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

by

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WMO, CAgM Rapporteur on Application of Models and
Forecasting of Development and Ripening of Crops

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MODELS AND FORECASTING OF DEVELOPMENT AND RIPENING OF CROPS

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FOREWORD

The Seventh Congress of WMO (1975) approved extended agrometeorological activities in aid of food production. Among the activities planned for implementation was the provision of advice and information on crop-weather relationships and models for developing countries. Towards this objective, an Expert Meeting on Crop-Weather Models was organized by WMO in Ottawa, Canada, 11-15 October 1977. One of the outcomes of this meeting was the recommendation that WMO form a Task Force on Crop-Weather Models and its Applications to Developing Countries. The terms of reference for the Task Force included the preparation of a manual on crop-weather models which would provide guidelines, particularly for developing countries where there is a noticeable lack of expertise on the subject. The seventh session of the Commission for Agricultural Meteorology (Sofia, September 1979) noted the establishment of the Task Force for the preparation of a manual on crop-weather models. The Commission was of the opinion that such a manual should draw special attention to the simple models which were already being used in many countries. The Commission further expressed concern over the non-availability of relevant data, including both meteorological and biological, in developing countries.

The Task Force agreed to prepare a summary of a number of models used in practical applications (see Chapter 3) and to provide adequate references and the names of contacts for those seriously interested in further pursuit of detailed information. Mr. George Robertson (Canada) served as the editor for this important task.

It is my pleasure to express the gratitude of the World Meteorological Organization to the following members of the Task Force who made valuable contributions to the various sections of this guide: Mr. M. Frère (FAO), Prof. Dr. H. Hanus (FRG), Dr. H. von Keulen (Netherlands), Mr. Koniijn (IASSA), Mr. H.A. Nix (Australia), Dr. D. Payen (France), Mr. G.W. Robertson (Canada), Dr. C.M. Sakamoto (U.S.A.), and Dr. O.D. Sirotenko (U.S.S.R.). Our grateful thanks are also due to Dr. W. Baier (Canada), the previous president of CAgM, who was instrumental in the establishment of the Task Force on Crop-Weather Models, for his personal contribution during the Expert Meeting and in the framing of the terms of reference of the Task Force in 1977. I also would like to place on record the appreciation of WMO to Mr. N. Gerbier, President of CAgM for his interest and cooperation in producing this publication.

Further, the Task Force recommended that the preparation of an open-ended handbook on the practical applications of models (data and methodology) to agriculture should be undertaken by WMO. Detailed descriptions of individual applications could be added to such a handbook from time to time as material and authors become available.

T. D. Potter
Director, WCP
for the Secretary-General
SUMMARY

Crop-weather modelling, the numerical interpretation of weather data in terms of crop development, growth and production, has many uses in agriculture. Among these are land use evaluation, crop adaptation, crop monitoring and forecasting, crop management, pest and disease control, and the planning of research strategy.

Although great advances in the understanding of the processes of energy and mass exchange in crop growth have led to very sophisticated mechanistic and dynamic models, the traditional empirical-statistical models continue to be developed, mainly because they can be made to operate with a minimum of readily available data. Their reliability, however, is compatible with the generality of their form and with that of the limited data on which they are based. For this reason they are usually only applicable to the local conditions for which they were developed. Dynamic models can be made to simulate the day-to-day assimilation of photosynthetic material based primarily on the exchanges of energy and mass among the various growth processes taking place in a plant. Such models may be very complex and demanding of both biological and meteorological data. They are most useful for studying the physiology of crop growth and development.

Over the past 15 years a vast assortment of models have been developed for various agrometeorological purposes. These all vary somewhat one from the other, depending on their application to a specific agricultural problem. Since it is impossible to describe all of these in detail in a technical report of this nature, a few examples are given which illustrate the application of models to the several problem areas in agriculture. The examples include a brief discussion of: (a) the problem area; (b) the objective; (c) model description; (d) computer requirements; (e) scale; (f) data requirements; (g) validation and application; and (h) limitations and remarks. These examples are supported by references to the scientific and technical literature on which they are based and the addresses of individuals who may be contacted for assistance with the application of a specific model to the user's problem.

A good data base is essential for the successful operation of any model, yet one of the most serious problems in agrometeorology is the lack of adequate data. Thus, before making use of any model it is necessary to carefully consider the available data. There are a number of ways in which missing information can be generated from fairly basic data. These include spatial and temporal interpolation techniques and the preparation of grid data; algorithms for calculating derived information such as soil water, evapotranspiration, and phenological dates; and techniques for simulating missing observations. Remote sensing is a promising new technology for providing certain data over wide areas including cloud cover, surface temperature distribution, and the distribution of growing crops.

Finally an extensive bibliography of over 200 items supports the material in this Technical Note.
CHAPTER 1

INTRODUCTION

1.1 General

Interpretation of weather in terms of crop development, growth, and production is the main purpose of numerical crop-weather models.

Numerical interpretation of weather data has many uses in operational and scientific agriculture. Some of these include land-use planning, crop zonation, management strategy, crop-physiological and morphological studies, genetical plant engineering, climatic-impact assessment, irrigation-water management, and forecasting crop development, maturity, yield, and production. In fact, for any agricultural enterprise wherein weather is thought to influence the final results, a numerical model will provide a more rational and objective interpretation of weather's influence than mere subjective guesses and considerations.

There are various types of models, each meeting the specific requirements of the weather sensitive agricultural problem in question. Predicting the maturity of canning crops, such as corn and peas, may require only a very simple temperature remainder index model (TRIM) (Robertson, 1982). For irrigation planning and management, a simple soil-water model may suffice. The study of crop physiology and morphology for genetical-engineering purposes may require a more complex mechanistic model. Empirical-regression models using simple weather data are required for many problems in land-use and crop zonation planning and in climatic-impact evaluations, whereas dynamic models are required for continuous crop-condition surveillance systems as used for early warning purposes.

Crop-weather modelling involves the consideration of two processes in the life cycle of the crop leading to the final harvestable product: (a) the influence of weather on crop growth, i.e. the accumulation of the products of photosynthesis, and (b) the influence of weather on crop development, i.e. the progress of the crop through various phenological stages during its life cycle from seeding or primordial initiation to maturity (Robertson, 1982). Most models, particularly those of the dynamic type, consider these two processes simultaneously by calculating net photosynthesis during various development stages (Malet, 1980).

The yield and production of crops are affected, not only directly by the influence of weather, but also indirectly by the influence of weather on the population dynamics of insects and diseases which are destructive to crops. Models are used, therefore, for estimating the effect of weather on the outbreak of epidemics of insects and disease, not only for estimating their effect on crop yield and production, but also for their control.

Different model types require different input data. The mechanistic type is most demanding of detail, requiring specific morphological and physiological observations on the biological side and special micrometeorological measurements taken within the crop on the physical side. The empirical-regression models require the least data detail but large amounts of data are needed for the least-squares calculations and for coefficient evaluation and testing.

Submodels are frequently required for converting basic weather data, such as rainfall, to crop-related factors which are more compatible with the known crop response to specific environmental factors such as available soil water or internal crop-water stress.
Remote sensing is a promising technique for providing both crop and meteorological information over large areas in a very short period of time. Remote sensing by earth resource and meteorological satellites holds forth a great potential for use in connection with global crop- and weather-surveillance systems. However, technology is complex, and both data acquisition and computer processing are expensive. Many models for data interpretation are still imperfect for real-time operational purposes on a routine basis. A great deal of research and development in this area is still required.

Great care must be exercised in selecting or developing a model to assure that it suits the purpose for which it is to be used. Not only must it provide answers which can be interpreted for practical purposes, but it must also be compatible with readily available data or with the facilities for obtaining special data. The need for computer and analytical facilities must also be carefully considered as well as facilities for data transmission and for the timely communication of final information and reports to the proper decision-making authorities.

In the following chapters of this guide, experts in various areas of crop-weather modelling discuss the types of models, their specific uses, advantages and shortcomings, data and computational requirements, and the interpretation and use of analytical results. Submodels for calculating special derived data and for areal interpolation are also discussed. Emphasis is placed on practical applications with actual examples.

Special attention is given to the application of models to problems in developing countries. Examples of model applications are supported by references as well as by a list of contacts who can offer assistance to prospective users of models. An extensive bibliography is also given which contains references to additional supporting and relevant technical papers.

1.2 References


CHAPTER 2

TYPES OF MODELS

2.1 Introduction

In recent years our knowledge concerning the environment-crop system has become much better and has been greatly extended. Considerable advance has been made in understanding the processes of energy and mass exchange and in determining the level of productivity of the ecosystem. Progress has been made in understanding such important physiological processes in plants as photosynthesis, transpiration, growth and development. Practical attempts to integrate this new knowledge has been incorporated in the form of dynamic models used for estimating the productivity of agricultural crops. At the same time, traditional empirical-statistical models, based on the direct statistical processing of data on yield and factors affecting yield, continue to be developed. Such investigations have been particularly revived due to possibilities of making use of new aerospace methods for the collection of data. These statistical models are also needed in areas where data availability may limit other forms of model development.

2.2 Methods

In its simplest form, climatic data can be analysed to provide information for problem applications. For example, weather data can be compared with the preceding year, with the average of several years, or with high and low crop yielding years (Ferre and Popov, 1976, 1979; Steyaert et al., 1978). These simple procedures can also be used under limited data conditions, e.g. in developing countries, where only small samples of weather and yield data are available.

The usefulness of these models increases as the correlations between single weather factors (e.g. precipitation) and yield increases. Results of the procedures described give only relative information with a high possible error which decreases, however, as additional data become available. Consideration of the range and the probability of the recorded deviations in the weather conditions may also increase the reliability of the estimations. When sufficient weather data are available, it is possible to put the environment-crop system into quantitative terms, described by models. Three types are briefly described.

2.2.1 Empirical-statistical models

The papers by R. Fisher (1924) and W. M. Obuhov (1949) are examples of basic works in the field of finding empirical-statistical relationships for calculating yields. Fisher showed that when the number of potentially influencing factors is of a certain order, the number of observations must also be of the same order or higher. This led to the concept of the degrees of freedom. Obuhov made wide use of multiple regression analysis for studying the influence of meteorological conditions on yields. This type of analysis is used quite extensively in models of the linear-regression type, expressed in the form:

\[ \hat{y} = a + \sum_{i=1}^{n} B_i \times x_i \]

where \( \hat{y} \) is the estimated yield, \( a \) is a constant, \( B_i \) (i=1 to n) are coefficients and \( x_i \) are the n factors influencing yield. The symbol \( \times \) signifies multiplication.
These factors include meteorological conditions, averaged over phenological stages or calendar periods; certain crop conditions such as height, density, phytomass, leaf area and so forth; information on soil characteristics; and, in some models, information on management such as amount of applied fertilizer and disease control. The crop, management and soil conditions do not readily lend themselves to quantitative evaluation and, therefore, cannot always be included as discrete factors in the empirical-statistical model. Thus the relationships are frequently localized. It is axiomatic that regression models should not be extended outside the data set and location for which they were developed.

The use of regression analysis can be limited by the lack of sufficient crop yield data and by its lack of uniformity and consistency (Sirotenko, 1981). Technological advances, including varietal changes and the increasing use of chemicals in agriculture, result in historical crop yield data quickly becoming out of date.

A special problem with multiple-regression techniques is the possible high correlations among the independent variables (multicollinearity), which can result in misleading variable selection with statistical methods. Special techniques can be used, however, to address this problem, e.g. principal component analysis (Sirotenko, 1971). The essence of this method consists of changing the initial set of variables to a new set in which the individuals are uncorrelated (orthogonal). Since multicollinearity does not apply to this new set of variables, multiple regression techniques can be used to select those giving the most information. The final regression equation is derived from these. In many cases stable prognostic relationships for small samples are achieved. However, this method cannot be used in all cases and it only enables some of the afore-mentioned difficulties to be overcome to some extent.

Other techniques include the generalized inverse regression (Marquardt, 1970) and ridge regression (Marquardt and Snee, 1975; a bibliography of ridge regression is given by Allredge and Gilb, 1976). These procedures are aimed at estimates with higher precision and more stable coefficients in the regression equations. They are also used in cases where the basic data do not fulfil pre-conditions for the application of multiple regression and where the least squares method is not the best method of estimation. They are not free from disadvantages and all cases do not produce better results. In the case of ridge regression the estimates are neither true nor unbiased.

It is important to note that, in spite of its limitations, the statistical method may be the only practical way to address a problem when data and other resources are lacking.

2.2.2 Physico-statistical models

These models attempt to mathematically describe the processes involved in yields formation by means of regression analysis (Dmitrenko, 1980; Baier, 1973). Baier proposed a model of the form:

\[ Y = \sum_{t=0}^{m} V_1 \times V_2 \times V_3 \]

where \( Y \) is the dependent variable representing the final yield or the yield of the economically valuable parts of the plant at any given stage of development, \( t \). The value of \( t \) is determined by the biometeorological time scale developed by Robertson (1968) and varies from \( t = 0 \) at time of sowing, to \( t = 1 \) at seedling emergence, to \( t = 2 \) at jointing, and so forth to \( t = m \) at maturity. \( V_1, V_2, \) and \( V_3 \) are nonlinear functions of the selected input variables, \( x_j \), such as:

\[ V_j = a_0 + a_1 x_j + a_2 x_j^2 \]
where $a_0$, $a_1$, and $a_2$ are fourth degree polynomial functions of $t_0$, the coefficients of which are evaluated by numerical optimization methods for each function. The functions $V_j$ may be functions of minimum or maximum air temperature, soil moisture, the ratio of actual to potential evapotranspiration, or global radiation. The most informative combination of the three factors, out of five enumerated, was found to be global radiation, minimum temperature, and the ratio of actual to potential evapotranspiration. The coefficients in the model were evaluated by using yield data for spring wheat in Canada.

