MATCHING THE CROP TO THE ENVIRONMENT

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ABSTRACT

Agronomists and breeders must often attempt to answer the questions: what crops can be grown productively in a given area, and where is the best place to grow a given crop? Both questions require the same sort of information on the environment and on the nature of crop response to the environment.

The objectives of this paper are to outline some of the ways in which crop growth can be related to climatic factors in general, and temperature in particular, and to illustrate some of the possible benefits.

In New Zealand in recent years, the importance of matching crops to the environment has grown because of the increasing diversification of agriculture and horticulture in many areas. Despite this, few of the available techniques are being used in New Zealand either in research or in crop production.

INTRODUCTION

Agronomists and breeders must often attempt to answer the questions:

(i) What crops can be grown productively in a given area?

and

(ii) where is the best place to grow a given crop?

To answer these questions we need to determine the responses of crops to environmental factors. In response to the first question we can use knowledge of the environmental factors in a given area to decide if these match crop requirements. In the case of the second question we can use our information on the response of a crop to identify the appropriate environments in which to grow it.

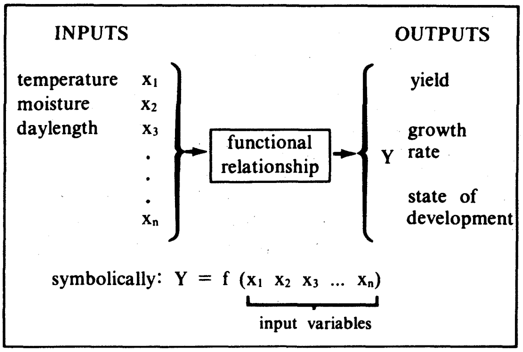
The objectives of this paper are to outline some of the ways in which crop growth can be related to the weather in general, and temperature in particular, and to illustrate the manner in which these relationships can be used to match crops to the environment. Strictly, our concern is with the "climate" as well as "weather". The former applies to average conditions over decades or more, while the latter applies to variations about this mean over shorter periods. For convenience we use the terms interchangeably.

CROP-WEATHER MODELS

A large and complex literature confronts the scientist who wishes to relate crop production to the weather. Numerous relationships have been used for this purpose and the choice of the best or most appropriate relationship is not clear-cut. In this section, we shall discuss some of the features of crop-weather models which have a bearing on this choice.

All methods of relating crop production to climatic factors share the characteristics shown in Fig 1. Climatic factors are conceived as inputs which drive the crop-weather system. The output of the system is some aspect of crop production such as yield, growth rate, or stage of development. Connecting inputs with outputs is a functional relationship, a crop-weather model.

Figure 1



In most general terms, the scheme shown in Fig. 1 can be described using the notation

$$Y = f(x_1, x_2, x_3 \ldots x_n) \qquad (1)$$

Here, Y is an output (yield, growth rate, stage of development), which is related to climatic factors, x_1 to x_n according to some functional relationship, f. Equation (1) symbolizes all models of crop-weather relations. The word model usually implies a relationship between effects and causes but it may also be used for statistical descriptions of systems. As Baier (1979) points out, both sorts of models are used in crop-weather relations, often without clear distinction between the two. For our present purposes it is sufficient to regard a model simply as any equation containing climatic factors as inputs and crop production as an output.

Inputs

The inputs for crop-weather models usually come from meteorological records. These include directly-measured data and scored data. Most of the latter (e.g. percent cloud cover) are of little use in crop-weather models and some of the former (e.g. wind run and direction etc.) are of limited value. The records of most value are of temperature, solar radiation and rainfall. Since these factors vary in time, some form of summation or averaging is required before they can be used as inputs. Thus, daily average temperature, cumulative daily radiation or cumulative rainfall are the usual forms in which these factors are used.

