]  \hspace{1cm} (3.1)

where \((T - T_0) = 0\), given that \(T < T_0\):

\( \Sigma \) is summation over a given phenological period from stage \(S_1\) to stage \(S_2\);

\( T \) is temperature, usually the mean daily temperature but can also be the daily maximum, daily minimum, or the mean for any given period;

\( T_0 \) is the threshold temperature;

\( k \) is summation constant or the temperature remainder index (TRIS).

In the summation process all temperatures equal to and below the threshold are ignored, i.e. for such cases \((T - T_0) = 0\).

To estimate the state of maturity it is simply a matter of calculating the value of \((T - T_0)\) for each day from some starting date (usually the date of sowing) and accumulating or summing these daily values until the sum is equal to or exceeds the TRIS \((k)\) for the species and variety of crop in question (Table 3.1).

Extensive tables of the summation constant are not of much practical use since these values vary widely from application to application depending on a number of factors. Some of these are discussed by Edey (1977):
(a) **Soil fertility level**

Low soil fertility causes slow growth. A high nitrogen level supports heavy stem growth and thus delays maturity. A high phosphorus level tends to hasten maturity.

(b) **Plant population**

A low plant population matures slightly earlier than a denser population, provided weeds do not make up the difference.

(c) **Soil type**

Sandy soil warms up earlier than clay soils. Other factors such as the fertility status and moisture characteristics are associated with soil type.

(d) **Soil temperature**

During the spring warm-up, soil temperature lags appreciably behind air temperature. Hence, if degree-days are accumulated on the basis of air temperature, the resulting totals may be too high. Soil temperature readings can be used instead, until plant emergence. Southern slopes warm up sooner in the spring than northern slopes. Seeds planted deep are cooler and usually emerge later than those planted shallow, provided moisture is not lacking.

(e) **Soil moisture**

Poorly drained soils are cold and also give rise to a variety of nutritional problems. If moisture is lacking at seeding time or during early growth, maturity is delayed even though the number of degree-days has been building up. Drought during the latter part of the life span of plants usually hastens maturity, or the plants may even die before they reach maturity.

(f) **Photoperiod**

Regional variation in the rate of maturity of a particular crop is usually attributed to variation in the length of photoperiod (day length). Longer periods of daylight reduce the heat (accumulated temperature) requirement of many crops, particularly those that thrive in cool weather. However, degree-day accumulations seem to provide fairly accurate guidelines without adjustment for photoperiod at any one location, because daylight hours do not vary much during the span of most crops in the temperature zone. In other zones or fringe areas in the north, the duration of daylight may have to be considered. Some plants mature more rapidly in the north, where days are long in the summer, than would be expected from temperature accumulation alone.
### TABLE 3.1

Approximate values of the threshold temperature and the summation constant from sowing to maturity for a few crops. (These values may vary with variety and from location to location for reasons explained below.) (See Holmes and Robertson, 1959; Treidl, 1978)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Threshold temperature $T_0$ (°C)</th>
<th>Summation constant TRIS (k) (Celsius degree days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canning peas:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- early</td>
<td>5</td>
<td>650</td>
</tr>
<tr>
<td>- late</td>
<td>5</td>
<td>930</td>
</tr>
<tr>
<td>Sweet corn:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- early</td>
<td>10</td>
<td>775</td>
</tr>
<tr>
<td>- late</td>
<td>10</td>
<td>1 000</td>
</tr>
<tr>
<td>Snap beans:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- early</td>
<td>10</td>
<td>620</td>
</tr>
<tr>
<td>- late</td>
<td>10</td>
<td>860</td>
</tr>
<tr>
<td>Cantaloupe</td>
<td>10</td>
<td>1 110</td>
</tr>
<tr>
<td>Pumpkins</td>
<td>13</td>
<td>*</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>13</td>
<td>*</td>
</tr>
</tbody>
</table>

* Not available

One criticism of TRIM is the fact that it makes use of the daily mean temperature which is calculated as one-half of the sum of the daily minimum (usually occurring in the morning shortly after sunrise) and the daily maximum (usually occurring a few hours after solar noon). Such a calculation makes no allowance for the duration of temperature above the threshold temperature. A clear day, for example, might have a minimum of 3 and a maximum of 13°C, while on a completely overcast day the values might be 6 and 10°C respectively. Both days have the same mean temperature, 8°C. If the threshold temperature for a specific crop is 2°C, for example, there is no problem. However, if the threshold is between the maximum and the minimum on the clear day, say 5°C, then part of the temperature for that day is ineffective, being below the threshold.

Lindsey and Newman (1956) proposed a method for overcoming this problem by calculating the daily number of degree hours (DH) above a given threshold using both maximum ($T_1$) and minimum ($T_2$) temperatures. They assumed that the daily rise in temperature from the minimum to the maximum and
fall again to the minimum formed a triangle with a base equal to 24 hours and the altitude equal to the range between minimum and maximum temperatures. The number of degree hours is related to the area of this triangle but adjustments have to be made for the value of the threshold temperature ($T_0$) relative to the minimum temperature. They noted three cases:

(a) **Minimum temperature equals threshold temperature**

Here the temperature for all hours throughout the day is above the threshold value and the number of degree-hours is:

$$DH = 24 \times \frac{(T_1 - T_2)}{2}$$

$$= 24 \times \frac{(T_1 - T_0) + (T_2 - T_0)}{2}$$

$$= 24 \times \frac{(T_1 + T_2)}{2} - T_0$$

$$= 24 \times (T_m - T_0)$$  \hspace{2cm} (3.2)

This is the same as multiplying the daily mean temperature minus the threshold temperature by 24 hours.

(b) **Minimum temperature is greater than threshold temperature**

Here the total area to be considered consists of a rectangle with base of 24 hours and height of ($T_2 - T_0$) degrees plus a triangle with base of 24 hours and a height of ($T_1 - T_2$) degrees. The total area is given as:

$$DH = 24 \times (T_2 - T_0) + 24 \times \frac{(T_1 - T_2)}{2}$$

$$= 24 \times \frac{(2T_2 - 2T_0) + (T_1 - T_2)}{2}$$

$$= 24 \times \frac{(T_1 + T_2)}{2} - T_0$$

$$= 24 \times (T_m - T_0)$$  \hspace{2cm} (3.3)

This gives the same answer as case (a) above.

(c) **Minimum temperature is below the threshold temperature**

Here a portion of the temperature during the 24-hour period is below the threshold and, therefore, is ineffective in contributing to crop development (see Figure 3.1).
Figure 3.1 - The relationship between maximum, \( T_1 \), and minimum, \( T_2 \), temperatures when the minimum is below the threshold temperature, \( T_0 \). The effective temperature (number of degree-hours) is given by the area of the triangle above \( T_0 \). The number of degree hours given by the area below \( T_0 \) is ineffective and must be discounted.

In this case effective temperatures during the day are those above the base of the triangle (see Figure 3.1) at \( T_0 \) and the total degree-hours is represented by the area of the solid triangle, the base of which is given by:

\[
B = 24 \times \frac{(T_1 - T_0)}{(T_1 - T_2)}
\]

and therefore

\[
DH = \frac{1}{2} \times (T_1 - T_0) \times 24 \times \frac{(T_1 - T_0)}{(T_1 - T_2)}
\]

\[
= 12 \times \frac{(T_1 - T_0)^2}{(T_1 - T_2)}
\]

Obviously the number of degree-hours in the latter case is greater than would be obtained if the mean daily temperature had been used. This formula is important in the early period of development of crops when temperatures are low and several days may have minima below the threshold value.

Using these methods and other suggestions of Lindsey and Newman (1956) and Arnold (1960), Williams and Joseph (1970) prepared simple tables for determining the number of degree days above or below any threshold temperature for both Fahrenheit and Celsius scales. In these tables the above determinations for degree-hours were divided by 24 hours to obtain the number of degree-days per day.
3.1.2 Determining the threshold temperature for TRIM

3.1.2.1 The coefficient of variation method

The determination of the threshold temperature and the summation constant for TRIM for a given crop species and variety is discussed by Arnold (1959). For this purpose it is necessary to have phenological observations, at least of the dates of sowing and maturity of the crop in question, together with daily observations of maximum and minimum temperatures. Such observations are required for the same crop variety over a period of several years and preferably from several sites in order to achieve as large a range in weather factors as is possible.