Models developed by Dmitrenko (1980) are another illustration of the physico-statistical type. They are used to estimate the yield of winter wheat, spring barley, maize, winter rice, potatoes, sugar beets and sunflower. The relationship between the yield and the influencing factors is expressed by the formula:

$$\hat{Y} = Y_j(1 - P) * f(k) * S(T,R) * h(I)$$

where $\hat{Y}$ is the estimated yield and $Y_j$ is the annual statistical maximum yield for the $j$th year. $P$ is the density of the plant stand, $f(k)$ is a function of tilling, $S(T,R)$ is an index of productivity involving a function of the meteorological elements during the spring and summer period. $h(I)$ is an index involving the level of yield for various ratios of harvested areas to sown areas.

### 2.2.3 Dynamic models

Several dynamic models have been developed in many countries (Table 2.1) for determining yields for the most important agricultural crops. Computer programmes have been used to calculate the dynamics of the accumulation of phytomass (Figure 2.1) as well as the phenological progress of the crop during the entire growing period, or a significant portion of it. Dynamic models differ appreciably from each other depending on their objectives. They differ in the degree of detail describing the individual processes, as well as the amount of data that are required. Nevertheless, in dynamic models there is a common structure to the differential equations of the form:

$$m_p^{j+1} = m_p^j + f_p(M^j, X^j, A^j) \Delta t, M^j_{j=0} = M_0$$

where $m_p^j$ represents a vector functional relationship for estimating the dry mass of the leaves, stems, roots, and reproductive organs; $M^j$ is a vector consisting of $m_p^j$; $X^j$ is a vector characterizing the current state of the environmental conditions (e.g. in the model $X_1^j$ is global energy, $X_2^j$ is air temperature, $X_3^j$ is air humidity, $X_4^j$ is precipitation); $A^j$ is a vector of the functional and numerical parameters of the model; $j$ is the current (present) time; $j+1$ is the next moment in time; $\Delta t$ is an increment in time (for the majority of present-day models this is 24 hours).
<table>
<thead>
<tr>
<th>Crop Modelled</th>
<th>Country</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley, spring</td>
<td>U.S.S.R.</td>
<td>Sirotenko, 1981</td>
</tr>
<tr>
<td>Cabbage</td>
<td>U.K.</td>
<td>Barnes et al., 1974</td>
</tr>
<tr>
<td>Clover</td>
<td>Australia</td>
<td>Fulai et al., 1978</td>
</tr>
<tr>
<td>Cotton</td>
<td>U.S.A.</td>
<td>Duncan, 1971</td>
</tr>
<tr>
<td>Cotton</td>
<td>U.S.A.</td>
<td>Gutierrez et al., 1975</td>
</tr>
<tr>
<td>Cotton</td>
<td>U.S.A.</td>
<td>McKinion et al., 1975</td>
</tr>
<tr>
<td>Cotton</td>
<td>U.S.A.</td>
<td>Stapleton et al., 1973</td>
</tr>
<tr>
<td>Lettuce</td>
<td>U.K.</td>
<td>Greenwood et al., 1974</td>
</tr>
<tr>
<td>Lucerne</td>
<td>Australia</td>
<td>Byrne et al., 1969</td>
</tr>
<tr>
<td>Lucerne</td>
<td>U.S.A.</td>
<td>Holt et al., 1975</td>
</tr>
<tr>
<td>Lucerne</td>
<td>U.S.S.R.</td>
<td>&quot;Metodika&quot;, 1979</td>
</tr>
<tr>
<td>Maize</td>
<td>U.S.A.</td>
<td>Curry et al., 1971</td>
</tr>
<tr>
<td>Maize</td>
<td>U.S.A.</td>
<td>Duncan, 1973</td>
</tr>
<tr>
<td>Maize</td>
<td>U.S.A.</td>
<td>Splinter, 1974</td>
</tr>
<tr>
<td>Maize</td>
<td>The Netherlands</td>
<td>de Wit et al., 1978</td>
</tr>
<tr>
<td>Potato</td>
<td>U.S.S.R.</td>
<td>Zabroda et al., 1979</td>
</tr>
<tr>
<td>Rye, winter</td>
<td>U.S.S.R.</td>
<td>Polevaj et al., 1979</td>
</tr>
<tr>
<td>Sorghum</td>
<td>U.S.A.</td>
<td>Arkin et al., 1978</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Australia</td>
<td>Cocks et al., 1978</td>
</tr>
<tr>
<td>Soybean</td>
<td>U.S.A.</td>
<td>Curry et al., 1975</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>U.S.A.</td>
<td>Fick et al., 1973</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>U.K.</td>
<td>Patfield et al., 1971</td>
</tr>
<tr>
<td>Sunflower</td>
<td>Japan</td>
<td>Horie et al., 1977</td>
</tr>
<tr>
<td>Wheat, winter</td>
<td>U.S.S.R.</td>
<td>Polevaj et al., 1979</td>
</tr>
<tr>
<td>Wheat, winter</td>
<td>U.S.A.</td>
<td>Rickman et al., 1975</td>
</tr>
</tbody>
</table>
Figure 2.1 - Dry matter accumulation of leaves, stems and grains in spring barley from emergence to maturity. (After Sirotenko, 1981.)

A fundamentally important property of dynamic models is the fact that duration of the period of calculations (months, season) and also the time step (hour, day), does not affect the number of coefficients. The dynamic model is determined purely by the degree of details described in the process. This property differentiates dynamic models from other types, e.g. those using regression equations in which the number of coefficients estimated depends, in addition to the number of factors, on the period of averaging and the duration of the growing period. Thus, with 10-day averaging periods and calculating coefficients for two factors (temperature and precipitation) for a 120-day growing period, the estimate may involve 24 regression coefficients.

To sum up, the basic difference between dynamic models and other ways of mathematically describing the relationship between environmental conditions and crop yield, is that the build-up of crop yield is regarded as a process in the dynamic model. At the same time, in order to design dynamic models, it is necessary to have a larger amount of initial data than for other types. Some investigators think that we still know too little to start designing detailed mathematical models of crop growth. A reply to supporters of such views is to be found in a paper by F. Mithorpe (1978) in which, in particular he says: "I think that this point of view is excessively pessimistic and reflects some degree of indifference to the actual understanding of the problem". The members of the Task Force cannot but agree with this statement.

2.2.3.1 Selecting a suitable design for the model

Designing a mathematical model for a dynamic system involves the following steps:

(a) Defining the purpose of the model;

(b) Defining the system and its boundaries;

(c) Developing the structure of the model with sufficient accuracy for the unknown parameters;
Solving the problem of identifying the parameters for the model on the basis of all available data (physical representation, results of laboratory experiments, and data from field observations);

Utilizing the results from experiments to determine the range of input and output variables. Here it is necessary to ensure that the spectrum of input variables influencing growth is not narrower than the spectrum of output variables when using the model (the input variables in the experiment should be determined at such a level as to exceed the possible range of their variations); and

Testing the adequacy of the model (verifying) by analysing the results of numerical experiments for the entire development process of the model. It is difficult to separate the two steps of "design of the model" and "verification" from each other. After designing the first version and analysing the results of calculations, faults are inevitably found which require changes in the structure of the model. These changes require further study and verification, and so on. Furthermore, in the process of development, the initial representation of the modelling process is improved upon, and the range of experimental data used is widened. In the final verification process, it is important to consider an independent data set which was not used in the development of the model.

The relationships of the algorithm for the model are shown in Figure 2.2 which is based on the technique of Forrester (1961). Dashed lines show where the input of any particular data occurs and where these data are used in the calculation process. Solid lines show the flow of assimilators. Double lines show the moisture flow. The variables of the model are associated with numerous relationships which are indicated in the diagram.

2.2.3.2 Input data for dynamic models

The possibility of using any method of calculation largely depends on the nature and amount of the initial data necessary for the calculations. Data requirements for the dynamic model described above are divided into the following four groups:

(a) Constants of time and location;

(b) Soil coefficients;

(c) Crop coefficients;

(d) Meteorological data.

The constants in group (a) include: the geographical latitude for which the calculation is being made, the calendar time, the number of the 24-hour period at the start of calculations determined from an arbitrary zero, biological time, and the total of effective temperatures from emergence to maturity.

The soil coefficients of group (b) characterize the soil-physical properties at the location for which the calculations are to be made. They may include available water in pre-selected layers in the soil profile. Initial moisture level can be specified, if known, or the moisture submodel may be started after a heavy rainfall fills the soil profile. The soil moisture submodel can also be run until stability is reached.
Crop coefficients, group (c), pertain to the rate of accumulation of dry matter for different varietal classes. Other coefficients which affect crop growth and development rates can also be included.

Experience shows that it is now possible to design fairly adequate dynamic models based on basic daily meteorological observations, group (d), consisting of precipitation amount, temperature extremes, vapour pressure and sunshine duration or cloud cover. All of these observations are available from the regular synoptic meteorological reports which are transmitted eight times each day from synoptic meteorological stations. Because of this timing it would be well to develop dynamic models having a time step of three hours, thus taking advantage of all data available and eliminating possible errors due to averaging.

Dynamical Statistical Model: Weather-Yield

Figure 2.2 - Correlation diagram of the dynamical-statistical model "Weather-Yield" showing: I - level, II - processes, and fluxes of: 1. information, 2. assimilation, and 3. water. (After Sirotenko, 1981.)

2.3 References


CHAPTER 3

APPLICATIONS

3.0 Introduction

Potential users of crop-weather models are confronted with an extensive literature. Even so, many successful operational models are not documented in formal scientific journals. In this chapter an attempt is made to provide a systematic description of representative examples of models which have been used in the following subject areas:

(a) Land Evaluation (for long-term planning and investment decisions);
(b) Crop Adaptation;
(c) Crop Monitoring and Forecasting;
(d) Crop Management (for short-term operational decisions);
(e) Pest and Disease Assessment and Management;
(f) Research Strategy (planning and priorities);
(g) Derived Data Submodels.

In each case an attempt was made to provide examples of applications across the whole spectrum from the simplest statistical to the most sophisticated dynamic and mechanistic models. Special attention has been given to documentation of details necessary for choice of an appropriate model. References are provided in order that the potential user might further study the theory and application of various models. For implementation and application of a model to a specific problem it may be necessary to consult the "contact" provided who might be able to assist with operational details and, in some cases, provide computer programmes.

It is emphasized that the models and submodels listed here are chosen, somewhat arbitrarily, as examples from a very extensive known series.

3.1 Land Evaluation

3.1.1 SOW Model: Physical Crop Production

3.1.1.1 Problem Area

Determination of possible future development courses for the food and agricultural sector at the national level.

3.1.1.2 Objective

Assessment of the production level for various agricultural crops as determined by environmental conditions and management practices, and the inputs necessary to achieve this production.
3.1.1.3 Model Description

The model is partly dynamic, partly static. It calculates, in a dynamic way (10-day periods), dry matter production from leaf area index and absorbed solar radiation. The dry matter increment is partitioned into roots, leaves, stems, and storage organs as a function of phenological development of the crop. The influence of water shortage is mediated through the ratio of actual evapotranspiration to potential evapotranspiration (AET/PET). PET is calculated according to Penman. AET follows from the water balance (rainfall, irrigation, run-off, soil evaporation, drainage, and upward movement from a ground water table). Senescence of leaves is taken into account.

This calculation provides yield levels with and without irrigation for crops sown in any given calendar month.

Nutrient requirements (N, P, K) are inferred from the yield level, using crop specific minimum concentrations of the element in the tissue. These are translated into fertilizer requirements on the basis of site-specific natural fertility levels and management-level dependent fertilizer recoveries.

The influence of weed competition is taken into account as is the effect of pests and diseases. Finally, the labour requirements are estimated at four levels of management. The model thus provides different yield levels based on crop, soil type, reclamation level, and the associated inputs necessary to achieve these yields.

3.1.1.4 Computer Requirements

The model is written in FORTRAN and installed on a DEC-10. Several of the modules are available for use on desk-top computers or programmable calculators.

3.1.1.5 Scale

The model may be used for individual plots and for larger areas up to the national level, compatible with the degree of data availability.

3.1.1.6 Data Requirements

3.1.1.6.1 Meteorological Data

Monthly averages of precipitation, radiation, air temperature, air humidity, and wind speed are required. (A procedure has been developed for generating meteorological data for a country grid system from spot data.)

3.1.1.6.2 Crop Data

Crop species and the length of its growing cycle are required. (Tables are available containing the relevant derived data for most annual agricultural crops.)

3.1.1.6.3 Soil Data

Soil physical properties are required, such as: field capacity, wilting point, and saturated hydraulic conductivity. (A set of 36 "standard" soils is available for estimating these data from soil survey information such as soil type, texture class, etc.)
3.1.1.7 Validation and Application

Validation is performed by comparing experimental spot data to model output for various crops at different levels of detail.

The model was applied to generate data for application in national econometric models of Thailand and Bangladesh.