Standard meterological observations are normally used in crop-weather models. However where local effects are important, it may be necessary to improve on the standard data. For example, topographical influences in hill country may produce microclimates on sunny and shady faces which differ from each other and the nearest recording site. The resulting effects on crop growth of such differences can be substantial (e.g. Sithamparanathan, 1979). However the effects are often systematic and can be allowed for (e.g.Bootsma, 1976).

Where the standard data cannot be adjusted in this way it may be more feasible to make direct routine measurements of the environment on site. Electronic integrators, for example, can be used to establish time averaged values for selected factors and small, battery operated data loggers with solid-state memory can be used for recording the time course of several variables.

Outputs.

Various types of output are used in practical applications of crop-weather relations, and these are illustrated in Fig. 2. Where the output is yield or growth rate, it is a direct step conceptually to relate these to climatic inputs because both inputs and outputs are continuous variables. However, the relationship between climatic inputs and phenological events, such as the initiation of spikelets or attainment of grain maturity in a cereal (Fig.2), is less obvious, since the occurrence of these events is discrete whilst the climatic factors change continuously. Implicit in phenological models is an abstract quantity which is called here a "state of development". This state alters continuously with time until it reaches a critical level at which point the phenological event occurs. Although the "state of development" may have a physiological basis (Landsberg, 1977), it is more often a concept which is merely implicit in empirical models.

Functional relationships.

It is convenient to classify into four groups, the functional relationships which have been used to relate inputs and outputs in crop-weather models. We shall call these (i) truth table, (ii) additive, (iii) multiplicative, and (iv) limiting factor relationships.

The simplest of all relationships between climatic factors and crop production is a truth table (Fig. 3). This is based on the idea that there are critical levels for a number of climatic factors in crop production and that all these levels must be exceeded before the crop can be grown successfully. Truth tables are commonly used to establish the likelihood of successful crop production in new areas. For these sites each climatic variable is assessed, and only if *all* variables meet the required conditions, is the site considered to be suitable for the crop. Thus the truth table approach is used to distinguish a "succeed/fail" situation for crop production (Fig. 3). Hurnard (1978) used the truth table approach to assess the suitability of a number of regions for grape production in New Zealand.

Figure 2

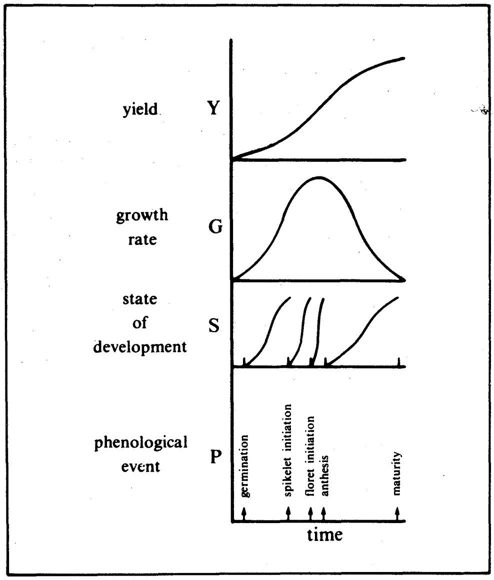
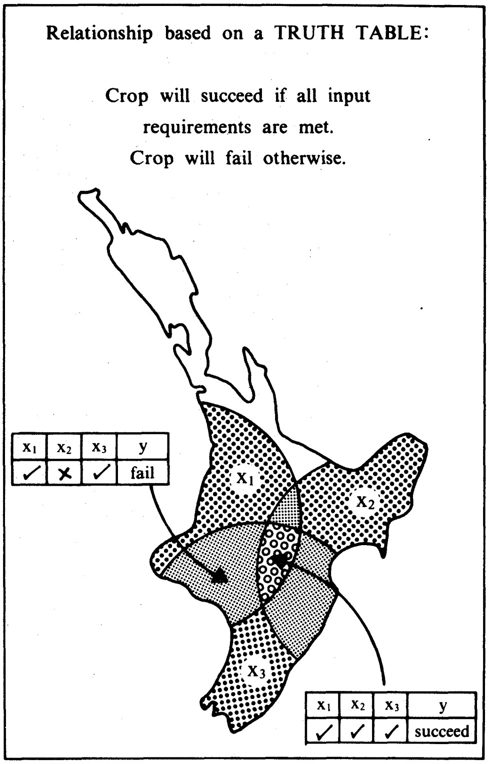
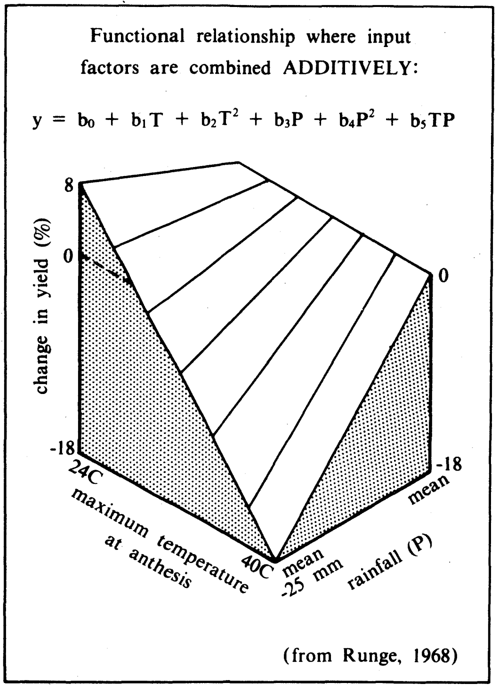