The objective, of course, is to calculate a value of the threshold temperature for use in TRIM (Eq. 2.10) that will give an estimate of the number of days to maturity with the smallest possible standard deviation for the data set in question. It can be shown algebraically that the same threshold temperature will give summation constants with a minimum coefficient of variation for the data set in question provided no daily temperatures are below the threshold. The coefficient of variation is defined as the ratio of the standard deviation of the data set divided by the average value and multiplied by 100 to express the result as a percentage.

TABLE 3.2

An example of the use of Arnold's (1959) minimum coefficient of variation for determining the threshold temperature in TRIM using the data set from Table 2.1

<table>
<thead>
<tr>
<th>Assumed threshold (°C)</th>
<th>Summation constant (degree-days)</th>
<th>Standard deviation (°C)</th>
<th>Coefficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.00</td>
<td>280</td>
<td>45.5</td>
<td>16.3</td>
</tr>
<tr>
<td>7.00</td>
<td>413</td>
<td>37.3</td>
<td>9.03</td>
</tr>
<tr>
<td>6.40</td>
<td>439.19</td>
<td>39.04</td>
<td>8.8889</td>
</tr>
<tr>
<td>6.34</td>
<td>441.84</td>
<td>39.27</td>
<td>8.8878*</td>
</tr>
<tr>
<td>6.30</td>
<td>443.61</td>
<td>39.43</td>
<td>8.8884</td>
</tr>
<tr>
<td>6.00</td>
<td>457</td>
<td>40.8</td>
<td>8.93</td>
</tr>
<tr>
<td>0.0</td>
<td>722</td>
<td>92.7</td>
<td>12.8</td>
</tr>
</tbody>
</table>

* Minimum value of the coefficient of variation. All calculations were carried out originally to six significant places.

This technique requires a number of calculations using assumed values of the threshold temperature. The process of "zeroing in" on the correct value to give the minimum coefficient of variation may be slow and laborious. An example of the calculations is given in Table 3.1, where the threshold temperature was determined previously by the regression method (Eqs. 2.12, 2.17). The two methods determine the same threshold temperature although
there is a small but non-significant difference in the summation constant resulting in an error of less than one day on the average considering that usually several degree-days are accumulated each day. To determine the threshold temperature to better than 1/10°C requires excessive significant figures in both the summation constant and its standard deviation.

3.1.2.2 The regression method

Bassett et al. (1961) developed a rational technique for evaluating both the threshold temperature, $T_0$, and the TRI or summation constant, $k$, in connexion with the study of the blooming of perennial trees and shrubs at Ottawa. Since the development of the plants began in very early spring, many days with temperatures below the threshold were experienced. The technique involved a series of objective iterative regression calculations to eliminate daily temperatures below the threshold which were assumed not to influence development.

They used an equation similar to Eq. 2.12, together with a series of several years of phenological and daily temperature observations for regression purposes. The daily temperatures were used for calculating the average temperatures during the phenological period from 1 March to the flowering date. Along with the rates of development, $1/N$, these formed a series of data pairs for regression purposes.

After the first regression calculation all days with temperatures below the indicated threshold were eliminated, a new average temperature for each phenological period calculated, counting only days with temperatures above the threshold, and the regression repeated. Since days with temperature equal to or lower than the threshold were omitted, different values for both the average rate of development, $1/N$, and the average temperature in each data pair were used for each iteration. This produced a second estimate of the threshold temperature.

The process was repeated until no change in the threshold temperature occurred. About four such repeated calculations were sufficient to produce a stable threshold temperature (Figure 3.2) and a value for the TRIS of reasonable reliability.

Where there are no daily temperatures below the threshold the regression technique works well and repeated calculations are not necessary. The advantage of the regression technique, using Eq. 2.12, is that the best fit (for the set of data used) threshold temperature and summation constant can be calculated without trial and error, or interpolation. Furthermore, certain statistics are also calculated during the regression analysis which permit the evaluation of the statistical significance of the correlation and regression coefficients.

In the study of Bassett et al. (1961) it was found that some species respond better to maximum temperature, others to minimum temperature, and still others appeared to have no temperature response or the temperature response was masked by responses to other factors.
Figure 3.2 - Regression lines and bivariate distributions showing the relationship between maximum temperature, T_{1}, and development rate in Populus grandidentata before (initial iteration) and after (final iteration) the removal of days with temperatures below the indicated threshold values. (N = number of days above threshold temperature from 1 March to flowering date in the equation 10000/N = a + bT, where the threshold temperature in °C, T_0 = a/b and the summation constant k = 10000/b (Bassett et al., 1961)

A unique modification of Eq. 2.12 was used by Kontturi (1979) for evaluating the threshold temperature, T_0, as well as the temperature sum, k, for wheat. He writes the equation in the following form:

\[ T_{a} = T_{0} + k(1/N) \]  \hspace{1cm} (3.6)

and proceeds to use a set of observed values from three stations taken over the years 1966-78 to evaluate the constant coefficients, T_0 and k, by regression or least square methods.

Here the problem is that the average temperature is the dependent variable instead of R_a or 1/N as is the case in Eq. 2.12. Unless the correlation coefficient is very high, the results from Eq. 3.6 will be different from the results from Eq. 2.12, where R_a or 1/N is the dependent variable and T_a the independent variable, as is customary when attempting to estimate development rate from temperature.
3.1.3 Effective temperature sums for barley

In Finland an attempt was made to use accumulated degree-days above a threshold of 5°C for zoning barley (Lallukka et al., 1978). It was discovered during tests at experimental stations that different sites required different amounts of accumulated degree-days from sowing to maturity for the same variety of barley. These amounts, called effective temperature sums, appeared to be positively correlated to the average temperature during the period in question.

Tests were made using other threshold temperatures and it appeared that 2°C gave the best results for early sowings when the average temperatures during the growing season were low. The threshold of 5°C gave best results for delayed sowings (due to wet weather), resulting in higher average temperatures during the growing season.

In this case it was assumed that some high day-time temperatures were not used effectively by the crop for development and by using the higher threshold the number of effective degree-days was reduced to agree with those calculated above the threshold of 2°C for the crops planted earlier. Differences in photoperiod were also recognized as a possible factor in causing a difference in the degree-day requirement of early and late planted crops.

It would be interesting to have applied Robertson’s ENTS (1968) to the Finnish data as was done by Williams (1974a) for barley data from Canada. This takes into account non-linear temperature influences as well as the influence of photoperiod.

3.2 Curvilinear models

The success or failure of TRIM to give a good estimate of the date of maturity or of other phenological events depends on the crop having a linear response to temperature. Often this is not the case and a non-linear or curvilinear relationship should be used as discussed in Chapter 2 (Figure 2.4 and Eqs. 2.20, 2.25).

3.2.1 Corn heat units

Some of the weaknesses of TRIM for predicting the maturity of corn were overcome by Brown (1963, 1978), who introduced separate functions for maximum and minimum temperatures in his model, which has become known as the corn heat unit (CHU) model. The function for minimum temperature is linear with a threshold temperature of 4.4°C and that for maximum temperature is quadratic with a threshold temperature of 10°C and an optimum of 30°C (Figure 3.3). Combining these two functions gives the daily rate of development:

\[
CHU = 1.8 \left(T_2 - 4.4\right) + 3.33 \left(T_1 - 10\right) - 0.84 \left(T_1 - 10\right)^2
\]

Corn hybrids, in Ontario, require an accumulated total from 2 600 to 3 500 CHU per season for maturity, depending on the hybrid and the kernel moisture content at harvest time. Physiological maturity is usually considered to be reached when kernel moisture is 40 per cent or less.
Figure 3.3 – Relationship between daily rate of development of corn and minimum and maximum temperatures. — = day-time (maximum) temperature relationship for °C and ---- = night-time minimum temperature relationships (After Brown, 1978)

The CHU model has been independently tested in other climatic areas. Baron et al. (1975) tested the performance of the model in Western Canada under much different climatic conditions than in Ontario where it was developed. Special plots of corn were grown at five sites for one to three years, giving a set of 14 station-years of phenological data along with their accompanying weather information. CHU and TRIM (threshold 10°C) gave equally good results as predictors of maturity.