3.1.1.8 Limitations and Remarks

The data requirements for the model are fairly heavy. It can be used with less available data but then the accuracy and reliability will decline accordingly.

3.1.1.9 References


3.1.2 Freezing Temperature Probabilities

3.1.2.1 Problem Area

The length of the freeze-free season in temperate climates determines the length of the crop-growing season and hence the kinds of suitable crops for the most economical use of land.

3.1.2.2 Objective

To calculate the probabilities of the dates of the last spring freeze and of the first autumn freeze of various intensities using historical meteorological data.

3.1.2.3 Model Description

Standard statistical methods are used for determining probabilities and for smoothing results to suppress anomalies arising from a small sample.

Output is in the form of tables ready for publication. These show the probabilities of the last spring freeze and the first autumn freeze of various severities occurring on or after given dates in the spring and on or before given dates in the autumn.

3.1.2.4 Computer Requirements

The original programmes were written in FORTRAN and can be run on most small computers.
3.1.2.5 Scale

Calculations and output is for point data which could be mapped on appropriate scales depending on station density.

3.1.2.6 Data Requirements

Historical daily minimum temperatures during the critical freezing periods are required, preferably for a period of 30 years or more.

3.1.2.7 Validation and Application

The model has been used for preparing tables of freezing temperature risks for many stations in Canada (Coligado et al., 1968) and selected values have been used for mapping the length of the freeze-free season in Canada.

3.1.2.8 Limitations and Remarks

It is important that minimum temperatures are representative of the surrounding area and not biased by being in a "frost pocket". If data for less than 30 years are used the probabilities may be biased by short-period climatic anomalies.

3.1.2.9 References

3.1.2.9.1 Source


3.1.2.9.2 Additional


3.1.2.10 Contacts

Agrometeorological Section
Land Resource Research Institute
Research Branch, Agriculture Canada
OTTAWA, Canada. K1A 0C6
3.1.3 FAO Agro-Ecological Zones Model

3.1.3.1 Problem Area

The model was developed for the FAO Project on Agro-Ecological Zones (AEZ) because of the lack of adequate information for the assessment of potential land use for food crop production in Africa, Asia and Latin America.

3.1.3.2 Objective

The model provides an assessment of the potential for food production based on rainfed agriculture in developing countries using a physical and biological approach.

3.1.3.3 Model Description

The model is of a dynamic type including a series of submodels and sub-programmes dealing with the following steps:

i. Selection and definition of land utilization types (crop and produce, production type, input level);

ii. Division of the eleven crops of the study into groups based on differences in their photosynthesis pathways and the response of photosynthesis to temperature and radiation, and compilation of a crop adaptability inventory including crop phenological climatic requirements;

iii. Assemblage of information on the soil requirements of the eleven crops at each of the two levels of inputs envisaged;

iv. Compilation of a quantitative climatic inventory (1:5,000,000 scale) based on major climates (characterizing temperature differences) and lengths of growing periods (characterizing time available when water and temperature permit crop growth from station data on climate and water balance);

v. Computer assemblage of a soil inventory, by countries, from the FAO/Unesco Soil Map of the World;

vi. Overlay of the climatic inventory on the soil map and area measurement of resultant climate/soil units, the agro-ecological zones;

vii. Computer calculations (from v and vi) of country extents of soil units (by slope classes, texture and phase) by major climates and growing period zones (30-day intervals);

viii. Matching of the climatic inventory (iv) with the crop groups (ii) and, where the climatic requirements of the crop groups are met, calculation of biomass and constraint-free individual crop yields by growing period zones;
ix. Matching of the soil requirements of crops (iii) with the soil units, slope classes, texture classes and phases of the soil map, by rating soil limitations at each of the two levels of inputs;

x. Compilation and rating of the various agroclimatic constraints to crop production occurring in the various major climates and growing period zones;

xi. Application of the agroclimatic constraints (x) to the constraint-free crop yields (viii) to derive anticipated (agroclimatically attainable) crop yields, by growing period zones;

xii. Estimation of benefit/cost ratios of production from the different growing period zones, as related to attainable crop yields;

xiii. Agroclimatic suitability classification of each growing period zone according to anticipated crop yields (xi);

xiv. Computer application of the soil limitation ratings (ix) on the agroclimatic suitability classification of each growing period zone according to the soil composition of the zone, to arrive at the land suitability classification, i.e., the extent of land variously suited to the production of the crop at each level of input.

3.1.3.4 Computer Requirements

All programmes and subprogrammes are written in FORTRAN installed on an IBM 370.

The subprogramme on climatic inventory has been developed on an HP9820 desktop computer and is presently operational on a PRIME mini-computer.

3.1.3.5 Scale

The model has been used at both continental and national scales. The final information in its original form has been mapped on scales of 1:1,000,000 and 1:5,000,000.

3.1.3.6 Data Requirements

3.1.3.6.1 Meteorological Data

The basic data requirements are monthly averages of rainfall, maximum and minimum temperatures, vapour pressure, wind speed, and duration of bright sunshine. Derived data include monthly averages of daily temperature, daytime and night-time temperatures, global solar radiation, and potential evapotranspiration. Also generated is the average length of the available growing season.

3.1.3.6.2 Crop Data

Information is required on the ecological requirements and characteristics of crop species, including the length of their growing cycle in relation with areal patterns of rainfall and prevailing temperatures. Crop calendars for each species are also required.
3.1.3.6.3 Soil Data

Soils are characterized according to the FAO/Unesco Soil Map of the World. Other relevant FAO Projects provide such information as slope, soil depth, soil drainage and texture classes, inherent fertility level, pH, salinity, and calcium carbonate and gypsum contents.

3.1.3.6.4 Management Data

Information is required on technology levels: (a) low input (traditional cultivation) and, (b) high input (seeds, fertilizers, mechanization, and pest and disease control).

3.1.3.7 Validation and Application

For validation purposes, comparisons of the assessments have been made with results obtained from many FAO Projects. Several reports have been prepared showing that the principles of the AEZ methods produce good results in several individual countries.

3.1.3.8 Limitations and Remarks

The method may be applied at the national scale in large countries in spite of limited available data. On a smaller scale it would be necessary to replace the notion of length of growing season based on average data by a probabilistic notion derived from an analysis of rainfall variability.

3.1.3.9 References


3.1.3.10 Contacts

G. Higgins
Land and Water Development Division
Food and Agriculture Organization
Via delle Terme di Caracalla
00100 Rome, Italy.
(For the climatic inventory):
M. Frere
Plant Production and Protection Division
Food and Agriculture Organization
Vie delle Terme di Caracalla
00100 Rome, Italy.

3.1.4 Biometeorological Time Scale (BMTS)

3.1.4.1 Problem Area

With the extension of agriculture into the northern parts of the Canadian Great Plains, questions arise as to the northern limits for the successful production of cereal crops and the effects of climatic change on these limits.

3.1.4.2 Objective

To determine the boundary of the area suitable for maturing wheat and barley in the Canadian Great Plains and to evaluate the effect of climatic change (temperature) on this boundary.

3.1.4.3 Model Description

The biometeorological time scale model is of the quasi-mechanistic-dynamic least squares type which uses certain meteorological data for estimating the rate of crop development. Submodels are required for calculating day length and for areal temperature interpolation. Model output includes the date of maturity (suitable for harvest) on a point basis. Other phenological dates are also calculated.

3.1.4.4 Computer Requirements

The models are adaptable to most mini or larger computers.

3.1.4.5 Scale

Estimates are made from point data interpolated on a grid basis. These can be plotted and mapped on any scale compatible with the reliability and density of the basic data.

3.1.4.6 Data Requirements

3.1.4.6.1 Meteorological Data

For model calibration, the basic weather data requirements are for daily values of minimum and maximum temperatures and daily day length (calculated or from tables).

For estimation purposes, the basic weather requirements are for historical values of daily minimum and maximum temperatures for about 30 years as well as for daily day-length values. Derived data for grid-point daily minimum and maximum temperatures are also required.

3.1.4.6.2 Crop Data

For model calibration, field observations of certain critical phenological events at a representative number of stations over a period of years are required.
3.1.4.7 Validation and Application

The basic algorithm for the model has been used in a number of crop-weather relationship studies. Modifications of the BMTS model have been used for wheat, barley, maize, and soybeans. Results of studies have been verified by comparison with independent plot and field data. (See additional references in section 3.2.2).

3.1.4.8 Limitations and Remarks

Coefficients in the model are species and variety specific, making it necessary for model recalibration for each crop.

3.1.4.9 References

3.1.4.9.1 Source


3.1.4.9.2 Background


3.1.4.10 Contacts

G. D. V. Williams
Atmospheric Environmental Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario, Canada. M3H 5T4.

Agrometeorological Section
Land Resource Research Institute
Research Branch, Agriculture Canada
Ottawa, Canada. K1A OC6.

G. W. Robertson
Consulting Agrometeorologist
Box 1120
Kemptville, Ontario, Canada. K0G 1J0.

3.1.5 Maize Hybrid Selection for Local Conditions

3.1.5.1 Problem Area

Under temperate climatic conditions the success of the culture of maize (grain corn), which is a tropical crop, is dependent on the choice of a hybrid which
best meets the climatic conditions of the local area in question. The problem is to choose the hybrid with the longest growing season (generally the most productive) which matures with an acceptable frequency under the local temperature conditions.

3.1.5.2 Objective

To determine the frequency of satisfaction of temperature requirements of various maize hybrids.

3.1.5.3 Model Description

The method is based on the growing degree-day concept (temperature remainder index). Each variety has a certain temperature requirement, expressed in growing degree days, to achieve the cycle from sowing to maturity at a certain grain moisture content. A simulation is made on a 30-year period calculating for each year the growing degree days between a possible date of sowing and a date of harvest.

The date of sowing is determined by a model (based on global solar radiation and soil water balance) and is supposed to be the earliest decade when soil temperature at 5 cm reaches 10 degrees C and simultaneously when soil water content falls below field capacity. The end of the growing cycle is determined by the date of the first autumn frost or October 31st, whichever comes first, because of a crop rotation constraint. Using the temperature sums between these dates, it is easy to calculate the frequency of satisfaction of temperature requirements for all varieties grouped according to earliness of maturity.

3.1.5.4 Computer Requirements

The model is written in FORTRAN for use on a CDC-175 computer.

3.1.5.5 Scale

The model made use of 120 stations in France and a map at a national level was produced.

3.1.5.6 Data Requirements

3.1.5.6.1 Meteorological Data

A 30-year data set is required which includes daily values of minimum and maximum temperatures, precipitation, duration of bright sunshine, wind speed, and vapour pressure.

3.1.5.6.2 Soil Data

Information is required concerning the available water holding capacity of the soil and its thermal characteristics.

3.1.5.6.3 Crop Data

Crop data from experimental plots is required for validation purposes.

3.1.5.7 Validation and Application

The model was tested with observations from experimental stations and fits well. The model was used to prepare a map on the scale of 1:5,000,000 showing favourable maize regions in France.
3.1.5.8 Limitations and Remarks

The maps produced from the model should be used locally to give a more accurate zonation.

3.1.5.9 References


3.1.5.10 Contacts

N. Gerbier
Meteorologie Nationale
2 Avenue Rapp
F 75007 Paris, France.

D. Bloc
Association Generale des Producteurs de Mais
8 Avenue du President Wilson
F 75008 Paris, France.

3.1.6 Spring Field Workday Probability Model

3.1.6.1 Problem Area

Planning for land use and for the type of equipment required for its economical preparation, requires information on the number of days that soil will be sufficiently dry for tillage purposes.

3.1.6.2 Objective

(a) To compare locations on the basis of their agroclimatic resources for planting crops;

(b) To assist in planning for the complementary equipment required for timely completion of planting.

3.1.6.3 Model Description

The model is of the empirical-statistical type. An array of binary data is created which indicates whether or not a given day is suitable for field work, based on estimated soil moisture. Workday probabilities required to determine the impact of persistence of the probability of different sequences of workdays and non-workdays are estimated. In addition, the probability distribution of workdays is evaluated using either a first, second or third degree Markov chain.

Submodels required are the versatile soil moisture budget and the Markov chain probability model.

3.1.6.4 Computer Requirements

The model is written in FORTRAN and is adaptable to most mini or larger computers.
3.1.6.5 **Scale**

Estimates are made from daily data at point locations. The software has been used for large area applications.

3.1.6.6 **Data Requirements**

3.1.6.6.1 **Meteorological Data**

Historical daily minimum and maximum temperatures and precipitation are required for a period of about 30 years.

3.1.6.6.2 **Soil Data**

Information on soil type and its water holding capacity is required.

3.1.6.7 **Validation and Application**

The model has been validated by checking the consistency of the prediction of field workdays against farm records of actual field workdays.

3.1.6.8 **Limitations and Remarks**

The software is not designed to account for partial days suitable for fieldwork.

3.1.6.9 **References**

3.1.6.9.1 **Source**


3.1.6.9.2 **Additional**


3.1.6.10 Contacts

Dr. H. N. Hayhoe
Agrometeorology Section
Land Resource Research Institute
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Ottawa, Canada. K1A OC6.

3.1.7 Estimation of Working Days for Equipment Planning

3.1.7.1 Problem Area

Material investment and manpower adjustment in a particular agricultural system is determined by the number of working days available to do a specific operation.