Figure 3



The second type of functional relationship commonly used in crop-weather studies is an additive combination of climatic factors. An example is shown in Fig. 4. In this case, a multiple regression has been used to relate to maize yield the two input factors, maximum temperature at anthesis, and seasonal rainfall. The method used by Runge (1968), enables variations in yield at specific periods in the growth of a crop to be explained in terms of deviations of climatic factors from average conditions.

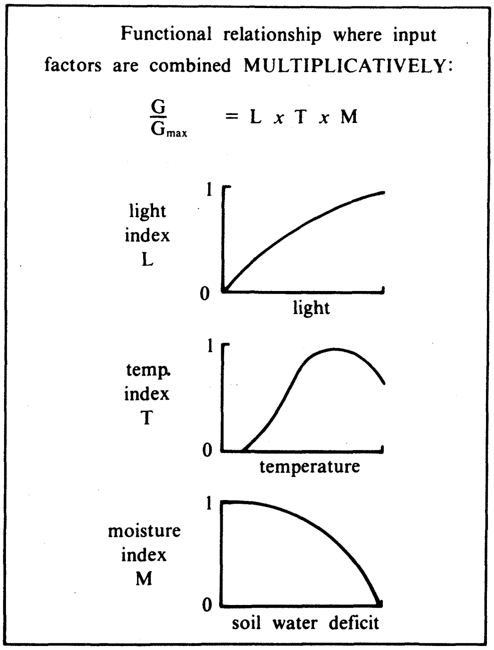
Figure 4



(from Runge, 1968)

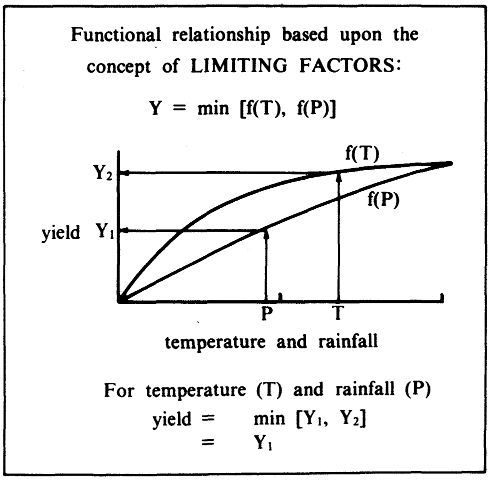
Multiplicative functional relationships are the third type used in crop-weather studies. In this case, crop responses to individual climatic factors are assumed to combine multiplicatively to give an overall crop response (Fig. 5). It is usual to normalize individual climatic responses to form indices which scale from zero to one. Thus if any of the indices is equal to zero, the multi-factor index is zero, whilst if all are unity, the multi-factor index is equal to its maximum possible value of unity (e.g. Gmax in Fig. 5). This approach has been used by Fitzpatrick and Nix (1970) to examine the combined effects of temperature, water and light on sorghum growth and similarly by Field (1978) in studies of pasture production, and by many others.