In England Bunting (1976) undertook a similar test of the model, using a data set of 40 station-years of information gathered at Oxford and Cambridge. His results indicated that the CHU model is somewhat superior to the use of TRIM (threshold of 10°C). Aspiazu and Shaw (1972) tested the CHU model together with several other temperature models of the TRI type, using some 43 dent-corn hybrids. The CHU model gave the least variability in the estimated length in days of the various phenological periods considered.

3.2.2 Development of medic

Clarkson and Russell (1979) recognized this fact when working with annual medicos in Australia. They assumed that, in Eq. 2.4, \( F(W) \) is a function of temperature only, i.e.:

\[
R = F(T_m)
\]  \hspace{1cm} (3.8)

and Eq. 2.5 becomes:

\[
D = \int_{S_1}^{S_2} F(T_m) \, dt = 1
\]  \hspace{1cm} (3.9)
where \( F(T_m) \) is a quadratic equation. In finite form, Eq. 3.9 becomes:

\[
\frac{S_2}{S_1} \left[ a_1 (T_m - a_0) + a_2 (T_m - a_0)^2 \right] = 1
\]  
(3.10)

This equation is similar to Eq. 2.24, or to Eq. 2.36 with the photoperiod term set to unity and using only daily mean temperatures instead of daily maxima and minima. The coefficients in Eq. 3.10 were evaluated using a set of observed studies and a special iterative non-linear least-squares analysis (Ross, 1971). The value of the function

\[ a_1 (T_m - a_0) + a_2 (T_m - a_0)^2 \]

for a given daily mean temperature and development period is the daily fractional increment of development. The sum of these increments should equal unity at the end of the phenological stage in question. This is identical to the concept expressed in Eq. 2.24.

The equation gave good results for the earlier phenological periods of medics. For the period first flower to first mature pod, however, it gave a very low threshold temperature and a nearly linear curve which is slightly convex upward from the threshold. Both of these are physiologically unrealistic and a better threshold might have been indicated if a linear relationship had been used for this period (Figure 3.4).

![Figure 3.4](image)

Figure 3.4 - Effects of daily temperatures on fractional daily increments of development on medics to first lateral, first flower and first mature pod. (a) - M. scutellata; (b) - M. trunculata. I - Sowing to first lateral; II - first mature pod (Clarkson and Russell, 1979)

3.3 Photothermal models

As early as 1875 Tisserand recognized the importance of day length in the calculation of the effect of temperature on the development of crops (Robertson, 1973). He multiplied the mean temperature by the length of time between sunrise and sunset and assumed that this represented the amount of work down by plants during the day. The sum of these products from emergence to maturity gave a better indication of the date of maturity than did the sum of the daily mean temperature alone.
Nearly half a century passed before Garner and Allard (1920) observed and described the phenomenon of photoperiodism in plants: the effect of the relative length of day and night on the rate of development of floral and leaf buds. They recognized that some plants (short-day plants) required short days or long nights for early flowering while other plants (long-day plants) required long days or short nights for early flowering. They also recognized the fact that there was a certain threshold of day length or night length at which this photoperiodic effect became active and that this threshold varied from species to species (see Section 1.3.3).

The need for a threshold photoperiod in development models was demonstrated by Robertson (1953) (see Section 2.5) and has since been used to advantage by him (1968), Williams (1974), and Major et al. (1975a) in complex models (see Section 3.3.2).

3.3.1 Simple models

Nuttonson (1948) showed that, for certain long-day plants such as some varieties of wheat, flax, eggplants, and peas, the number of TRIS units from sowing to maturity multiplied by the average day length was more constant from station to station than was the TRIS alone (see Eqs. 2.10 and 2.30). He did not attempt to use a curvilinear response for temperature.

Soybeans are short-day plants (Garner et al., 1920). A review of the response of soybeans to temperature and photoperiod is given by da Mota (1978).

Brown (1960) studied the results of phenological observations of soybeans obtained from controlled environments at various temperatures and day lengths. He noted that the same number of accumulated dark hours were required for the plants to develop from sowing to flowering, at a given temperature but regardless of photoperiod. The number of accumulated hours of darkness varied, however, with temperature and this variation was not linear. He postulated a model similar to the following:

\[
\frac{10,000}{\Sigma D_i} = a_1 (T_a - T_0) + a_2 (T_a - T_0)^2
\]  

(3.14)

where \( \Sigma D_i \) is the sum of the daily night length from sowing to flowering; 

\( T_a \) is the average temperature during the same period; 

\( T_0 \) is the threshold temperature; 

\( a_1 \) and \( a_2 \) are constants; 

10,000 is an arbitrary constant.

Here it is assumed that the influence of night length is known and therefore it is considered together with the length of the phenological period as the dependent variable. The equation can be transformed to one similar to the photothermal type (Eq. 2.31).
CHAPTER 3

Since
\[ \sum D_i = ND_a \]  \hspace{1cm} (3.15)

where \( N \) is the number of days from sowing to flowering;
\( D_a \) is the average night length;

it can be shown that Eq. 3.14 is equivalent to

\[ \sum \left[ (T_m - T_0) + (T_m - T_0)^2 \right] D_a = K_d \]  \hspace{1cm} (3.16)

where \( T_m \) is the daily mean temperature;
\( K_d \) is the summation constant when night length is used.

Note that the night length value is outside the summation term and therefore the average of the night length for the phenological period in question is used.

In his analysis, Brown (1960) found that the threshold temperature for two varieties of soybean was 10°C and that there was only a slight but statistically non-significant difference between the curves for the two varieties above a temperature of about 21°C. He therefore assumed a single relationship for the daily development rate (in terms of fractional development per dark hour) as a quadratic function of the average temperature during the period from sowing to flowering for the two varieties. The numerical values provided by this equation were called Soybean Development Units (SDU) (Brown and Chapman, 1961). The equation is as follows:

\[ SDU = \frac{10,000}{\sum D_i} = 3.258 \ (T_a - 10) - 0.08195 \ (T_a - 10)^2 \]  \hspace{1cm} (3.17)

Pascale (1969) found that the SDU of Brown and Chapman could be related to the sum of the daily mean temperatures above a threshold of 15°C for many soybean-growing areas in the southern hemisphere.

The development of sunflowers was studied by Goyne et al. (1977), using field data for two varieties sown at the beginning of each month for two years, 1974 and 1975, at Biloela Research Station in Central Queensland, Australia (24°24'S, 150°30'E and 173 m above mean sea level). Independent check data were available from the same research station for several sowings during the period 1973 to 1976. It was determined that, for the period emergence to 50 per cent flowering, the threshold and the TRIS for one variety, Sunfola 68-2, were -1.3°C and 1351 Celsius degree-days respectively.

For the other variety, Hysun-30, the threshold temperature was found to be -5.9°C but the TRIS had a large variability and appeared to be a function of day length. A significant improvement in the prediction of the length of the phenological period was made by expressing the TRIS as a linear function of the average day length, \( L_a \), during the 30-day period immediately following sowing date, thus
\[ TRIS = \sum (T_m + 5.9) = (2835.0 - 133.1L_a) + 668.2 \quad (3.18) \]
\[ = 3503.2 - 133.1L_a \quad (3.19) \]

This indicates that an increase in day length decreases the TRIS, in keeping with the long-day characteristics of the variety. It was assumed that the variety Sunfola 68-2 had a very small short-day response or was day neutral.