3.1.7.2 Objective

To determine the number of working days in Central France mainly to avoid over-equipment.

3.1.7.3 Model Description

The method consists in finding a relationship between experimental observations of the possibility of completing a particular operation (during five years) and certain meteorological factors (mainly precipitation of the day, of the day before, etc.) through linear programming techniques and then, with this relationship, to simulate the number of working days during a 30-year data set. The statistics of the working days so determined can then be used in economical planning calculations and for decision making.

3.1.7.4 Computer Requirements

The calculations for a single station may possibly be undertaken with pencil and paper. However, if more than one station is to be used, the repetitive calculations require the use of at least a mini computer. The model was developed on an IRIS-80 and programmes were written in FORTRAN.
3.1.7.5 Scale

The results are given on a station to station basis.

3.1.7.6 Data Requirements

3.1.7.6.1 Meteorological Data

Historical daily precipitation is required for at least a 30-year period for a number of stations in the area to be studied.

3.1.7.6.2 Agricultural data

Experimental observations of the number of work days completed with given equipment.

3.1.7.7 Validation and Application

Simulation calculations are compared with actual field experience. The results are used by extension services to help farmers in their decisions.

3.1.7.8 Limitations and Remarks

The model is applicable on a local basis.

3.1.7.9 References


3.1.7.10 Contacts

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75014 Paris, France

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Chambre Interdepartementale d'Agriculture de l'Ile de France
2 Avenue Jeanne d'Arc
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M. Boiret
Meteorologie Nationale
2 Avenue Rapp
75007 Paris, France.

3.1.8 Agroclimatic Resource Index (ACRI)

3.1.8.1 Problem Area

There is a need to preserve agricultural land that, in some areas, is disappearing due to urbanization and industrial development. A method is required for interpreting climatic data to assist decision making concerning the identification of the better agricultural areas which should be selected for preservation or alternate use.
3.1.8.2 **Objective**

To compare the agricultural production potential of different parts of Canada as affected by climate.

3.1.8.3 **Model Description**

The model uses simple arithmetical relations. It requires submodels to adjust for moisture limitations and for cool summers.

The output is in the form of an index by means of which it can be ascertained that the agricultural production potential of one location is, for example, 2.3 times that of another from the climatic standpoint.

3.1.8.4 **Computer Requirements**

A mini computer or a programmable calculator is sufficient.

3.1.8.5 **Scale**

The output from the model is most applicable for national or regional overviews, e.g. for comparing the production potential of an area in one region with that in another.

3.1.8.6 **Data Requirements**

3.1.8.6.1 **Meteorological Data**

Agroclimatic information is required concerning: duration of the frost-free season, the climatic moisture index (for submodel), and the number of degree days (for cool temperature submodel).

3.1.8.6.2 **Crop Data**

Crop yields are required in dry areas (the submodel could be readily altered to eliminate this need).

3.1.8.7 **Validation and Application**

The model is checked by using commercial crop production statistics. Soil information also helps to differentiate climate-related production potential differences from those that are largely soils-related.

3.1.8.8 **Limitations and Remarks**

The use of a single index ignores the variation in climatic needs among various crops or types of agriculture. The index is not applicable to detailed local comparisons.

3.1.8.9 **References**

3.1.8.9.1 **Source**

3.1.8.9.2 Additional


3.1.8.10 Contacts

G. D. V. Williams
Canadian Climate Centre
Atmospheric Environment Service
Environment Canada
Downsview, Ontario, Canada. M3H 5T4

J. L. Nowland
Research Branch
Agriculture Canada
Ottawa, Ontario, Canada. K1A 0C6.

3.1.9 Agricultural Drought Assessment Model (ADAM)

3.1.9.1 Problem Area

Drought and its frequency in the Canadian Prairie Provinces is an important factor in determining land use and its management.

3.1.9.2 Objective

To determine the years with agricultural droughts in a 53-year weather series in the Canadian Prairie Provinces.

3.1.9.3 Model Description

The model is of the regression type, using dummy variables to specify year and location. Submodels are required for estimating soil moisture and for its conversion, along with yield and acreage data, to a grid point basis in a manner analogous to the Thiessen polygon weighting system.

Output from the model consists of water-based crop-yield estimates made with technological trend removed. These estimates are sorted to show worst and best years in the study period for each grid point. The point rankings, and also the overall estimated regional yield ranking, are used with predetermined thresholds to indicate drought years.

3.1.9.4 Computer Requirements

A computer is necessary, particularly for the regression analysis computations. The programme for the model was written in FORTRAN and installed on an AS/6 computer.
3.1.9.5 Scale

The procedures were designed for use with data for grid "squares" approximately 100 km each side. Estimates can be made for larger areas, by aggregation, but not for smaller areal units.

3.1.9.6 Data Requirements

3.1.9.6.1 Meteorological Data

Precipitation and estimated potential evapotranspiration are required on a 10-day basis for calculating soil moisture during the growing season for each year in the long-term series.

3.1.9.6.2 Crop Data

Commercial crop yield and acreage data for each year for crop districts in the Prairie Provinces are required.

3.1.9.7 Validation and Application

Water-based yield estimates made before removing technological trend were compared with observed crop yields. Results were also compared with various economic indicators.

3.1.9.8 Limitations and Remarks

Calculations may occasionally fail to identify a drought year or area, indicating the need for further development research on the model. Inadequate data may also contribute to the failure.

The model was applied to spring wheat and probably could be used with other spring-sown annual crops. At present it is not applicable to perennial forage and pasture crops. It did not identify those drought years which severely affected these crops but not the annual cereals.

3.1.9.9 References


3.1.9.10 Contacts

G. D. V. Williams or B. F. Findlay
Canadian Climate Centre
Atmospheric Environment Service
Environment Canada
Downsview, Ontario, Canada. M3H 5T4.
3.1.10  **Crop Production Potentials**

3.1.10.1  **Problem Area**

FAO projections estimate that to support the predicted world population in the year 2000 would require an increase in agricultural production of 60 per cent. It is uncertain whether there are sufficient global land resources to accomplish this increase. At present, there is insufficient precise data upon which to base a reliable answer. This model was used for evaluating the constraint free potential yield and the yield reducing constraints required in estimating the agronomically attainable or anticipated yields for wheat, maize, soybean, potato, and phaseolus bean crops in Canada.

3.1.10.2  **Objective**

To compute: (a) growing season climatic conditions; (b) growing season water balance; (c) estimates of crop biomass, yield and production potential.

3.1.10.3  **Model Description**

The model is physically based and incorporates climatic data, crop phenological data and soil limitations. Output consists of growing season biomass, yield estimates, and production potential based on long-term average growing season climatic conditions (i.e. 30-year normals) and growing season water balance information.

3.1.10.4  **Computer Requirements**

The model is written in FORTRAN and is installed on an IBM 360/370.

3.1.10.5  **Scale**

The output is mapped on a scale of 1:5,000,000 based on the soil map units from the soils of Canada.

3.1.10.6  **Data Requirements**

3.1.10.6.1  **Meteorological Data**

Climatological normals are required for monthly maximum and minimum temperatures, rainfall, snowfall, wind speed, vapour pressure, and global solar radiation or duration of bright sunshine. Soil moisture is derived from the versatile soil moisture budget sub-model.

3.1.10.6.2  **Crop Data**

For calibration purposes yield data are required from variety trials conducted at agricultural research stations.

For estimation purposes the requirements are for crop type characteristics, maximum leaf area index, maximum growing season length, moisture use efficiency, and harvest index (fraction of the crop net biomass production that is economically useful).
3.1.10.6.3 **Soil Data**

Soil moisture holding capacity is required.

3.1.10.7 **Validation and Application**

3.1.10.7.1 The model and its submodels provide estimates of the following:
(1) growing season data including start, end and length; (2) average growing season data including corn heat units, precipitation, radiation, maximum photosynthetic rates, and potential evapotranspiration; (3) soil moisture data including climatic available moisture usage index (CAMUI); and (4) biomass estimate including potential net biomass production (NBP), potential dry matter yields, anticipated potential NBP taking into account the CAMUI, and the anticipated dry matter yield taking into account CAMUI.

3.1.10.7.2 Use is made of long-term yield estimates.

3.1.10.8 **Limitations and Remarks**

The model:

(a) uses long-term climatic normals, not daily information;
(b) is based on growing season averages;
(c) does not consider various crop development stages;
(d) uses bulk crop phenological characteristics;
(e) is applicable to large areas on a long-term basis only;
(f) does not take into account management variations (i.e. fertilizers, pesticide use, etc.).

3.1.10.9 **References**


3.1.10.10 **Contacts**

R. B. Stewart  
Resources and Environment Section  
Crop Production Division  
Regional Development and Internal Affairs Branch  
Agriculture Canada  
Ottawa, Canada. K1A OC5.

J. Dumanski  
Land Resource Research Institute  
Research Branch, Agriculture Canada  
Ottawa, Canada. K1A OC5.
3.1.11 Land Evaluation Model (LEM-2)

3.1.11.1 Problem Area

Because of increasing pressures for land by urbanization and industry there is a need to evaluate land in Ontario in regard to its production potential and to provide a rating of its value for agriculture.

3.1.11.2 Objective

The Land Evaluation System developed at the University of Guelph provides comprehensive assessments of the land resource relative to conditions and requirements that the use of land must satisfy.

3.1.11.3 Model Description

The model is a mathematical type involving linear and nonlinear objective functions with linear constraints. It uses a sub-model (Crop Productivity Model) involving soil-moisture-based regression models for estimating agricultural crop yields. Output provides information on: (i) production potential; (ii) feasibility; (iii) overall flexibility of use of land; and (iv) importance of land areas for agriculture.

3.1.11.4 Computer Requirements

A large computer with 3-4 megabytes of memory is required. The programmes are written in PL/I and FORTRAN.

3.1.11.5 Scale

The output is mapped on a base map of Ontario on a scale of 1:250,000.

3.1.11.6 Data Requirements

3.1.11.6.1 Meteorological Data

The basic climatic data requirement is for derived information on corn heat unit zones (CHU) (Brown, 1963, 1978) which makes use of monthly averages of minimum and maximum temperatures.

3.1.11.6.2 Crop Data

Estimates of crop yield data are required. These are derived from the Crop Productivity Model based on climatic data and soil and management information. Also required is information on commodity demands and crop sequence.

3.1.11.6.3 Soil Data

Information is required concerning land types based on the Canada Land Inventory, and concerning land availability obtained from the Canada Geographic Information System.

3.1.11.7 Validation and Application

Land evaluation estimates are checked against experimental plot records and provincial statistical reports.
3.11.8 **Limitations and Remarks**

Limitations to the use of the model are the lack of basic soil series information at the provincial scale for productivity models and lack of present land use data. The size of the model causes some operational difficulties.

3.11.9 **References**

3.11.9.1 **Source**


3.11.9.2 **Background Papers**


3.11.10 **Contacts**

Land Evaluation Project
University School of Rural Planning and Development
University of Guelph
Guelph, Ontario, Canada. N1G 2W1.

K. B. MacDonald
Scientific Reporting Authority
Land Resource Research Institute
Research Branch, Agriculture Canada
Ottawa, Canada. KIA 0C6.

3.2 **Crop Adaptation**

3.2.1 **Basic Crop Growth Simulator (BACROS)**

3.2.1.1 **Problem Area**

There is a need to increase the understanding of crop growth and production on the basis of the physiological, chemical, biochemical and physical properties of plants.

3.2.1.2 **Objective**

To develop a process-based detailed model of crop growth: (a) that accounts for as much as possible of the experimental data available which can be used to evaluate the results of experiments and help in the design of new ones; (b) that will pinpoint gaps in the knowledge of crop growth; (c) that can assist in evaluating the results of changes in plant properties.
3.2.1.3 Model Description

The model, BACROS (Basic Crop Growth Simulator), calculates the time course of dry matter production of a crop under optimum supply of water and nutrients, without weed competition and in the absence of pests and diseases.

The processes of assimilation and respiration are modelled in detail and can each be validated individually. Assimilation is obtained from instantaneous values of solar radiation, taking into account leaf area index, spatial arrangement of the leaves and their optical properties. Respiration follows from the amount of material present, its chemical composition, the current rate of growth and canopy temperature. Transpiration is obtained through a combination method from the heat balance of the crop.

Growth depends on the current assimilate supply, accumulated reserves and temperature, and may be affected by the internal water status of the plant.

3.2.1.4 Computer Requirements

The model is written in CSMP (Continuous System Modelling Programme) and is operational on computers to which this system is available (IBM 360, IBM 370, DEC-10). It can easily be installed on systems having access to a language of the CSSL (Continuous System Simulation Languages) group.

3.2.1.5 Scale

The model is used on an individual plot scale.

3.2.1.6 Data Requirements

3.2.1.6.1 Meteorological Data

Daily values of global radiation, minimum and maximum air temperature, air humidity, and wind speed are the basic weather data requirements.

3.2.1.6.2 Crop Data

Plant measurements are: photosynthesis-light response curve for individual leaves; stomatal resistance; cuticular resistance; chemical composition in the course of the growing season (preferably leaf area index development since morphology is not treated).

3.2.1.7 Validation and Application

The model has been validated extensively for different crops (maize, wheat, rye-grass, Rhodes grass) in different geographical regions (The Netherlands, U.S.A., Israel, Peru). It is used permanently as a research tool.