Figure 5



A fourth class of functional relationship used in crop-weather studies is based upon the concept of limiting factors. Here, as in multiplicative relationships, individual crop responses to climatic factors are required. In a situation where an evaluation of a crop response to a number of factors is required, the outputs of each function relating crop performance and a climatic factor are determined and the predicted crop performance is taken as the smallest of the outputs. An example involving temperature and precipitation is shown in Fig. 6. In common with truth tables and multiplicative indices this approach makes no allowance for interactions among variables - for example, the situation where the minimum rainfall required for growth may be higher at high temperatures because of higher evapotranspiration rates. However, more elaborate forms of limiting factor analyses are possible and the approach is often the basis of computer simulations of crop growth.

Figure 6



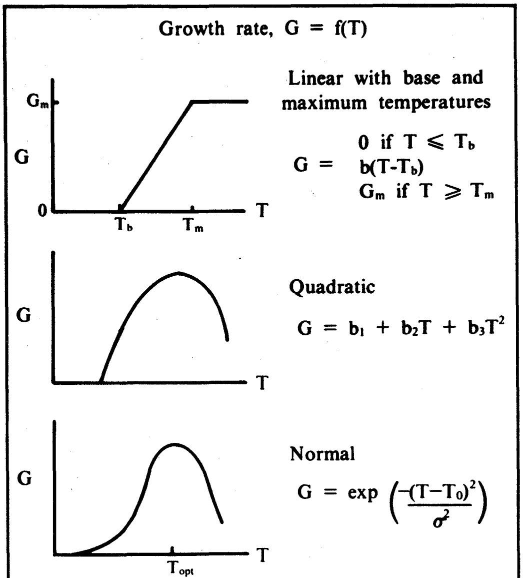
The classification given above is intended only to illustrate the types of relationships which are used in crop-weather studies. Many alternative classifications are possible (Baier, 1979). The key point is that more than one climatic factor is commonly required to relate crop production to the envrionment. Under these circumstances, functional relationships of the types outlined above must be used. However, in many situations most of the variability in crop performance can be related to a single climatic factor. Relationships of this sort have been developed with water (de Wit, 1958; Nix and Fitzpatrick, 1969), light (Monteith, 1977) and temperature. In the next section, relationships specifically between temperature and crop production will be discussed.

TEMPERATURE MODELS

For a long time it has been understood that temperature has an important influence on plant growth and phenology. Agronomists have tended to focus on phenology or the timing of key events such as germination, flowering and grain maturity. Attempts to quantify these effects go back 250 years. Physiologists have put more emphasis in the past on growth. However there is increasing recognition that growth and phenology have important interactive effects on yield.

A number of equations have been used to relate temperature to crop production and some of these are illustrated in Fig.7. In all cases, the basic relationship is between a rate of growth or development (taken as growth rate in these examples) and temperature. Linear relationships are most commonly used in agronomy and take many different forms. For example, 20 different kinds of linear relationship between temperature and flowering dates for maize are discussed by Cross and Zuber (1972). Quadratic and normal relationships reflect the type of response which is common in physiological experiments (Mitchell and Lucanus, 1962; Lansberg, 1977). The "Ontario heat units", which are sometimes used in agronomy, are based essentially upon a quadratic response (Brown, 1960). The Arrhenius equation has a theoretical basis in physical chemistry and is only rarely applied in plant physiology or agronomy, and then usually via the related Q_{10} concept (Christophersen, 1973) which gives the ratio of two growth rates measured at temperatures 10C apart.