The additive form of the temperature and day-length terms in Eq. 3.19 is unusual when dealing with photothermal models for crop development and one wonders if a multiplicative form, such as Eqs. 2.15 or 2.17, might not have resulted in a more realistic threshold value nearer to or above zero.

3.3.2 Complex models

A complex model might be described as one in which the rate of development is related to two or more environmental factors in a non-linear system, developed by using a quasi-mechanistic modelling approach. In such a system the environmental factors are usually multiplied by each other to account for interactions and the characteristic coefficients in the model are evaluated separately for at least the major phenological periods of the crop in question.

Because of their nature, complex models are usually valid over a larger range of environmental factors and, therefore, unlike the simple models, are useful in a wider range of climates and geographical locations as well as for a number of species and varieties. Of course the characteristic coefficients in the models must be evaluated for each species and variety of crop for which it is used. Examples of complex models are the tri-quadratic model applied to wheat by Robertson (1968), to barley by Williams (1974a) and, with modifications, to corn by Amores-Vergara (1973), and to soybean by Major et al. (1975a). A different approach is the biophotothermal model to predict tassel-initiation time in corn by Coligado and Brown (1975b).

The tri-quadratic model (Robertson, 1968, and Williams, 1974a) was discussed in some detail in Section 2, Eq. 2.36.

Major et al. (1975b) used a model for soybeans which was based on the tri-quadratic model. However, instead of using maximum and minimum temperatures separately, they combined them into daily mean temperatures. The final equation, which was similar to Eq. 2.36, was:

\[ 1 = M = \frac{S_2}{S_1} \left[ a_1(L - a_0) + a_2(L - a_0)^2 \right] \times \left[ b_1(T - b_0) + b_2(T - b_0)^2 \right] \quad (3.20) \]

The coefficients in the equation were evaluated by an iterative regression analysis method and the model was therefore called the IRA model.

Data used for evaluating the coefficients in the model were obtained from field date-of-sowing experiments at several sites in Missouri and Iowa in the central U.S.A. In some experiments day length was extended by the use of artificial illumination. Part of the data was used for calculating the coefficients in Eq. 3.20 while another part was reserved for an independent check of model performance.
Coefficients were determined for five phenological periods: 1 - sowing to emergence; 2 - emergence to beginning of flowering; 3 - beginning of flowering to beginning of pod fill; 4 - beginning of flowering to termination of flowering and 5 - beginning of flowering to maturity. Ten cultivars were used, representing both early maturing and late-maturing varieties.

The results of the evaluation of the coefficients used were interesting. In almost all cases (phenological periods and cultivars) the value of the threshold photoperiod, \( a_0 \), was larger than the longest day length at the sites where the crops were grown. This would result in a negative value of the term \( L - a_0 \). This negative value was countered by the sign of the coefficient, \( a_1 \), which was generally negative. This combination of signs is characteristic of short-day plants (requiring a long dark period (Garner et al., 1920). These negative signs could have been avoided by using the length of the dark period, \( D = 24 - L \), in which case the value of the threshold coefficient, \( a_0 \), would be the threshold dark period (see Eqs. 3.12 and 3.13). In Major's results the value of the threshold dark period is calculated to range from about three to nine hours. A few cultivars exhibited long-day characteristics during the period emergence to first flowering with a threshold photoperiod varying from about 8 to 9.6 hours. Temperature thresholds varied from about 1 to 9°C during the period emergence to first flowering and from about 7 to 17°C for the period first flowering to pod maturity.

The IRA model predicted development more accurately than calendar days or TRIM at all location studies. Since the IRA model has a different set of characteristic coefficients for each phenological period and for each cultivar, it was possible to use the model to characterize different cultivars as to their sensitivity to day length and temperature during different periods.

In an attempt to improve on existing models for estimating the date of tassel initiation in maize, Coligado and Brown (1975b) developed a model based on a concept which differed from the usual TRIM and photothermal models. This model was based on certain biological characteristics, temperature, temperature range and photoperiod and was therefore called the biophotothermal model. The final form of the equation was:

\[
\text{TII}_i = \frac{1}{[G + (dt)_{T_1, P_1, R_1}] \left[1 - (t_{e_1} - 5)b_{DP} \right]}
\]  

(3.21)

where \( \text{TII}_i \) is the daily tassel-initiation index;

\( G \) is the minimum time from emergence to tassel initiation under optimum conditions for development: \( T = 25^\circ \text{C}; P = 10 \text{ h}; R = 0^\circ \text{C}; \)

\( dt \) signifies an increment of time, to be added to \( G \), representing a small correction due to departures of \( T, P, \) and \( R \) from optimum;

\( T_1 \) is daily mean temperature;

\( P_1 \) is daily photoperiod or day length;

\( R_1 \) is the daily temperature range between maximum and minimum temperatures;
\( t_{ej} \) is the number of days from sowing to emergence, where the minimum number of days = 5;

\( b_{DP} \) is the rate of development potential and was determined to be approximately = 0.01.

The term

\[
(Dt)_{Ti, Pi, Ri} = k_T^{m_T} (T_i - 25)^{-m_T} + k_P^{m_P} (P_i - 10)^{-m_P} + k_R^{m_R} (R_i - 0)
\] (3.22)

where the coefficients \( k_T, k_P, k_R, m_T, m_P \) and \( m_R \) were determined for two maize hybrids using data from controlled climate experiments. The duration of time from emergence to tassel initiation is determined by summing the daily value of TTI until it is equal to unity, at which time tassel initiation is indicated. It would be noted that daily mean temperature appears in the model in three places. This may over-emphasize its importance. Daily mean temperatures greater than 25°C were set to 25.

The coefficients vary from hybrid to hybrid but do not appear to provide meaningful physiological characteristics of the hybrid in question. The equation gave good estimates of tassel initiation for the two hybrids grown under field conditions.

The hypothesis and background for the model and its development are very involved and reference should be made to the original paper (Coligado and Brown, 1975b) for details.

3.4 Miscellaneous models

Several investigators have found it necessary to develop special models: (a) to make use of limited available data; (b) to meet local climatic requirements; and (c) to satisfy the special characteristics of a specific crop. These requirements have resulted in a number of very specific models which meet the requirements for which they were designed but may not necessarily be transferable to other applications. However, it is worth noting a few of these approaches.

3.4.1 Models involving duration of bright sunshine

Daily data for the duration of bright sunshine as measured with a Campbell-Stokes sunshine recorder are, next to precipitation and temperature, fairly readily available. Furthermore, some investigators consider that sunlight duration can be used as a substitute for photoperiod and also provides some information on the additional heat that crops receive. It is not surprising then that sunshine-duration data have been used directly in models for estimating crop maturity or other phenological stages, particularly for long-day crops in which increases in both temperature and photoperiod result in an increase in development rate (see Eq. 2.15) (Primault, 1969a; Varga-Haszonits, 1971).

In a study of winter wheat, Varga-Haszonits used a model involving both daily mean temperature and duration of bright sunshine. He found that the correlation of length of development period with average temperature
during the period was negative as expected but that the correlation with total sunshine hours during the period was positive. The latter relationship is not consistent with the theory. There are two explanations.

Firstly, the correlation may be spurious because both the independent and the dependent variables contain a common term due to summation over the duration of the phenological period. This will cause a high positive correlation even though no causative relationship exists between duration of the period and total sunshine duration. This spurious correlation could be avoided by dividing the independent variable by the duration of the period correlating this with the reciprocal of the duration of the period (similar to Eqs. 2.11, 2.12). This problem is discussed by Cross and Zuber (1972).

Secondly, the high correlation may result from the often observed fact that long sunny days are usually associated with cooler polar air masses in temperate zones and are not necessarily accompanied by the highest temperatures; minimum temperatures in fact might be lower on sunny days than on cloudy days and this would contribute to the increase in the length of the development period. His model involved the ratio of temperature to sunshine duration:

\[ I_0 = 1000 \frac{T_a}{\Sigma H} \]  

(3.23)

where \( I_0 \) is the photothermal index;

\( T_a \) is the average temperature during the phenological period;

\( \Sigma H \) is the sum of the bright sunshine, in hours, during the period;

and 1000 is a multiplier to avoid decimal fractions.