3.2.1.8 Limitations and Remarks

The model is applicable only under optimum growing conditions. It does not take into account distribution of dry matter between vegetative and reproductive organs. Crop data demands are fairly heavy.
3.2.1.9  References


3.2.1.10  Contacts

Centre for Agrobiological Research (CABO)
Dept. of Theoretical Production Ecology
Agricultural University
P.O. Box 14
Wageningen, The Netherlands.

3.2.2  Factorial Least Squares Technique

3.2.2.1  Problem Area

It is accepted that weather variability throughout the life cycle of a crop has a profound influence on the variability of the rate of development and the final yield of the crop. This model can be used for gaining an understanding of some of the complex influences of weather on crop development and yield.

3.2.2.2  Objective

The model permits the analysis of historical weather and crop yield information for the purpose of determining the influence on development and final yield of various weather factors at critical phenological periods in the life cycle of the crop.

3.2.2.3  Model Description

The model is of the dynamic quasi-mechanistic type making use of a factorial least squares technique which permits the evaluation of the influence on yield of each of a number of weather elements during each of several phenological stages. In the case of yield analysis, the influence of the weather during a given stage is carried forward to the next stage by means of a special connective function which reduces the chances of error escalation due to progressive multiplications.

3.2.2.4  Computer Requirements

A mini-computer or larger model is required to handle the data and least squares analysis which is performed on an interactive basis to calibrate various growth functions in the model.
3.2.2.5 Scale

The model is applicable over a wide range of scale values ranging from plot information to information from large fields or homogeneous crop districts.

3.2.2.6 Data Requirements

3.2.2.6.1 Meteorological Data

Minimum requirements are for daily values of minimum and maximum temperatures, day length, and daily global solar radiation or daily duration of bright sunshine. For yield analysis daily wind run and some measure of daily humidity would be useful.

3.2.2.6.2 Crop Data

Minimum requirements are for seasonal crop yield data for 50 or more station-years gathered under as wide a range of weather conditions as possible. Information on sowing and harvesting dates, dates of two or three intermediate phenological periods, rooting depth, and the degree of maximum canopy closure would be useful.

3.2.2.6.3 Soil Data

Information on soil structure and its water holding capacity would be useful.

3.2.2.7 Validation and Application

The model, with slight modifications for each application, has been used for studying the effect of weather on the rate of development of wheat (Robertson, 1968), maize (Amores-Vergara, 1973), barley (Williams, 1974), and soybeans (Major et al., 1975); for studying the areas in the Canadian Great Plains favourable for wheat production (Williams, 1969); for studying the effect of weather on wheat yield (Baier, 1973; Robertson, 1974); and for studying the effect of weather on the yield of oil palm (Robertson and Foong, 1976, 1977 and Foong, 1980). The model is readily adaptable for crop-condition monitoring and yield forecasting.

3.2.2.8 Limitations and Remarks

The coefficients in the model are specific for crop species and variety. These coefficients must be redetermined for each new crop being studied. Since the coefficients are determined by a least squares method, a large sample of field data is necessary. Care must be exercised to assure that ineffective weather elements during certain periods of development are eliminated during the iterative evaluation of the coefficients; otherwise unrealistic results may be indicated.

3.2.2.9 References

3.2.2.9.1 Source


3.2.2.9.2 Additional References


3.2.2.10 Contacts

E. Amores-Vergara
Philippines Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)
1424 Quezon Avenue
Quezon City, Philippines.

W. Baier
Agrometeorological Section
Land Resource Research Institute
Research Branch, Agriculture Canada
Ottawa, Canada. K1A 0C6.

S. F. Foong
Federal Land Development Authority
Agricultural Services Corporation
Pusat Perkhidmatan Pertanian Tun Razak
Jerantut, Pahang, Malaysia.
3.2.3 Ontario Corn Heat Unit (CHU) System

3.2.3.1 Problem Area

With the advent of hybrid corn it was found necessary to develop a method for characterizing the climatic requirement of numerous hybrids as well as the climatic suitability of various areas for hybrids.

3.2.3.2 Objective

To provide a method for selecting the most suitable maize (corn) hybrid(s) for each corn growing area in Canada.

3.2.3.3 Model Description

The model is of the empirical-statistical type that relates development rate of corn to temperature.

3.2.3.4 Computer Requirements

The minimum requirement is for a pocket-size calculator, preferably one that is programmable.

3.2.3.5 Scale

Data for specific sites are used to provide ratings for zoning purposes.

3.2.3.6 Data Requirements

The only data required are daily minimum and maximum temperatures.

3.2.3.7 Validation and Application

Phenological records on corn over a four-year period were used to help develop the model and seasonal checks have been maintained since the system was first introduced in 1964.

3.2.3.8 Limitations and Remarks

The same equations are used throughout the whole corn-growing season, even though it is known that corn responds to temperature in a slightly different manner during each period of development.
3.2.3.9 References

3.2.3.9.1 Source


3.2.3.9.2 Additional References


3.2.3.10 Contacts

D. M. Brown
Agrometeorology
Dept. of Land Resource Science
University of Guelph
Guelph, Ontario, Canada. N1G 2W1.

3.3 Crop Monitoring and Yield Forecasting

3.3.1 Relative Assessment of Potential Food Production

3.3.1.1 Problem Area

The relative assessment of potential food production in developing countries as early as possible in the season is very important to mitigate the humanitarian/economic impact. Many problem areas are data-limited.

3.3.1.2 Objective

To provide a qualitative assessment of crop production based on agrometeorological data in data-limited situations.

3.3.1.3 Model Description

This method is based on using agrometeorological indices such as R-index, Yield Moisture Index, etc. and ranking the data sets by normalizing the data for the period of record. In this manner a plot of the yearly index can be shown as a time series (period of record). Percentiles are derived by a ranking procedure. Low ranks are usually associated with unfavourable crop years; high ranks with favourable years. Although quantitative estimates are not determined, the relative amount can be compared with production in previous years.

3.3.1.4 Computer Requirements

Simple mean and standard deviation are calculated to develop a normalizing scale. This can be done with a hand-held desk calculator. With numerous station data, the analysis should be done on a computer. It is recommended, if done by computers, to
develop a data file for which data input can be updated with time for operational use.

3.3.1.5 Scale

Individual stations could be used, but it is desirable to assess large areas including the monitoring at the province or national level. In both cases, interpolation of the meteorological input depends on the reporting network density.

3.3.1.6 Data Requirements

3.3.1.6.1 Meteorological Data

Monthly precipitation (and, if available, temperature) and derived data including potential evapotranspiration are needed.

3.3.1.6.2 Crop Data

This method is designed for use when crop yield data are missing. Crop Crop calendar data (sowing, flowering, harvesting) are useful if available.

3.3.1.6.3 Soil Data

Available water capacity for areas considered could be used, but is not essential. The method is designed so that analysis can be completed using only the basic meteorological data.

3.3.1.6.4 Management Information

Management information would be useful if available but is not completely necessary.

3.3.1.7 Validation and Application

The method has been applied operationally in the Caribbean, Africa, Latin America, and South and South-east Asia. The results served as supplementary information on the relative productivity level. Early warning with one to two months lead time is possible in the areas where the method is applied when it is used in association with past reports or description of unfavourable years.

3.3.1.8 Limitations and Remarks

The method is appropriate for providing a general overview of relative conditions which may alert officials of the need to investigate further. It is not quantitative. It has been used with monthly data, but could be refined to consider decadal periods. The procedure is cost-effective.

3.3.1.9 References


3.3.1.10 Contacts

Centre for Environmental Assessment Services
Room 200, Federal Building
600 E Cherry Street
Columbia, Missouri 65201
U.S.A.

3.3.2 Multiple Regression Models for Yield Estimates

3.3.2.1 Problem Area

There is a need by national governments for early information about the production situation of the main cultivated crops in the European Community (EC) countries.

3.3.2.2 Objective

To enable governments to react to the expected production situation with imports or exports.

3.3.2.3 Model Description

The models are based on monthly weather data and a trend. Multiple regression equations are set up for each month from January until harvest and for each weather station. The necessary number of weather stations depends on the geographical situation of the country and the planted area of the crop. The results of all stations are summarized to an average for each month and over the months to a final forecast. After each month a new forecast is possible which includes the results of the preceding months. The errors, therefore, decrease with the advancing season. The predicted values are in tonnes/ha averaged on a country basis.

3.3.2.4 Computer Requirements

The capacity of the computer must be sufficiently large to accommodate the multiple regression programmes needed for calculating the equations required for the predictions. The forecasts themselves can be made by hand or by using a small pocket computer but are easier with a mini or larger computer which can stock the regression equations.

3.3.2.5 Scale

The models were used at the national and EC levels.
3.3.2.6 Data Requirements

The models use monthly averages or sums for: minimum and maximum temperatures, sunshine, precipitation, wind speed, relative humidity, and number of wet days (rain > 1.0 mm). Besides weather data, the trends are required. The number of weather stations used in the models ranged from 3 for Luxembourg to 43 for the EC-total. Not all weather data were used in all models.

3.3.2.7 Validation and Application

The models have been used in Federal Republic of Germany since 1973 and in EC and its member countries since 1978 for official forecasts.

The relative errors of forecasts vary from country to country (3-8%), with crops (3-5%), and were in total 4% with a range from 1-10% for forecasts in a single country for a single crop.

Models have been developed for the following crops: winter wheat, winter rye, winter barley, spring barley, oats, total cereals, maize, rice, potatoes, and sugar beets; and for the following countries: EC-total, Federal Republic of Germany, France, United Kingdom, Italy, the Netherlands, Belgium, Luxembourg, Denmark and Ireland.

3.3.2.8 Limitations and Remarks

The application of such regression type models are limited by the existing historical data set for weather and yields. Selection or aggregation of weather data may reduce statistical problems with low numbers of remaining degrees of freedom. It is necessary to produce the prediction equation by multiple regression for each single case (crop, country).

3.3.2.9 References


3.3.2.10 Contacts

Prof. Dr. H. Hanus
Institut für Pflanzenbau und Pflanzenzuchtung
Lehrstuhl Allgemeiner Pflanzenbau
Olshausenstrasse 40-60
2300 Kiel
Germany (FR).

3.3.3 The Champagne Model

3.3.3.1 Problem Area

Forecasting the date of harvesting, the quality (degree of alcohol and acidity) of the three varieties of grapes (Pinot Noir, Pinot Meunier, Chardonnay)
used to make champagne is very important for the management of production units and for organizational purposes.

3.3.3.2 Objective

To enable a better organization of harvesting by an estimation of the date of harvest for highest quality with a lead time of a month.

3.3.3.3 Model Description

The models are based on regression techniques, using meteorological data, for forecasting the date of harvesting, the date when the degree of alcohol is expected to be more than 8 degrees, the final degree of alcohol and the acidity of each variety.

3.3.3.4 Computer Requirements

The models have been developed on a CDC-175 and programmes were written in FORTRAN. As the equations are now developed the calculations can be done with pencil and paper.

3.3.3.5 Scale

The champagne region around the cities of Reims and Epernay.

3.3.3.6 Data Requirements

For the development of the models a 30-year series of meteorological data for Reims was used. This included daily values of minimum and maximum temperature, precipitation, sunshine, vapour pressure and wind speed.

Consideration is given to the choice of the period during the crop cycle in which meteorological factors appear to be most active.

3.3.3.7 Validation and Application

The models have been working operationally since 1975 and rather well, except in 1981 for the date of harvesting.

3.3.3.8 Limitations and Remarks

The model is applicable to champagne only.

3.3.3.9 References


3.3.3.10 Contacts

N. Gerbier
Météorologie Nationale
2 Avenue Rapp
F 75007 Paris, France
3.3.4 FAO Model for Crop Monitoring and Yield Forecasting

3.3.4.1 Problem Area

National food assessments from the current crop situation are not easy to ascertain and often biased information is obtained by subjective or other appraisal methods. In developing countries food assessments are critical for national food security purposes.

3.3.4.2 Objective

To enable an objective, qualitative assessment of the forthcoming harvest based on agronomic data. Availability of good crop yield data would also allow quantitative assessments.

3.3.4.3 Model Description

The method is based on a 10-day (or weekly) water balance accumulated over the whole growing season for the given crop. Joint use is made of actual rainfall data and climatological information. A "crop coefficient" links the water requirements of each crop at different phenological stages to the climatological potential evapotranspiration. The model provides an index which represents the cumulative ratio of the available water to the crop water requirements expressed as a percentage, taken over the complete growing cycle of the crop. The index is closely related to the final yield (yield potential).

The model's output is an assessment of the crop situation for a given 10-day (or weekly) period. It may also provide a cumulative assessment from the beginning of the cropping season to the current period in the life cycle of the crop.

3.3.4.4 Computer Requirements

The model can be utilized with pencil and paper. It can also be transferred to a computer for the processing of data coming from numerous stations.

3.3.4.5 Scale

The model may be used for individual stations up to any level compatible with availability of data. Generally it is used for provincial or national monitoring of crops.

3.3.4.6 Data Requirements

3.3.4.6.1 Meteorological Data

Observed total precipitation for weekly or 10-day periods are required together with climatological estimates of weekly or 10-day potential evapotranspiration calculated after Penman's method using historical data.

3.3.4.6.2 Crop Data

The species of crops grown, the length of the growing cycle, and crop calendar information are required.
3.3.4.6.3 **Soil Data**

Available soil water retention capacity for the crops in question is required.