Figure 7

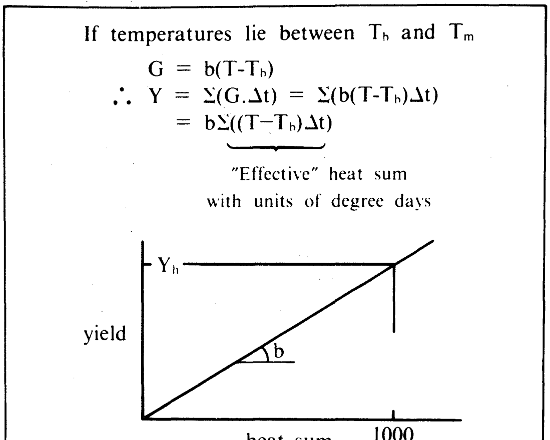


Where it is necessary to determine the timing of phenological events or accumulation of yield, the basic temperature-plant response equations which are expressed in terms of a rate (Fig.1) must be integrated (summed) over some period of time. This will be illustrated first in terms of yield because the concepts are more straight-forward. Consideration will then be given to phenology which has been the more common area of application.

The method is illustrated in Fig. 8 using, as an example, the linear relationship of Fig. 7. Here, the sum of growth rates over a number of time intervals, Δt, is yield, and this is related to the heat sum, or the product of days times temperature above some base temperature. As the heat sum involves both temperature and time the term "degree days" is often used. Other terms include "heat units", "growing degree days" and "growth units".

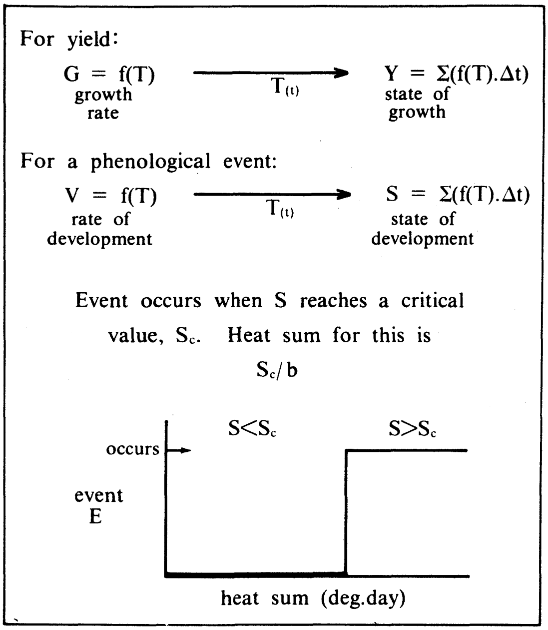
For convenience of presentation, we have illustrated the heat summation method using growth rate and yield. It is more usual to relate the

Figure 8



accumulating heat sum to phenological events, as shown in Fig. 9. Here, a state of development is linearly related to the heat sum and a phenological event, E, occurs at some critical value of this state and, therefore, at some critical heat sum. This is the key idea behind the heat sum method; if growth or development rates are functions of temperature, then a heat sum will be a more reliable indicator for the occurence of phenological events than calendar days. Wang (1963) provides a useful introduction to the concept of heat units and reviews early work.