The photothermal index was then related to the length of the phenological period, \( N \), by the equation:

\[ N = \frac{a}{I_0^b} \]  

(3.24)

The values of the coefficients, \( a \) and \( b \), were evaluated by a logarithmic transformation and regression using field observations. They were found to vary from one phenological period to another as follows:

<table>
<thead>
<tr>
<th>Stage of Maize Development</th>
<th>( a )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowing to sprouting</td>
<td>963</td>
<td>0.82</td>
</tr>
<tr>
<td>Shooting to earing</td>
<td>715</td>
<td>0.75</td>
</tr>
<tr>
<td>Earing to waxy ripening</td>
<td>531</td>
<td>0.64</td>
</tr>
</tbody>
</table>

The photothermal index model proved superior to a model using temperature alone for estimating the length of phenological periods.

Primault (1969a) developed a technique for calculating a biometeorological index, \( I \), for the maturity of maize. The technique consisted of a model involving TRIM to which were added the sum of the duration of bright sunshine, \( \Sigma H \), and the sum of the precipitation, \( \Sigma P \). The model could be written as follows:
I = \sum (T_m - T_0) + n \sum H + p \sum P

(3.25)

Daily precipitation amounts of 30 mm or less are summed while amounts over 30 mm are considered as 30 mm. The coefficients n and p were determined from field observations and vary from variety to variety as well as from one phenological period to another.

The prediction of maturity of most varieties required the TRIM term in the equation. The estimates for all varieties benefited from the inclusion of the sunshine term during the period from tasselling to maturity. The precipitation term was important in the period emergence to tasselling for only two of the four varieties tested. Two varieties required only TRIM during the period emergence to tasselling and one variety required only the sunshine term during the tasselling to maturity period.

3.4.2 Models involving global energy data

If intensity of sunlight plays a role in determining the rate of crop development then it would appear logical to use measurements of global energy (the intensity of total solar radiation from the sun, sky and clouds falling on a horizontal surface) or estimates of global energy from observations of the duration of bright sunshine (Robertson, 1976). Some researchers have used global energy data along with temperature to account for variation in the rate of development of various crops.

Caprio (1971a and 1974) developed a concept of solar-thermal units (STU) which was defined by the following simple equation:

\[ \text{STU} = \sum QT_m \]

(3.26)

where \( \sum \) signifies summation over a phenological period;

\( Q \) is global energy in g cal cm\(^{-2}\) day\(^{-1}\);

\( T_m \) is the daily mean temperature in °C.

He observed, from hundreds of records over the western U.S.A. for ten years, that the common lilac begins blooming when the STU reaches a value of 21 100 units based on summations beginning when the temperature first rises above 0°C (actually above 31°F) in the spring. During the period from first to last bloom 15 600 units accumulated. In his studies it was shown that the variation of STU from site to site was much less than the variation of TRIS units using a threshold of -0.6°C.

The STU has been applied to a number of crop species for estimating date of blooming (Caprio, 1971b). A few of these are (STU in thousands of units):

- Alfalfa (Medicago sativa) 10% flowering: 256
- White clover (Trifolium opulus): 294
- Apple (Malus pumila): 211
- Plum (Prunus domestica): 200
- Pear (Pyrus communis): 172
- Peach (Prunus Persica): 128
Amores-Vergara (1973) also used temperature and global energy in a model to explain the variability in the development of maize (sweet corn). She used the tri-quadratic model of Robertson (1968) but substituted daily global energy (Q) for day length (L) (see Eq. 2.17). She also tested the performance of three other models for estimating the duration of various phenological periods. Model A assumed that the average rate of development, based on the reciprocal of the average length of a phenological period in days, was constant (Eq. 2.1); model B was TRIM with a threshold temperature of 10°C (Eq. 2.10); model C was TRIM multiplied by the day length (Nuttonson's photothermal model; Eq. 2.30); and model D was the tri-quadratic model using global energy in place of day length (Eq. 2.36).

In each model the summation constant was assumed to be 1.0 for the set of experimental field data used in developing the model and for evaluating the coefficients so that there would be a common basis for model comparison.

The temperature-energy model performed quite well, as is shown in Table 3.3.

| Period            | Model  
|-------------------|--------
|                   | A (%)  | B (%)  | C (%)  | D (%)  |
| Plant - emergence | 14.6   | 14.0   | 13.8   | 9.6    |
| Emergence - jointing | 13.4   | 12.7   | 13.9   | 2.3    |
| Jointing - heading | 13.6   | 12.0   | 11.2   | 1.5    |
| Heading - soft dough | 15.7   | 13.9   | 13.2   | 1.9    |
| Soft dough - maturity | 19.5   | 18.6   | 17.8   | 8.6    |

Sierra (1977) used global energy together with temperature and photoperiod to study the development of soybeans. His model consisted of a series of linear relationships starting with the summation of global energy over a phenological period. This summation, in turn, was related by regression to photoperiod from which a photo-energetic summation was determined. This, in turn, was related by regression to temperature, the summation of which became the energetic-photo-thermal development model.

Although the method reduces calculations for a four-variable model to a minimum, the use of an environmental variable (or a function of an environmental variable) along with summations of these as dependent variables in a regression equation may lead to serious spurious relationships (Cross and Zuber, 1972) (see discussion in Section 3.4.1).
3.4.3 Models involving heat balance calculations

In preliminary attempts to relate crop development to meteorological factors, Robertson (1953; 1973) noted the shortcomings of temperatures measured in the standard temperature shelter to represent the crop's effective temperature which affects its rate of development. Realizing the importance of using standard meteorological data, a model was devised for calculating the crop's effective temperature using a heat balance approach and making use of only standard meteorological observations.

The basic model for effective temperature is:

\[ T_c = T_m + c \frac{Q_N - Q_E}{1 + 0.01w} \]  \hspace{1cm} (3.27)

where
- \( T_c \) is the effective crop temperature for development;
- \( T_m \) is the daily mean air temperature;
- \( Q_N \) is the daily radiation balance (net radiation) over the crop;
- \( Q_E \) is the heat equivalent of the actual evapotranspiration from the crop;
- \( c \) is a crop coefficient depending on, among other things, the height and density of the crop and is determined by regression analysis using crop development data;
- \( w \) is the wind speed (km day\(^{-1}\)) six metres above the crop.

There is a certain similarity between this equation and Penman's (1948) equation for evapotranspiration. The radiation balance term can be calculated from standard meteorological data using the technique employed by Penman in his equation. Actual evapotranspiration can be estimated by using rainfall and potential evapotranspiration information together with crop and soil characteristics for calculating a soil water balance (Baier and Robertson, 1966; Robertson, 1977).

The equation provided a means of estimating the effective crop temperature for a wide range of weather condition on four selected days in Ottawa in 1952 (Table 3.4).