3.3.4.6.4 **Management Information**

Date of planting is required although this can also be estimated from actual rainfall distribution at the beginning of the season.

3.3.4.7 **Validation and Application**

The final indices, as determined by the model, have been compared with the actual statistical yields obtained in the field. A good agreement is observed with a lead time of 6 to 8 weeks before harvest.

3.3.4.8 **Limitations and Remarks**

The method is intended mainly for use in developing countries where the main constraint is water availability. Temperature constraints are not directly considered but are reflected, however, in the length of the growing cycle of the crops.

The index gives a "very satisfactory and early qualitative appreciation of the yield" (Frere and Popov, 1979). Precise local agricultural yield statistics are needed to derive quantitative results.

3.3.4.9 **References**

3.3.4.9.1 **Source**


3.3.4.9.2 **Additional**


3.3.4.10 **Contacts**

M. Frere and G. Popov
Crop Ecology Group
Crop and Grassland Service
Plant Production and Protection Division
Food and Agriculture Organization
Via delle Terme di Caracalla
00100 Rome, Italy.
3.3.5 Soil Moisture Evaluation Programme (SMEP)

3.3.5.1 Problem Area

Soil moisture is the single most important weather factor affecting the production of cereal crops in the Prairie Provinces of Canada. A knowledge of soil moisture reserves at sowing time and from time to time during the growing season is needed for planning seeding operations and for estimating the expected yield at harvest time.

3.3.5.2 Objective

The objective of the programme is to quantify plant available soil water throughout the Prairie Provinces for the purpose of delineating possible drought areas and for periodically assessing, during the growing season, crop growth and potential yield.

3.3.5.3 Model Description

The programme is based on the Versatile Soil Moisture Budget which is of the quasi-mechanistic empirical type. A submodel generates crop district values of plant available water using a Thiessen polygon technique. Another submodel "SYMAP" is used to produce a series of maps of regional soil moisture reserves from estimated point values.

The output from the programme provides: (a) point data of available water for selected soil water-holding capacities; (b) areal evaluations of available water by crop districts; and (c) maps showing the zonal distribution of available water.

Soil water information is required on a near-real time basis so that it is necessary to use current weather data for updating the estimates once each week during the growing season.

3.3.5.4 Computer Requirements

Computer programmes are written in FORTRAN and can be used on a mini-computer or larger.

3.3.5.5 Scale

The output can be mapped at any scale from point data to very large area maps.

3.3.5.6 Data Requirements

3.3.5.6.1 Meteorological Data

Basic data requirements are for daily values of minimum and maximum temperature, precipitation, and calculated values of incident solar radiation at the top of the atmosphere for selected latitudes.

3.3.5.6.2 Crop Data

The average time span for selected phenological events are needed for various crop species.
3.3.5.6.3 **Soil Data**

Soil water holding capacities (texture of various soils) are required.

3.3.5.6.4 **Management Information**

Information on the land area committed to summer fallow and to crop is required.

3.3.5.7 **Validation and Application**

The programme has been operational since 1975. Soil moisture estimates were checked against gravimetric measurements on a routine basis over a period of two years. The effect of soil moisture on field crop conditions was checked against average crop conditions reported periodically throughout the crop year.

3.3.5.8 **Limitations and Remarks**

Lack of homogeneity in the assumed soil texture as well as sparsity of weather reporting stations relative to the large areal land mass involved, cause unreliable results in some areas.

3.3.5.9 **References**


(See also paragraph 3.7.2.)

3.3.5.10 **Contacts**

S. N. Edey
Agrometeorology Section
Land Resource Research Institute
Research Branch, Agriculture Canada
Ottawa, Ontario
Canada. K1A OC6.

3.3.6 **Weather-Soil Yield Projection Model**

3.3.6.1 **Problem Area**

An early assessment of crop conditions and yield projection is required in agricultural food strategy planning.

3.3.6.2 **Objective**

To provide real-time cereal crop yield projections throughout the growing season for the Canadian Prairies.
3.3.6.3  **Model Description**

Yield projections are provided for wheat, oats and barley on a weekly basis from 1 May to 31 July. The multiple regression model is based on meteorological data, physiographical data, and technological trend. Included in the model are sub-models for areal data interpolation and interpolation or derivation of unobserved daily data. Also, certain indices are calculated for input into the model.

3.3.6.4  **Computer Requirements**

The computer used for the model must be able to handle large amount of data, both in the developmental and operational stage. It is necessary to evaluate the coefficients in 9 regression equations based on 10 independent sets of variables. The programs necessary for providing the projections are in FORTRAN.

3.3.6.5  **Scale**

The meteorological input data are collected on a station basis but are transformed to crop district for use in the model. The model was developed to provide prairie yield projections; however, provincial and crop district yields are provided as intermediate steps.

3.3.6.6  **Data Requirements**

3.3.6.6.1  **Meteorological Data**

Basic data requirements are for daily values of minimum and maximum temperature, and incident solar radiation at the top of the atmosphere for estimating potential evapotranspiration (PET), and precipitation. Monthly precipitation and PET data are required for coefficient evaluation whereas daily data are needed for operational purposes.

3.3.6.6.2  **Crop Data**

Historical statistical crop yield data by crop district are required for coefficient evaluation purposes.

3.3.6.6.3  **Soil Data**

Topography and soil type and texture are required on a land unit basis.

3.3.6.7  **Validation and Application**

Current statistical information on field crop conditions and yields are used as check data for the calculated projections.

The operational yield projections have been used since 1979 as one source of information for those involved in marketing decisions within Agriculture Canada.

3.3.6.8  **Limitations and Remarks**

As with all regression models there are limitations based on existing data. The model is based on monthly data and this tends to override the effect of critical fluctuations of daily weather on growth. Plans for improving the model include introducing soil moisture values based on phenological stages. Consideration should also be given to physiological stress of high temperature during critical phenological stages. These considerations should put more weight on abnormal weather con-
dictions at critical stages of growth. There have been considerable fluctuations in the amount of fallow land in Canada over the past two decades and introduction of fallow information in the model should also prove to be useful.

3.3.6.9 References


3.3.6.10 Contacts

L. H. Garron
Agrometeorology Section
Land Resource Research Institute
Research Branch, Agriculture Canada
Ottawa, Ontario
Canada. K1A 0C6.

3.3.7 The Productivity of Agro-Ecosystems: A Dynamic Model

3.3.7.1 Problem Area

In order to make operational decisions concerning food production, a system of continuous yield forecasting during the growing period should be available.

3.3.7.2 Objective

To undertake quantitative assessment of past and expected agrometeorological conditions influencing yield and to make consecutive yield forecasts.

3.3.7.3 Model Description

The basis of this crop-weather model is a system of differential equations describing the dynamics of phytomass (leaves, stems, roots, and reproductive organs) of plants. The system takes into account plant processes such as photosynthesis, respiration, growth, and development.

The model comprises a water-regime block which makes it possible to compute soil moisture in 10-cm layers up to the depth of 150 cm. This considers the processes of infiltration of precipitation, movement of moisture in the soil, absorption of water by the root system, evaporation from the soil, etc.

3.3.7.4 Computer Requirements

A medium-speed computer is necessary.

3.3.7.5 Scale

The model makes it possible to compute the dynamics of phytomass, leaf area, final yield, soil moisture, and evapotranspiration and other components of the water balance using data from individual meteorological stations.
3.3.7.6 Data Requirements

3.3.7.6.1 Meteorological Data

Daily data are required for precipitation, mean air temperature and humidity, and duration of bright sunshine.

3.3.7.6.2 Crop Data

Date of crop emergence and the plant density at emergence are required.

3.3.7.6.3 Soil Data

Soil moisture observations are required for 10-cm layers to a depth of 150 cm on the date of emergence. Physical properties of the soil are also required.

3.3.7.7 Validation and Application

The model represents fairly well the interannual variability of final yield. The accuracy of computation of water content is close to that of the observed values. The model has been tested and is being applied by the Hydrometeorological Service of the U.S.S.R.

3.3.7.8 Limitations and Remarks

The model is applicable for any field crop after the adjustment of its parameters, giving due consideration to new biometric information. Sets of model parameters for spring wheat, spring barley, winter wheat, and potato are available.

Model application to new crop varieties or crops under new field management and soil conditions, may require an adjustment of 2-3 model parameters which can be achieved by considering local crop production data.

3.3.7.9 References


3.3.7.10 Contacts

O. D. Sirotenko
State Committee for Hydrometeorology and Control of National Environment
Hydrometeorological Service of the U.S.S.R.
12 Pavlik Morozov Street
D-376 Moscow 123376
U.S.S.R.

3.3.8 Simulator of Seasonal Forage Yield (SIMFOY)

3.3.8.1 Problem Area

For the Ontario dry weather crop insurance plan there is a need for an early evaluation of the influence of seasonal weather on the productivity of forage crops.

3.3.8.2 Objective

To estimate the relative yield of forage crops at the end of the growing season.
3.3.8.3 Model Description

The model is of the dynamic type which simulates daily growth from recorded minimum and maximum temperatures and estimated soil moisture. Submodels are required for calculating degree days above 5 degrees C., and for estimating soil moisture from rainfall and the modified energy balance approach for estimating evapotranspiration. Output is in the form of dates of harvest and the estimated yields for each of three growth cycles in a single growing season.

3.3.8.4 Computer Requirements

A large mainframe computer is required that accepts the FORTRAN programming language.

3.3.8.5 Scale

Estimated yields are made for specific farms. These can be plotted or mapped on any scale.

3.3.8.6 Data Requirements

3.3.8.6.1 Meteorological Data

Daily data are required for precipitation, minimum and maximum temperatures, and duration of bright sunshine for the duration of the growing season.

3.3.8.6.2 Crop Data

Dates of harvesting of the forage crops and their yields are required for model calibration and for validation purposes.

3.3.8.7 Validation and Application

Data from a growth-curve experiment in which forage harvests were made at weekly intervals during three growing seasons were used to develop the model. Yield data from other forage experiments harvested on the usual cutting dates were used for validation purposes.

3.3.8.8 Limitations and Remarks

Coefficients in the model are fairly specific as to species and location and would require adjustment for other environments and species.

3.3.8.9 References

3.3.8.9.1 Source


3.3.8.9.2 Background


3.3.8.10 Contacts

D. M. Brown
Agrometeorology
Department of Land Resource Science
University of Guelph
Guelph, Ontario, Canada. N1G 2W1.

Crop Insurance Commission of Ontario
Ontario Ministry of Agriculture and Food
Legislative Buildings, Queen's Park
Toronto, Ontario, Canada. M7A 2G1.

3.4 Crop Management

3.4.1 Crop-Water Balance Assessment and Prospective

3.4.1.1 Problem Area

The day-to-day management of land and rain-fed crops in semi-arid zones depends greatly on the timing of operations in harmony with the variability of rainfall and, particularly, the stored soil-water patterns throughout the growing season.

3.4.1.2 Objective

To provide assistance to farmers in determining the timing of weather-related farm operations by interpreting rainfall information in terms of soil water and related farm management practices and operations.

3.4.1.3 Model Description

The model is of the dynamic type and provides a quasi-real time monitoring of crops and their water balance. From this information advice is formulated for farm operations such as soil preparation, sowing, weeding, fertilizer application, supplemental irrigation, and plant protection measures.

Model output provides information of crop water use, estimated soil water deficits, 10-day water balance assessments and outlook for the next 10-day period, followed by advice on farm operations.

3.4.1.4 Computer Requirements

The minimum requirements are for hand-held calculators and programmable pocket calculators.

3.4.1.5 Scale

The information is provided on a minimum scale of a district consisting of groups of villages.
3.4.1.6 Data Requirements

3.4.1.6.1 Meteorological Data

Observations of rainfall, minimum and maximum temperatures, duration of bright sunshine or global radiation, atmospheric humidity, and wind run are required on a daily basis. Statistical information is required on the distribution of 10-day rainfall.

3.4.1.6.2 Crop Data

Crop calendar information is required.

3.4.1.6.3 Soil Data

Information is required on the hydrological characteristics of soil such as water holding capacity, infiltration rate, and rooting depth.

3.4.1.7 Validation and Application

The model is being field tested for rainfed crops in semi-arid areas in a pilot project in Mali.

3.4.1.8 Limitations and Remarks

The model does not consider water losses by surface or sub-soil drainage.

Advice on farm operations varies from locality to locality and needs to be formulated in consultation with an officer of the agricultural extension service.

Lack of meteorological data is a major limitation. A fairly long series (20 years or more) of 10-day rainfall totals and their variability must be available for each location, as well as current basic agrometeorological data.

3.4.1.9 References


3.4.1.10 Contacts

M. M. Kanate
Division Agrometeorologie
Meteorologie Nationale
B.P. 237
Bamako, Mali.

3.4.2 Optimal Use of Nitrogen on Pastures in Springtime

3.4.2.1 Problem Area

Applying nitrogenous fertilizers to pastures too early before spring growth starts is wasteful of fertilizers due to leaching. Applications made too late do not benefit the development of new root and top growth when the need for nitrogen is greatest. The determination of the optimum date is critical and is weather-dependent.
3.4.2.2 **Objective**

Using a weather-based model, to provide a service to farmers in regard to the timing of the application of nitrogenous fertilizers in order to assist in reducing nitrogen fertilizer losses and to increase pasture productivity.