Figure 9

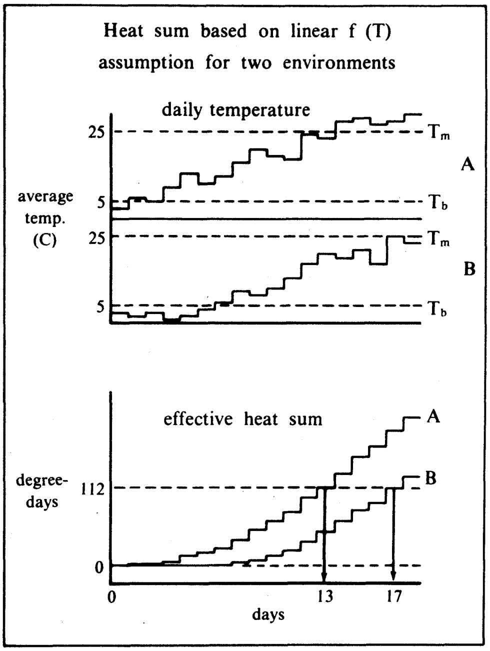


The accumulation of degree days for a "warm" and "cold" environment is illustrated in Fig. 10. It is apparent that any critical heat sum (related for example, to a phenological event) will be reached sooner in the "warm" environment than the "cold".

It is important to realise that although the heat sum can be related to a physiological basis, the method is essentially empirical and the equation and constants which give the best results for the particular crop and range of temperatures likely to be experienced should be used. The selection and development of heat sum models is discussed by Arnold (1959, 1960). He points out that the appropriate values of "b" (Fig. 8) for different cultivars may differ. For this reason "b" is sometimes called "the varietal constant". Other factors such as photoperiod, which can be seasonally correlated with temperature, may influence the choice of the base temperature, T_b. Because the method is empirical it is important that the various constants are established where the crop and environment are representative of the situation that they will later be used in. This needs to be borne in mind when using overseas data and techniques in New Zealand.

Heat sum models are not always adequate by themselves and other factors are sometimes included.

Figure 10



For example, Idso *et al.* (1978) and Selirio and Brown (1979) altered their temperature model by including water stress effects whilst Franquin (1976) and Coligado and Brown (1975) made modifications to include day length.

So far we have discussed temperature models starting with a relationship between growth rate, or development rate and temperature. Such relationships would best be obtained from controlled environment studies where responses at fixed temperatures can be measured and with other variables held constant. These relationships can then be used predictively in field situations. In practise this has not been the most common way of developing temperature response models. Typically agronomists measure the dates of occurrence of a phenological event or attainment of a harvestable yield in difference seasons or sites. They seek to improve upon the predictive value of a calendar date by transforming their time scale to degree days (e.g. Taylor and Hughes, 1979). If a satisfactory relationship is obtained from field data in this manner it can then be used predicitively in other situations.

THE VALUE OF CROP-WEATHER INFORMATION

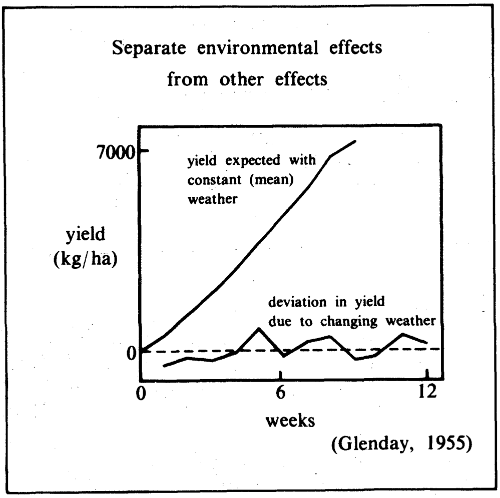
There are a number of ways in which an understanding of crop-weather relationships can be used to provide information that is not otherwise available.

1. Separate environmental effects from other effects

While little can be done about weather-induced variability among sites and seasons, it can be very useful to know what effects that variability is having, and to allow for it in any particular season and at any given site.