The main reasons for temperature differences between open air and crop were the variations in the supply of soil water to meet the transpiration requirements of the crop and variations in the supply of global energy for heating the crop and the entrapped air within its canopy. On the average the effective crop (millet) temperature at Ottawa was calculated to be 2.5°C warmer than air temperature measured in a standard thermometer shelter. This was equivalent to a 23 per cent increase in the seasonal value of the TRIS (threshold 10°C) available for millet development.
TABLE 3.4

Examples of the heat balance of a crop and the influence on its effective temperature, Ottawa, 1952 (After Robertson, 1953)

<table>
<thead>
<tr>
<th>Daily mean air temperature (°C)</th>
<th>11 May</th>
<th>12 June</th>
<th>8 July</th>
<th>8 Sept.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean dew point temperature (°C)</td>
<td>10.0</td>
<td>15.6</td>
<td>25.0</td>
<td>9.4</td>
</tr>
<tr>
<td>Wind run (km day⁻¹)</td>
<td>7.2</td>
<td>7.2</td>
<td>21.7</td>
<td>8.9</td>
</tr>
<tr>
<td>Energy (g cal cm⁻² day)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>285</td>
<td>135</td>
<td>232</td>
<td>85</td>
</tr>
<tr>
<td>Balance (net)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transpiration equivalent</td>
<td>120</td>
<td>357</td>
<td>373</td>
<td>173</td>
</tr>
<tr>
<td>Available for crop heating</td>
<td>-13</td>
<td>42</td>
<td>22</td>
<td>82</td>
</tr>
<tr>
<td>Resulting crop temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase over mean air temp. (°C)</td>
<td>-1.1</td>
<td>4.4</td>
<td>2.2</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Newman et al. (1967) are among the few researchers who have attempted to calculate the heat balance of a crop for purposes of predicting its rate of maturity. Their approach was not to consider temperature, but what they called the net radiant heat load on the vegetative surface (oranges in this case). This consisted of calculating the excess of actual heat flux on the vegetative surface above a threshold flux of 0.524 g cal cm⁻² min⁻¹ corresponding to a threshold temperature of 10°C.

The actual heat flux was computed from microclimatic observations within the orange grove. Observations consisted of air temperature, wind, and black-globe temperatures taken bi-hourly. The results, applied to the estimation of the development of oranges, were found to be superior to the accumulation of TRI units above a threshold of 12.8°C but were limited to temperatures below 35°C.

3.4.4 Models_involving_rainfall_or_plant-water_stress

Clarkson and Russell (1976) reported on the results of tests conducted to determine the influence of water stress on the phasic development of six species of Medicago. The plants were grown in soil in plastic pots and four levels of soil water stress were achieved by controlled irrigation. Not only did the stress reduce the yield in the ratio of 100:53:35:20 respectively for the four treatments, but the length of time to reach flowering was significantly increased; by as much as 14 days for the most severe stress. However, the length of the flowering period and of the period from first flowering to mature seed pod was shortened somewhat by stress. The authors point out, however, that the effect of water stress on delaying flowering is not as large as are the effects of vernalization, photoperiod and temperature.
Sometimes development models for the same crop based on one set of conditions will not satisfactorily explain development under other conditions. This was the case with a model for soybean development which was based on observations and data from controlled-environment studies for the period sowing to first flowering (Brown, 1960) (see Section 3.3.1, Eq. 3.14). When it was attempted to use the model to interpret the development of field-grown crops it was found that it performed satisfactorily for the period sowing to first flowering but not for the periods first flowering to maximum podding and maximum podding to maturity.

The rate of development was shown statistically to increase with decreasing adjusted rainfall during the period first flowering to maximum podding (Brown and Chapman, 1960). Adjusted rainfall was used as an index of the available water during the period, amounting to the rainfall during the period plus the rain in excess of potential evapotranspiration, PE, prior to first flowering minus the excess (if any) of rain over PE prior to maximum podding. Five equations were used to express the relationship of daily development rate (SDU = soybean development units) to temperature and adjusted rainfall:

Optimum (100 mm): \[ SDU = 4.390T_m - 0.2560T^2 - 155.18 \]

25 mm below optimum: \[ SDU = 4.715T_m - 0.02755T^2 - 167.17 \]

50 mm below optimum: \[ SDU = 5.060T_m - 0.02950T^2 - 179.06 \]

75 mm below optimum: \[ SDU = 5.395T_m - 0.03145T^2 - 190.96 \]

100 mm below optimum: \[ SDU = 5.730T_m - 0.03340T^2 - 202.86 \]

The temperature relationship found for the period sowing to first flowering also did not apply during the period from maximum podding to maturity. The slope of the development-temperature curve as well as the threshold temperature appeared to be different for the later period. Rainfall did not appear to play a role here. Insufficient data were available to determine a practical relationship.

Primault (1969) also used rainfall in a model for maize together with sunshine duration and temperature. The model was discussed in Section 3.4.1. It appears that precipitation was not too important as the developmental response of only two or four varieties required precipitation in the model for the period emergence to tasselling and none of the four varieties required the precipitation term in the model for the period tasselling to maturity.

3.5 References


CAPRIO, J. M., 1971a: The Solar-Thermal Unit theory in relation to plant development and potential evapotranspiration. Montana Agricultural Experiment Station, Montana State University, Bozeman. Cir. 251. 10 pp.

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CHAPTER 4

APPLICATIONS

4.1 Crop zonation

Models for estimating the life span of crops from sowing to maturity have been used quite extensively for crop zonation purposes. In temperate areas where there is a distinct warm season bounded at both ends by cold temperatures unfavourable for crop development and growth, it is most important to determine whether or not a newly introduced crop species or variety can be matured within the warm season, without undue risk of damage by freezing temperatures. This problem has been discussed in detail by Bunting (1975).

The simplest approach is to determine the number of TRIS units or the length of the BMTS required by the specific crop to develop from sowing to maturity and then to determine whether or not this number of units is available in the selected area where the crop is to be introduced. This approach has been a useful and successful application of crop development models.

Normal TRIS units, usually above a threshold of 5 or 10°C, have been calculated from long-term climatic records by national meteorological and agricultural agencies and published in tabular form by station (Holmes and Robertson, 1959; Boughner, 1964; Edey, 1977; Treidl, 1978). A useful addition to the usual normal values are tables which show the probability of accumulating certain numbers of units over specified intervals of time (Felch et al., 1972). For regional and national zonation purposes, data presented in the form of maps (Figure 4.1) are most useful for planning purposes (Hough, 1975; Bloc et al., 1978; Simpson-Lewis et al., 1979).

Maize zonation has received much attention since the introduction of early maturing hybrids. The CHU model proposed by Brown (1963) (Eq. 3.7) has been used for preparing maps of maize zones in Canada (Chapman and Brown, 1966) and in Great Britain (Hough, 1978). In Switzerland maps were prepared to show the probability of ripening of four varieties of maize before 15 October (Primault, 1972) using Primault's model (1969). In Brown's approach it is customary to map the total number of CHU accumulated throughout the growing season. Then desirable hybrids with known CHU ratings can be selected to fit the CHU availability of a given area (Brown, 1978) (see Figure 4.2).

The zonation for wheat of the Canadian Great Plains was undertaken by Williams (1969) using the tri-quadratic model and the BMTS (Robertson, 1968). Since the latitude of this area ranges from 49°N to about 62°N the day lengths during the wheat growing season range from 13.5 to 19.8 hours (Figure 2.5). As most Canadian spring wheat varieties are long-day plants and strongly photoperiodic, the tri-quadratic model (Eq. 2.36) which includes a photoperiodic term was found quite useful for this purpose (Robertson, 1973).

All of Canada was zoned for barley and wheat (Williams et al., 1978) making use of the tri-quadratic model (Robertson, 1968; Williams, 1974). A unique application of the model in this study was to determine the impact of a climatic change of 1°C cooling on the reduction of the area in which these two crops could mature.
Figure 4.1 - Areas where, on the basis of temperature records, maize is likely to reach the milk ripe stage (whole crop dry matter greater than 25 per cent) in nine years out of ten (average accumulated temperatures above 10°C exceeded 728 Celsius degree-days or 678 Celsius degree-days for sheltered fields) (After Hough, 1975)
Figure 4.2 - Average number of Corn Heat Units (CHU) (see Eq. 3.7) during the maize-growing season in southern Ontario (After Brown, 1978)

Soybean models have been used for preparing soybean zonation maps in several areas. The SDU model of Brown and Chapman (1961) (Eq. 3.17) has been used for soybean zonation around the Great Lakes. A linear modification of the SDU model using a threshold temperature of 15°C has been used for soybean zonation in Brazil and Argentina (Pascale, 1969; da Mota, 1978).