3.4.2.3 **Model Description**

The model is quite simple, being based on the temperature remainder index model (TRIM) used for estimating development of crops. In this case it makes use of the sums of daily mean temperatures above zero degrees C, starting at 1 January. The optimum time for fertilizing pastures with nitrogen is reached when the sum of the positive temperatures exceeds 250 degree days.

3.4.2.4 **Computer Requirements**

Computers are not necessary.

3.4.2.5 **Scale**

Scale depends on the representativeness of the weather data. Models are used normally on a site scale level.

3.4.2.6 **Data Requirements**

Daily mean temperatures.

3.4.2.7 **Validation and Application**

The model is used by the German Agrometeorological Service. When the critical temperature sum is reached at a given station the fact is recorded in the weekly reports issued by the Agrometeorological Service.

3.4.2.8 **Limitations and Remarks**

The validity of the model is verified with data obtained from experimental plots at several weather stations. Weighting factors for certain months are necessary and these have been determined from the experimental data. Temperature summation is usually taken from 1 January but may be from a later date should there be a cold spell that introduces late plant dormancy.

3.4.2.9 **References**


3.4.2.10 **Contacts**

Zentralamt des Deutschen Wetterdienstes
Abt. Agrometeorologie
Frankfurter Str. 135
Offenbach
Germany (FR).
3.4.3 Sorghum Growth Model (SORGF)

3.4.3.1 Problem Area

Mechanistic crop weather models can be effectively used to answer management "what if" questions. For example, what if crops are planted late, or early; what if precipitation does not arrive? How much irrigation will be required to produce a successful crop?

3.4.3.2 Objective

(a) To monitor potential productivity of sorghum;

(b) To provide management (farmers, ministry of agriculture, etc.) with a tool to investigate the feasibility of alternative strategies.

3.4.3.3 Model Description

The model is of the dynamic type which simulates daily development and growth, and final yield of sorghum. A unique feature of the model is the capability of updating the computations at any point in the growing season with actual values of observed field parameters. This process has been termed "feedback".

3.4.3.4 Computer Requirements

The programme was written in FORTRAN, but an interactive version in BASIC has been written for the microprocessor.

3.4.3.5 Scale

The programme can be used at the farm level or for a region depending on the aggregation of the meteorological stations.

3.4.3.6 Data Requirements

3.4.3.6.1 Meteorological Data

Requirements are for the basic data: daily minimum and maximum temperatures, precipitation, and global radiation. Latitude of the site is also required.

3.4.3.6.2 Crop Data

The required crop data include row spacing, plant population, planting date, depth of planted seed, and maximum leaf area and number (maturity genotype).

3.4.3.6.3 Soil Data

The maximum water holding capacity of the soil and the initial water content in each layer of the root zone is required. The number of layers is defined by the user.

3.4.3.6.4 Management

Irrigation is required if possible.

3.4.3.7 Validation and Application

The model has been used successfully in Texas and Kansas in the U.S.A. and by ICRISAT in India.
3.4.2.8 **Limitations and Remarks**

Soil water balance may be biased towards excessive use. For microprocessors, execution time is approximately 20 minutes for a crop year.

3.4.3.9 **References**


3.4.3.10 **Contacts**

G. F. Arkin or B. Jackson
Texas A & M University
College of Agriculture
Blackland Research Center
Box 748
Temple, Texas, U.S.A. 76503.

3.5 **Pest and Disease Assessment and Management**

3.5.1 **Epidemics Prediction and Prevention**

3.5.1.1 **Problem Area**

Pest and disease problems during the growth period of winter wheat, especially during the grain filling phase may cause yield losses. Indiscriminate use of biocides may cause environmental problems due to residues, etc.

3.5.1.2 **Objective**

To provide a supervised pest and disease control service that incorporates the existing knowledge of the biology of the pests and pathogens and leads to economically sound recommendations to the farmer.

3.5.1.3 **Model Description**

The system predicts the development of a certain pest or disease (including yellow rust, septoria SPP, mildew, brown rust, English grain aphid, rose-grass aphid, and bird cherry oat aphid) for a given prognosis period, the length of which is dependent on the phenological development stage of the crop. From the predicted pest or disease development, an expected yield loss is calculated, taking into account the type of pathogen involved, the phenological stage of the canopy, the yield expectation in the absence of pests and diseases, and the weather expectations for the prognosis period.

On that basis the system formulates a recommendation to the farmer: (a) to apply a biocide within a certain period, if the expected yield loss exceeds the economic threshold, i.e., if the value of the yield loss exceeds the cost of the treatment; (b) to supply the system with a new set of observations within a specified period if it is a border-line case; and (c) to refrain from action if there is little or no expected damage.
3.5.1.4 Computer Requirements

The system is formulated in FORTRAN and is operational on a number of computer systems, amongst which is a PDP-11.

3.5.1.5 Scale

The system operates on an individual field basis.

3.5.1.6 Data Requirements

3.5.1.6.1 Meteorological Data

Observations of actual air temperature and global radiation are required on a real time basis up to the beginning of the prognosis period and are used to update the yield expectation. Estimated air temperatures are required for each prognosis period.

3.5.1.6.2 Crop Data

Farmers periodically report the phenological stage of the crop and the incidence of various pests and diseases (incidence counts on a limited number of plants). Also required at the beginning of the season is information on the crop variety, sowing date, and sowing density.

3.5.1.6.3 Soil Data

Soil type is obtained from the National Soil Survey Classification.

3.5.1.6.4 Management Data

Information is required from the farmer on the previous crop, fertilizer application (time and rate), application of growth regulators (type and time), and application of biocides (type, rate and time).

3.5.1.7 Validation and Application

Actual validation is not possible. The system is operational at this moment in the Netherlands, Switzerland and Belgium on a routine basis and in England, France and Sweden on an experimental basis.

3.5.1.8 Limitations and Remarks

Application of the system depends on the willingness and ability of the farmer to recognize the symptoms of the most important pests and diseases. The successf ulness may be estimated from farmer's participation rate since he pays for the participation.

3.5.1.9 References


3.5.1.10 Contacts

K. Reinink
Experimental Station for Arable Crops and Horticulture (PAGV)
Lelystad, the Netherlands.

R. Rabbinge
Department of Theoretical Production Ecology
Agricultural University
PO Box 14
Wageningen, the Netherlands.

J. C. Zadoks or F. H. Rysyk
Phytoconsult Ltd.
Wageningen, the Netherlands.

3.5.2 Integrated Pest Management System for Cotton

3.5.2.1 Problem Area

High input irrigated cotton production has involved increasingly heavy applications of pesticides with associated problems of cost and pollution of the environment. A reduction in the use of insecticidal treatment while maintaining economic control is necessary.

3.5.2.2 Objective

To provide an integrated system of pest management service for irrigated cotton that takes account of pest population dynamics and its influence on yield accumulation and which estimates the potential cost/benefit ratio associated with discrete control events.

3.5.2.3 Model Description

The model simulates the growth and development of the cotton crop, paying particular attention to those components of the system that determine harvested yield. Water and nitrogen applications are accounted for in terms of plant response. Sub-models simulate the population dynamics of pests and associated damage.

3.5.2.4 Computer Requirements

Currently the entire system is centralized with data inputs fed into the CYBERNET system controlled by a CYBER-76 computer in Canberra. Sub-models and components can be run on a minicomputer such as PDP-11.

3.5.2.5 Scale

The model is applied to each management block of irrigated cotton. This might mean as many as 10 separate simulations for any given farm.
3.5.2.6 **Data Requirements**

3.5.2.6.1 **Meteorological Data**

The model requires daily observations of precipitation, minimum and maximum temperatures, estimated global radiation, and estimated potential evapotranspiration.

3.5.2.6.2 **Crop Data**

The model requires information on cultivar characteristics and the densities of pest species in a sample area as determined by regular “scouting”.

3.5.2.6.3 **Soil Data**

Information on available water extraction capacity, infiltration rates, and hydrological parameters is required.

3.5.2.6.4 **Management Data**

The model required information on the date of planting, row spacing and population density, irrigation timing and amount, and pesticide application timing and amount.

3.5.2.7 **Validation and Application**

The system is established and is now in commercial operation. Field sampling and monitoring of actual crop performance provides feedback to maintain and correct the calculations during the crop cycle if necessary. The system has been operational in the major cotton district of northern New South Wales since 1980 and is being extended to include districts further north in Queensland, in Australia.

3.5.2.8 **Limitations and Remarks**

Input data requirements are simple, but some are labour intensive and therefore costly. Attempts are being made to increase efficiency.

3.5.2.9 **References**

A number of papers, reports, technical manuals have been issued by the CSIRO Division of Plant Industry, Cotton Research Institute.

3.5.2.10 **Contacts**

Cotton Research Institute  
Division of Plant Industry  
CSIRO  
Narrabri, New South Wales  
Australia.

3.5.3 **Sclerotinia sclerotiorum on Sunflower**

3.5.3.1 **Problem Area**

Sclerotinia sclerotiorum development on sunflower is limited by one main factor, the presence of free water on the flowering heads for 40 consecutive hours. This is closely dependent on climatic conditions. An operational model has been established to predict the duration of wetness on the heads from standard meteorological parameters.
3.5.3.2 **Objective**

The objective is to assess the zones where the disease could be frequent since the surface area being sown to sunflower is increasing.

3.5.3.3 **Model Description**

The model simulates the water balance of the sunflower head, giving consideration to evaporation and interception of precipitation and condensation (dew). The model is a biophysical type, functioning on an hourly time scale, and based on the energy balance equation. It needs a reconstitution of the rycthemeral profiles of temperature and relative humidity, and a parameterization of the global radiation. The long periods with a positive water balance on the sunflower head can be memorized and after simulation using a 30-year historical meteorological data set, it is possible to determine the frequency of occurrence of periods with 40 hours or more with free water at the surface of the sunflower head.

3.5.3.4 **Computer Requirements**

The programme was written in FORTRAN and installed on a CDC-175.

3.5.3.5 **Scale**

The model is applied on a subnational basis.

3.5.3.6 **Data Requirements**

3.5.3.6.1 **Meteorological Data**

The model requires daily observations of precipitation, minimum and maximum temperatures, wind speed, duration of bright sunshine, and relative humidity or vapour pressure. Derived hourly values of these factors are calculated by means of submodels.

3.5.3.6.2 **Crop Data**

The model requires information on the resistance of the crop canopy to heat and water vapour transfers. The capacity of the sunflower head to intercept rainfall is also required.

3.5.3.6.3 **Soil Data**

Information on available water capacity and on soil thermal characteristics is required.

3.5.3.7 **Validation and Application**

The model was tested by a comparison with observations. Short periods of wetting are not detected by the model with accuracy. Periods of wetting longer than 24 hours are well detected and those above 40 hours are adequately detected.

A good match has been obtained between observation and the predictions of the model. A simulation study has also been carried out on the basis of 30 years' meteorological data for a number of sunflower-growing areas. This establishes the zones with climatic conditions favourable to S. sclerotiorum and hence the climatic potential of the disease in France.
3.5.3.8 Limitations and Remarks

The results are local. For instance, orographic effects are very important.

3.5.3.9 References


3.5.3.10 Contacts

D. Payen or E. Choisnel
Meteorologie Nationale
2 avenue Rapp
F 75007 Paris, France.

3.6 Research Strategy

3.6.1 Identification and Selection of Technology

3.6.1.1 Problem Area

The allocation of limited resources available for research between different subject areas is an increasing problem for management concerned with research strategy.

3.6.1.2 Objective

To develop a tool that can be used to identify economically or otherwise promising new technologies for a given region, taking into account the regional resources and, from these, infer areas for research and development.

3.6.1.3 Model Description

The model determines a time series of an optimum mix of technologies ("agricultural systems") on the basis of a preset objective function which may be, for instance: "maximizing the output of the region" or "optimizing the available labour in the region". For this purpose a linear programming model is applied, in which the relevant technologies are defined in terms of input/output relations, i.e. for each of the agricultural systems the marketable (or otherwise economically important) output is defined along with the necessary inputs to achieve that output.

The regional resources are defined by its borders, the available land classes, physical and financial capital, available labour, and plant and animal genetic stock.

The algorithm applied is multiperiod, which means that one year's outcome is used to initialize the next year's calculations, whereas physical capital may be transferred from one year to the next.
3.6.1.4 Computer Requirements

Application of the model requires a large computer system (e.g. IBM-370 or DEC-10) and the availability of a relatively sophisticated linear programming algorithm.

3.6.1.5 Scale

The model has been applied to a district within a country. It could be applied at a national level, provided that the exchange at the borders can be described in quantitative terms.

3.6.1.6 Data Requirements

In this case, the data requirements cannot be schematically defined in terms applicable to crop-weather models, since the output of such models serves as input to the model described here. For data requirements, reference is therefore made to the description of the various crop-weather models in Sections 3.1 and 3.3 of this chapter.

3.6.1.6.1 Meteorological Data

Long-term weather records are necessary to define the sequence of "normal" and "deviating" years.

3.6.1.6.2 Crop Data

The possible crops suitable for the region should be considered.

3.6.1.6.3 Soil Data

The extent of the various soil types in the region should be available.

3.6.1.6.4 Management

This is probably the most important criterion in this model: different management systems must be defined based on such criteria as labour intensity, degree of use of outside resources, application of resources generated inside the region, etc. It requires a thorough knowledge of the alternative land use possibilities of the region.