The effects of weather on results of field trials can be substantial. Collis-George and Davey (1960) pointed out that failure to allow for the effects of weather can, even in the best circumstances, lead to 20-25% of the total variation being associated with experimental error. The effect of short term fluctuations in weather on pasture yield during a Manawatu spring were assessed by Glenday (1955) from time-replicated experiments. He used a mathematical technique to separate measured yields into components attributable to the mean envrionment for the period and the short term "noise" due to day to day changes in the weather. The relative magnitude of the weather and non-weather effects can be seen in Fig. 11.

Figure 11



(Glenday, 1955)

Allowance can be made for weather variables using analysis of covariance. This technique uses knowledge of the effect of uncontrolled variables on the response variable to make it easier to detect true differences due to treatment (Montgomery, 1976). While used in a number of fields it is seldom used to allow for crop-weather effects.

Rather than seeking to reduce the effects of weather the inclusion of an appropriate range of weather may be planned deliberately. This might affect selection of sites for field trials and suggest the use of sequential plantings. Sites or times of planting may be substituted for years in comparing crop responses and thereby save considerable time and resources. Nix (1975) suggested from his agroclimatic analysis of Australia that "by sowing experimental crops in each month from February to August at a site in western New South Wales (the area of contact between all major climatic divisions) it would be possible to simulate almost all genotype-environment interactions occuring throughout the entire Autralian wheat belt".

An approach which has been used by plant breeders to test the ability of varieties to perform well over a wide range of environments does not require an implicit account to be taken of the environment. The yield of each variety at each of a range of sites is compared with the mean yield of all varieties for each site and season (e.g. Finlay and Wilkinson, 1963). The mean yield for each site and season, in essence, provides an index of the environment. However the value of the technique could be enhanced by using explicit environmental information for selection of the most appropriate range of test sites and to help identify the particular combinations of crop and weather factors which are most important in regulating yield.

2. Assess probabilities of survival, phenology or yield.

Past experience can indicate the average performance and the expected range in performance for any particular crop. However, if crop-weather responses are understood, even in a crude way, they expand our ability to assess risks and gains and to adopt the best biological and financial strategies in crop production.

Survival probabilities can be established quite simply where thresholds are clearly defined as is the case with freezing injury. Survival data can be used to define effective season length and this, in combination with heat sum calculations for the growing season can be used to assess crop phenology and yield probabilities. Young's (1973,1974) analysis of 30 years of Lincoln meteorological records demonstrated this by combining a probability analysis with growing degree day summations for an average freeze-free season (Table 1). Weather data could be of considerable practical value if it were made available in this way.

TABLE 1. Growing degree days above a base of 10°C for a given risk. GDD are summed between average spring freeze dates and the dates shown (Adapted from Young, 1974)

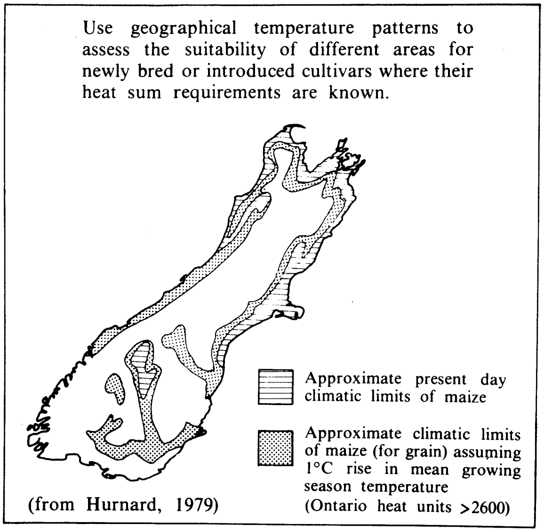
	Probability of receiving at least the number of GDD shown			
To date	19 yrs in 20 (5% risk)	9 yrs in 10 (10% risk)	7 yrs in 10 (30% risk)	5 yrs in 10 (50% risk)
28 Oct	–	2	11	17
23 Dec	148	167	208	236
17 Feb	416	452	528	581
21 Apr	635	680	775	840

3. Assess performance of new cultivars.

New cultivars are continually being developed and introduced into established crop growing areas. If the continuing process of cultivar testing can be improved in efficiency by using weather data to assist in selecting the most appropriate field test sites and allowing for the effects of weather in interpreting results, the potential gains in time and resources saved would be quite considerable.