4.2 Operational planning and management

Commercial vegetable growers and processors of perishable food crops have probably been the longest and most extensive users of crop-development models. These users require information on rate of crop development both for planning the dates and amounts of crops to be sown at a given time and for monitoring the effect of weather on the time of crop maturity (Holmes and Robertson, 1959; Ekey, 1977). The simple TRIM (Eq. 2.10), with appropriate threshold temperatures for different crops, has usually been found adequate for these purposes.

There are several reasons for this:

(a) Varieties have been selected for optimum development and growth in the local climatic and soil zone. The development response to temperature, therefore, will be nearly linear (between the lower threshold and the optimum temperatures) with temperatures exceeding the optimum only on rare occasions:
CHAPTER 4

(b) Photoperiod variation from field to field is practically negligible. Although the variation from early sowings to late sowings may be significant, adjustments can be made in the number of TRIS units based on comparisons of later sowings with the performance of earlier ones;

(c) The threshold temperatures and accumulated TRIS units can be determined for specific crops under local conditions with practical reliability;

(d) Usually food crops for commercial processing are grown in areas with adequate rainfall or where irrigation is available, thus the influence of plant-tissue water stress on development rate is minimal.

In order that food-processing plants are not swamped with produce at harvest time, it is customary to sow crops at various dates in the spring in order to spread the harvest over several days or weeks. TRIM can be used together with the known TRIS units required to mature a given crop, and historical daily temperatures to establish general harvesting dates for assumed sowing dates; or conversely, to control a smooth and even flow of produce to a processing plant at harvest time, TRIM can be used backwards, starting at harvest time and working back to sowing time, making use of historical data to establish general sowing dates in order to achieve a desirable spread in the time of maturity of crops.

In actual day-to-day operations, because of departures of temperatures from the historical expectation, it is necessary to monitor the accumulation of TRIS units on a daily basis, accumulating as many units between spring sowings as are desirable between autumn harvests in order to achieve an even flow of harvested produce at the processing plant.

As the season progresses after sowing, it is necessary to monitor daily temperatures and calculate TRIS units to determine whether the crop is progressing faster or slower than planned. With the approach of maturity, as indicated by the accumulation of TRIS units, it is possible to make adjustments in size of labour force, hours of work, and amount of equipment in order to compensate for a harvest which is earlier or later than usual.

The forecasting of blossoming in fruit trees is another practical application of weather-based crop-development models. Such forecasts are required for planning protection against freezing temperatures and for applying protective sprays against disease and insect pests. This problem has been investigated by several people (Blackburn et al., 1982; Pearce and Preston, 1954; Remund and Boller, 1971; Theiler, 1978). The formation and development of the floral bud in fruit trees begin sometime during the summer or autumn of the previous year. Weather conditions, mainly temperature, in the autumn, winter and early spring influence the time of blossoming. TRIM, often with modifications, is the basis for estimating the effect of temperature on the rate of development of the floral bud. For example, Pearce and Preston (1954) used TRIM with a threshold temperature of 5°C but weighted the summations for different months according to their influence on the rate of development. The weighting factors were determined by multiple regression analysis.
The determination of the optimum time to begin the grazing of grass or to cut it for conservation purposes has been extensively investigated in the United Kingdom. As with so many other crops, temperature appears to be the most important factor in determining the rate of development of perennial grasses. The optimum time for grazing or cutting is at about the time of heading. In this problem it is not so much a case of monitoring the progress of the grass towards heading as it is to predict at some very early date in the spring when heading can be expected to occur.

Roy (1972) used March and April soil temperature at 30 cm as an indication of the date of heading of perennial rye grass. Camlin (1975) studied nine cultivars of the same species. He found that soil temperature at 10 cm during March and April affected the date of heading of early varieties but that the later varieties were influenced more by soil temperatures during May and June.

Keatinge et al. (1979) studied the rate of development of four cultivars of perennial rye grass in relation to a number of weather factors. Temperature was measured hourly by means of a thermograph in a thermometer shelter near the surface. This gave the air temperature at 10 cm, about the height of the apices in the grass sward. Global energy was also measured hourly. Daily maximum and minimum temperatures at the standard meteorological level were also measured. TRIM was used to calculate hourly TRI units above a temperature threshold of 0°C. It was also used to calculate daily TRI units above zero, using daily maximum and minimum temperatures. The authors concluded that photoperiod may have triggered the initiation of floral apices and that temperature affected the rate at which these progressed to the point where the heads or ears were visible. Hourly TRI units gave only a slightly better measure of the predicted date of heading than did daily TRI units based on standard measurements of maximum and minimum temperatures. It was considered that the latter would be more useful as standard data are more readily available. Accumulated sums of global energy provided mixed results but were not considered as useful for prediction purposes as standard temperatures.

4.3 Crop testing

Plant breeders are well aware that cultivars, hybrids or varieties of commercial crops can be bred or selected which will have certain characteristics for avoiding undesirable weather situations. Maize hybrids have been developed which mature sufficiently early to avoid freezing temperature damage before maturity in many areas where maize could not be grown 15 to 20 years ago. In crops such as sunflower it is desirable that flowering take place at a time when heat and drought stress are least likely. Most cereal crops benefit from a cool period at about the time of jointing or tillering. These and other climatic requirements of crops demand that some knowledge of the influence of weather on the rate of crop development be not only understood, but used to estimate the time of jointing, flowering, maturity and other weather-sensitive stages in order to take advantage of periods of good weather and to avoid periods of bad weather during the cycle of weather events as they unfold during the course of the growing season. To this end agronomists and agrometeorologists have studied and tested numerous genotypes of various crop species in order to characterize their rate-of-development response to various weather factors.
Maize development has been studied extensively in Canada and Europe mostly because of the interest in classifying hybrids as regards their maturity date near the climatic limit for the crop. Primaut (1969) used four hybrids (or varieties) in the development of his biometeorological model (Eq. 3.25). He found that there were different threshold temperatures and different summation constants (indices) for the different hybrids and their phenological periods. Hunter et al. (1974) tested four varieties of maize under controlled environmental conditions using three levels of temperature and five levels of photoperiod. Results indicated that each variety had a different response to temperature and photoperiod. Unfortunately, the data were analysed by linear multiple regression, using the number of days from emergence to tasselling as a dependent variable. With this procedure it was not possible to evaluate either the effect on the rate of development of temperature and photoperiod or their thresholds. Baron et al. (1975) used three hybrids in their study of the relation of corn maturity to climatic factors. They showed that kernel moisture as a measure of maturity could be influenced by different factors in different hybrids.

Sunflower varieties have also been studied as to their rate of development response to environmental factors. Robinson (1971) studied six varieties, sown at different dates over a period of years, primarily to evaluate their response to TRIM (Eq. 2.10). It was found that TRI units (threshold 7.2°C) summed over the period sowing to maturity varied less than day summations among both years and dates of sowing, yet showed the same range of differences among varieties. TRIS units for the six varieties ranged from about 1300 to 1400 units. No attempt was made to determine threshold temperatures for individual varieties.

Doyle (1975) studied the influence of temperature and day length on sunflower phenology in order to define potential new areas for the crop and to determine the optimum sowing dates. Four cultivars were sown at different dates over a period of three years. Artificially extended photoperiods were used. Various threshold temperatures were tested and 1.0°C was selected as best for all cultivars combined. TRIS units from sowing to first anther ranged from 1245 for the earliest to 1439 for the latest of the four cultivars. Photoperiod had a small and negligible effect on the rate of development.

Goyne et al. (1977) studied two cultivars by using monthly sowings over two years and testing the results using independent data for four years. He used the TRIM and determined the threshold temperature for each cultivar. One variety, SUNfola, had a threshold temperature of -1.3°C while the other, Hysun, had a threshold of -5.9°C. The latter was also photoperiodically sensitive over the range of day lengths experienced during the period emergence to head visibility. It was considered that this difference in response to photoperiod by the two varieties was largely responsible for the varietal variations in the rate of development.