Crop-weather responses can also be used to assess the likely benefit of making any particular change in crop performance. For example a heat unit analysis, such as that used by Hurnard (1979) to assess the consequences of climatic change (Fig. 12), can be used to assess the potential increase in maize growing areas that would result from any given improvement in maize cold tolerance (Eagles, 1979).

Figure 12



4. The use of "old" crops in "new" areas

A number of established crops are now being grown in areas of New Zealand where they have not been grown before. For example, the area committed to maize, kiwifruit, several process crops, and grapes has been expanding rapidly. New irrigation schemes provide possibilities for crops to grow in areas where they could not before. If energy farming becomes a reality there will be further impetus for changing crop boundaries.

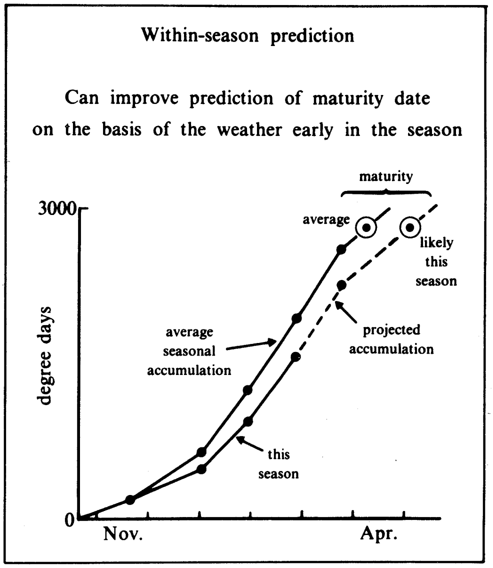
The better the available information on crop-weather responses, the better will be the chances of making these changes effectively. The analysis of Carr and Hough (1978) of the influence of climate on maize production in north-western Europe illustrates the possibilities of this approach. Season length probabilities were estimated using records of soil temperatures to determine sowing dates and air temperature heat sums to estimate maturity in terms of grain moisture content. Probabilities of growing successful maize crops were then presented as a series of maps, using in essence a combination of the approaches used in Table 1 and Fig.12.

In many cases the "old" crops are being introduced from overseas. New Zealand interest has been increasing in crops as diverse as sub-tropical grasses, oil crops, eucalyptus and blueberries. Analysis of crop-weather responses can help in deciding on the areas of origin that the introductions should be made from. For example, in seeking the best provenances of *Eucalyptus regnans* for use in New Zealand, Rook *et al* (pers. comm.) found signficant differences in frost tolerance using controlled environments for screening. These differences correlated well with temperature-related features of their various sites of origin in Australia. Climatic criteria for the introduction of plant material is discussed in general terms in this symposium by Dawes (1979).

5. Within-season prediction

The ability to predict occurences such as harvest dates on the basis of the season's weather to date, can allow more effective scheduling of harvesting and processing operations. Fig. 13 shows how a degree day analysis can be used in predicting maturity date part way through the season with a precision substantially greater than could be achieved at planting time. Some of the implications of scheduling for horticultural crops are discussed by Gurney (1977).

Figure 13



CONCLUSIONS.

Considerable benefits can accrue from improving our description and understanding of crop-weather relationships. These benefits can be expressed in the areas of research, development, production and processing. They can be used with existing systems of production and help in the search for new ones.

Many approaches have been used to help match crops and environment. Which is the most appropriate will depend on the extent to which an immediate, engineering-type solution is required, or the extent to which an advancement in understanding is sought. We believe there is scope for making more use of crop-weather relationships in agronomic research in New Zealand.

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