Soybean varieties have been studied for their differences in the effect of environmental factors on the rate of development. Brown (1960) used two varieties, both of which had a positive rate-of-development response to night length and to temperature. The model he used was discussed in Section 3.3 (Eq. 3.14). It appeared that both varieties had the same threshold temperature and rate of development per degree of temperature up to about 21°C. Above 21°C the response levelled off to an optimum at about 30°C and there was a small but statistically non-significant difference in the response of the two varieties.
Major et al. (1975) made a comprehensive study of the effect of temperature and photoperiod on the rate of development of ten varieties, consisting of two cultivars in each of five maturity groups. He had data from several dates of sowing at several sites over a number of years. A model similar to the tri-quadratic model (Eqs. 2.35 and 3.20) was used to determine the effect of daily mean temperature and photoperiod on rate of development during five phenological periods. It was demonstrated that there was a range of responses by different cultivars in different phenological periods as evidenced by different values of the threshold and optimum values of temperature and photoperiod.

Medics have been studied in Queensland, Australia, as there was a problem there of field behaviour of the crop during the mild winter and the need to predict developments under such conditions. Clarkson and Russell (1979) studied two varieties, using a quadratic form of TRIM (Eq. 3.10). It was possible to determine different response characteristics between the two varieties during three phenological periods. One of the varieties was also affected by a vernalization constraint.

Sorghum does not appear to have been studied as much as other crops regarding its rate-of-development response to environmental factors. Sierra and Murphy (1977) used a unique model involving special non-linear functions of temperature and photoperiod which they applied to the classification of 14 cultivars. They were able to divide these into three main groups and three sub-groups according to their response to temperature and photoperiod.

4.4 Time scale for yield models

It has been shown time and again that crops do not progress from sowing to maturity according to a fixed calendar time scale. Instead, the time span from one phenological stage to another is influenced by at least temperature and photoperiod. Since temperature varies from year to year as well as from place to place, and with date of sowing at the same place, while photoperiod varies from place to place as well as from one date of sowing to another, it follows that the rate of development of crops or their time span from sowing to maturity will vary from place to place, from year to year and even for different dates of sowing at the same place. Thus Robertson (1968) recognized the need for a biometeorological time scale (BMTS) against which to mark the advancement of crops towards maturity and which would have the same numerical value no matter where or when the crop was grown.

The value of such a time scale, whether it is in the form of the BMTS, TRIS units, or development indices, for zonation, planning and operational purposes or for characterizing the rate of development of crop species and varieties, has been demonstrated. Another use for the BMTS is in crop-yield modelling (Angus and Zandstra, 1980; Stansel and Fries, 1980). Here it is important to relate yield at harvest time to certain environmental factors such as water stress, temperature and global energy during different phenological periods (biological time intervals).

In early warning systems and other practical operational uses where it is not always possible to observe phenological stages (biological time), a development model is essential. Since the BMTS can be calculated using the same source data as are used in weather-based crop-yield models, it is convenient to build a BMTS into the yield models. This was done by Baier (1973) in his tri-quadratic model for wheat yield. In their review of crop-yield literature, Doraiswamy et al. (1979) discussed the need for some form of a
BMTS. Hodges et al. (1979) reviewed a number of techniques for calculating the dates of phenological stages for use in yield models for a number of commercial crops.

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Chapter 5

Conclusions

5.1 Recapitulation

Models for relating the rate of development of the crops to environmental factors are required for a number of practical reasons. These include crop zonation, land-use planning, management and operation of enterprises dealing with the growing and processing of perishable food crops, characterizing new hybrids and genotypes regarding their climatic requirements and as an estimate of the biological time scale for use in crop-yield models.

The development of a plant consists essentially of changes in its morphological structure and accompanying biochemical activity. These changes include seed dormancy, seed germination, development of the vegetative primordia, differentiation of the floral primordia, rapid stem elongation, flowering, pollination, and the setting, filling and ripening of the seeds. These changes are triggered and controlled by the production of various hormones, most of which are temperature-sensitive and some of which are photosensitive to very low light intensity. Nutrients and water stress may also have some influence on the production of the hormones. Thus the development of crops appears to be regulated primarily by external environmental factors of temperature and length of photoperiod, and possibly in some cases by water stress and nutrition.

Development, which is the progress of the crop through its various phenological stages, must be distinguished from growth, which is the process of the accumulation and translocation of photosynthesized matter, controlled mainly by water stress, nutrition and intensity of irradiance.

It is not surprising then that the rate of development of most crops is influenced primarily by temperature. Where crops are grown in regions of extreme temperatures, the rate-of-development response may be curvilinear instead of linear because of the deleterious effect on hormone production of temperatures above a certain optimum value. Models relating rate of development to temperature have only a limited reliability but may serve a very useful purpose in local areas where conditions other than daily temperatures are fairly uniform.

If rate-of-development models are to be used over a wide area covering more than one climatic zone and several degrees of latitude, then a photoperiod term, possibly a water-stress term, and curvilinear response functions for temperature and photoperiod may be desirable. Since maximum and minimum temperatures and their ranges differ from region to region and since some crops respond differently to day and night temperatures, it is preferable to use models embodying both.

Analyses of the effect of temperature and photoperiod on the rate of development during individual phenological periods for various species and varieties indicate that each period of each variety and species may have its own characteristic response to temperature and photoperiod. This is evident when using the more complex models (Major et al., 1975; Robertson, 1968; Williams, 1974).
The tri-quadratic model of Robertson (1968) appears to have the potential for universal usage. It makes use of the product of photoperiod (or dark period) with representative day- and night-time temperatures. Photoperiod and the two temperatures can be given a curvilinear form, allowing for the three cardinal points of developmental response to temperature and photoperiod. Characteristic coefficients are evaluated for each major phenological period in the development of a crop. Although the model itself appears to have universal potential, the characteristic coefficients must be determined for each species and variety, since each may respond to the same environment in a different manner.

Models have several practical uses in agricultural activities and in agrometeorology. Maps and charts of the results of the various models have been used extensively for land-use decisions and crop-zonation purposes. They are also used by the growers and processors of perishable crops for planning field sowings and monitoring the time of harvest to provide a uniform flow of prime produce to the processing plant. Models have also been used for characterizing the length of time to maturity of a number of varieties of various species of grain crops. Crop-development models can be used as sub-models for calculating biometeorological time scales in other models for calculating the effect of various environmental factors on crop yield, for crop-yield forecasting, and for use in early warning systems.

5.2 Research suggestions

Temperature is the single most important factor in weather-based crop development models. In most models reviewed, this factor was obtained from the standard maximum and minimum temperatures, as measured in the meteorological instrument shelter. It is felt that better temperature terms in all models would result if some measure of actual crop-tissue temperatures were used. Since this temperature cannot easily be observed on a routine basis, it is suggested that a model should be developed for estimating, from standard meteorological observations, the effective day-time and night-time temperatures of the crop’s developing tissue. Robertson (1953) made an attempt to do this but the idea does not appear to have been put to practical use (Eq. 3.27 and Section 3.4.3). Now that high-speed computers can handle such problems with ease it appears logical to pursue this problem further.

Information from the infra-red bands of meteorological and LANDSAT satellites are increasingly being used for estimating crop surface temperature (Byrne et al., 1979). Such information might well be used as input to TRIM and models of the photothermal type in place of the meteorological air temperature.

Some crops have a very definite photoperiodic (long day or long night) response which has been successfully worked into certain types of model. Most models which include a photoperiod term consider the photoperiod to be day-length taken from astronomical tables. The photoperiodic response of crops takes place in very weak light, possibly nearer the intensity at the beginning or ending of civil twilight (when the sun is six degrees below the horizon) than the intensity at sunrise or sunset. Such a consideration might be important when working with a single variety of a crop over a large area such as the Canadian Great Plains. Only one paper was reviewed in which civil twilight was used (Doyle, 1975).
A further point to consider about the duration of the photoperiod is its variability as affected by cloudiness during the civil twilight period. Thin high clouds might effectively lengthen the period while heavy overcast conditions might shorten the period. Research on a model to estimate such influences on the length of the photoperiod might improve models for some crops.

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