3.6.1.7 Validation and Application

Since the model generates "feasible courses of development" for a given region, on the basis of agrotechnical and (some) economic information, it cannot be validated as such.

3.6.1.8 Limitations and Remarks

The present computer requirements are a serious limitation to application of the model. However, when applied in the framework of regional development programmes they could constitute an important tool.

3.6.1.9 References

3.6.1.10 Contacts

I. Spharim or N. G. Seligman
Agricultural Research Organization
Volcani Centre
P.O. Box 6
Bet Dagan, Israel.

3.6.2 Exploring Potential Improvements to Production Systems

3.6.2.1 Problem Area

Given limited research resources available for the whole complex of factors influencing crop (potato) production across the wide range of production environments in Australia, how can critical experiments be devised, current field experimentation be upgraded, and alternative research approaches be identified?

3.6.2.2 Objective

To develop a biophysical model of the crop system that can be used at:
(a) site level for experimental crops; (b) district or regional level for commercial crops; and (c) national level for development of a potato crop monitoring and forecasting system.

3.6.2.3 Model Description

The model is simple, deterministic and empirical, but functions are based on an understanding of the physiology and the yield accumulation in potato crops.

The model simulates the time course of development and the pattern of tuber bulking, given inputs of weekly mean minimum and maximum temperatures, global solar radiation, day length, and an estimate of the maximum soil-water deficit experienced during bulking. Because all functions are based on crop time and not calendar time, the model is general and not location-specific in its application. The model generates the time course of yield of fresh weight of tubers.

3.6.2.4 Computer Requirements

The model can be calculated directly using paper and pencil, but a hand-held calculator version, in combination with a set of tables, is available.

Initial programming, testing and subsequent operation of the model, involved programming in FORTRAN IV and use of a CYBER-76 computer. A listing of the programme is available from the authors.

3.6.2.5 Scale

The model was developed initially using data from individual experimental crops and then extended to cover district and regional aggregates. The model operated satisfactorily over this range of scales, but some adjustments are necessary when considering aggregate crops within a broad region.

3.6.2.6 Data Requirements

3.6.2.6.1 Meteorological Data

Weekly averages of minimum and maximum air temperature, global solar radiation, and day length are required for the model.
3.6.2.6.2 **Crop Data**

It is necessary to know the cultivar and certain factors concerning its performance. For new cultivars where key factors are unknown a series of simple experiments will be necessary to determine the timing of emergence, tuber initiation, start of tuber growth, attainment of maximum bulking rate, cessation of bulking, and attainment of tuber maturity or skin hardening. The values of these factors have been established for the cultivars Sebago, Kennebec, Pontiac and Sequoia. First approximation of the new cultivar's performance can be derived usefully be comparison with that of any one of these established standards.

3.6.2.6.3 **Soil Data**

At this stage soil factors are regarded as non-limiting since, in Australia, potatoes are a high value crop grown under relatively high-input conditions.

3.6.2.6.4 **Management**

Date of planting is required; also a derived management factor \( m \) where \( m = 1 \) indicates optimum management.

3.6.2.7 **Validation and Application**

The model was developed and functions fitted using experimental data from well-managed field crops at four widely separated locations spanning 25° of latitude (15°S to 40°S). Parameters were optimized using these data sets and a single, general model comprising eight basic equations was shown to give a good fit to the data from each location.

With minor modification necessary for adjustment to aggregated commercial crops in major production areas, the same basic model was shown to give good predictions of commercial yields throughout the whole range of environments in Australia.

Simulation studies using the model showed that there is considerable scope for yield improvement in many districts; that in well-established districts the optimum timing of production has been fixed by trial and error experiment, but that predicted optimum times in potential new districts are sometimes unexpected; and that hopes of exporting seed potatoes to lowland tropical regions appear to be impractical on physiological grounds.

Further studies highlighted gaps in knowledge of physiology and suggested alternative research strategies, including:

(a) the collection and publication of a standard minimum data set from field experiments;

(b) the collection of similar data sets from selected commercial crops so that the influence of management can be quantified and commercial yields predicted more accurately;

(c) greater use of innovative experimental designs that facilitate the acquisition of data needed for development of general functional relationships.

3.6.2.8 **Limitations and Remarks**

The major assumptions and weaknesses of the model have been detailed in the third paper describing the model and its application.
The most important weakness of the model, in so far as rainfed crops are concerned, is the lack of a component for water balance. Also, specification of the management rating is subjective.

3.6.2.9 References


3.6.2.10 Contacts

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3.6.3 Technique for Planning Research Strategy

3.6.3.1 Problem Area

During the development of crop-weather models, it is sometimes necessary to have information regarding critical periods during the development of crops, together with important environmental factors during these periods, which affect various aspects of crop production. Ordinary correlation techniques often provide misleading results, particularly when only small samples are available.

3.6.3.2 Objective

(a) To assess the relative importance, in the long term, of various phases of development on crop production or any other phenomena which one might want to study such as winter survival, etc. (b) To determine which environmental factors are influential at various stages of development.

3.6.3.3 Model Description

The model provides a statistical, non-parametric test. The output consists of the number of significant climatic differences for various stages between the poor and the good years. Also shown is the relative importance of various developmental phases which affect the growth or development factor of interest.

3.6.3.4 Computer Requirements

The programme is written in FORTRAN and is adaptable to most mini or larger computers.
3.6.3.5 **Scale**

The technique which is based on non-parametric test is applicable for any location.

3.6.3.6 **Data Requirements**

The calculations can be made for any crop factor for any location for which at least six years of biological and environmental data are available.

3.6.3.6.1 **Meteorological Data**

Any desired or available observed weather data together with the relevant derived data corresponding to the period of the biological data are required on a daily basis.

3.6.3.6.2 **Crop Data**

Biological data for the factor of interest is required for a period of at least six years.

3.6.3.7 **Validation and Application**

The technique is simply a synthesis of the existing situation. It can be used to find some general information on a particular problem.

3.6.3.8 **Limitations and Remarks**

This technique is based on a non-parametric test and for this reason the information is not of an absolute nature. The general conclusions are not likely to be affected by one bad data set.

3.6.3.9 **References**

Desjardins, R. L. and C. E. Ouellet, 1977a. Climatic determinations of critical periods for (1) alfalfa winter survival, and (2) spring wheat yields. In: Proceedings of the Thirteenth Agriculture and Forest Meteorology Conference, Purdue University, 29a-29b.


3.6.3.10 **Contacts**

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3.7 Derived Data Sub-Models

3.7.1 Global Solar Radiation: The Malaysian Model

3.7.1.1 Problem Area

In many crop-weather models it is desirable to use weather factors which are more closely related to crop response than the basic weather elements which are readily available. A good example is soil water which can be derived from daily rainfall observations and derived potential evapotranspiration (PET). PET in turn can be derived from basic observations of air temperature, humidity, wind speed and global solar radiation. Global solar radiation in turn can be derived from the duration of bright sunshine. Global solar radiation is also more useful in crop-weather models than is any measure of sunshine duration or cloud cover.

3.7.1.2 Objective

To estimate daily global solar radiation from observations of daily duration of bright sunshine and daily rainfall amount.

3.7.1.3 Model Description

The model makes use of the familiar Angstrom formula for estimating global solar radiation from observations of the duration of bright sunshine, making use of the calculated value of the incident solar radiation entering the upper atmosphere. Two corrections are made to the original equation, however.

The first is based on research by Fitzpatrick and Stern (1965) which deals with the non-linearity of the relationship which occurs when skies are overcast and when daily values are used. The second deals with a correction due to the variable transmissivity of clouds under completely overcast conditions. This correction is based on daily rainfall amount which gives some indication of the density and hence the transmissivity of clouds. These two corrections appear to remove the necessity to separate transmission coefficients for each month of the year and for each location, particularly in the humid tropical areas.

3.7.1.4 Computer Requirements - are minimal.

3.7.1.5 Scale

Calculations should be made daily on a point basis.

3.7.1.6 Data Requirements

Daily observations of the duration of bright sunshine (as measured by sunshine recorder) and of daily rainfall are required. Also required are calculations or tabulated values of daily day length (from sunrise to sunset) and the daily intensity of incident solar radiation at the top of the atmosphere. If available, observations of daily global solar radiation (from a pyranometer) would be useful for validating the model for a specific location.

3.7.1.7 Validation and Application

The model and its coefficients were developed by making use of data for Singapore. It has been validated by making use of data from a different rainfall regime in central West Malaysia and has been used throughout Malaysia in connection with oil-palm yield studies.
3.7.1.8 **Limitations and Remarks**

Since the rainfall correction term is zero if there is no rain and since both correction terms rapidly approach zero as sunshine duration increases from zero, the model should be applicable to a wide range of climatic conditions. However, validation under other climatic conditions is advisable. The transmissivity coefficient for clear skies may need adjustment depending on a number of factors including vapour pressure, altitude, dust and other pollutants, and latitude.

3.7.1.9 **References**

3.7.1.9.1 **Source**


3.7.1.9.2 **Background**


3.7.1.10 **Contacts**

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3.7.2 **Soil Water: The Versatile Soil Water Budget**

3.7.2.1 **Problem Area**

Soil water information is probably the most important data requirement in the development and use of crop-weather models. Such information is very difficult to come by as it does not exist in historical weather records and it is expensive and laborious to measure on a routine basis. Fortunately there are a number of good sub-models for estimating soil water from basic weather data and certain soil and crop parameters.
3.7.2.2 **Objective**

To estimate daily soil water from observations of daily rainfall and calculated potential evapotranspiration.

3.7.2.3 **Model Description**

The sub-model described herein is called the Versatile Soil Water Budget (Robertson, 1977) and is a modification of the Versatile Soil Moisture Budget developed by Baier and Robertson (1966). It considers the soil as made up of a number of zones each having a specified available water holding capacity and a water release curve, both of which are dependent on the physical characteristics of the soil.

Some knowledge of the relative root concentration in each zone is required. This can be estimated from knowledge of the soil profile and the general rooting habits of the crop. Information concerning the degree of canopy closure is necessary in order to partition the amount of water transpired by the crop and evaporated by the soil surface.

The budget can be used for any crop on any soil by the proper selection of soil and crop parameters. In fact it has been used for multiple story and interplanted crops by running two or more parallel budgets simultaneously (Robertson, 1976).

3.7.2.4 **Computer Requirements** are minimal.

3.7.2.5 **Scale**

Calculations should be made daily on a point basis but apply generally to areas of a few hectares or larger, depending on the representativeness of the meteorological observations and of the soil and crop parameters.

3.7.2.6 **Data Requirements**

3.7.2.6.1 **Meteorological Data**

Daily rainfall amount and measured or estimated daily potential evapotranspiration (PET) are required.

Since daily rainfall amount is highly variable it is the most important factor in the model and, therefore, PET determinations need not be too precise. In fact weekly or monthly averages may suffice in many cases.

3.7.2.6.2 **Soil Data**

The total available water in each selected zone is required as well as some knowledge of the water release curve for the soil in each zone. Where evaporation from bare soil is sufficiently significant to be included in the calculations a knowledge of the porosity of the soil and its cracking characteristics are also required.

3.7.2.6.3 **Crop Data**

The relative root concentration in each zone is required. This can be estimated from knowledge of the rooting habit of the crop. Also required is information on the degree of canopy closure at progressively later phenological stages in the development of the crop.
3.7.2.7 Validation and Application

The versatility and universality of the model has been demonstrated by applications to many agronomic problems both in Canada and in other countries with climates ranging from temperate to tropical and from humid to semi-arid.

3.7.2.8 Limitations and Remarks

The main restriction to the use of the model is lack of information concerning the required crop and soil parameters. Although these can be estimated from general knowledge of the specific crop and soil being considered, actual measurements of these parameters would improve the reliability of the results.

Although the model permits the calculation of soil water in any number of soil zones, a minimum of three zones appears to be a practical number.

Tests using actual measurements of soil water indicate that soil-water calculations are as reliable as are actual observations for areas of a few hectares and larger. Furthermore, the budget has the additional advantage of making it possible to calculate soil water on a daily basis using either historical or current weather data depending on the application.

3.7.2.9 References

3.7.2.9.1 Source


3.7.2.9.2 Background (see also paragraph 3.3.5.9)


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CHAPTER 4

DATA REQUIREMENTS AND PROBLEMS

4.1 Introduction

This chapter will address some of the problems associated with acquiring and building a database for operational applications. Techniques that can be applied to a usable and effective database will also be discussed.

A basic limitation to using the models described in Chapters 2 and 3 is the availability of data. The database not only includes historical data for model development and validation but also current data to be used in an operational system. Furthermore, these databases may include those of an ancillary nature such as narrative description of episodes of disease, insects, flood, and wind. As discussed in the previous chapters, the selection of the model is determined by the purpose and objectives of the problem. These are dictated by the users who may be national policy makers, farmers, bankers, or scientists, concerned with food production issues.

4.1.1 Operational Problems

In this guide, the term "operational" refers to the accessibility of the model applied to a specific problem after undergoing a test period and creating information for a management decision. In most cases, these models are documented. This is in contrast with models under development. In some cases, operational models are continually being improved while they are being used to provide information and assist in management decisions.

A major issue for an operational model involves the time and space scales. The temporal scale may include a period from a day (hour if the model specifies this requirement) to a period of a few months. The shorter time scale might include applications in production forecasting, phenological development or management decisions involving pesticide application for disease and insects. The longer time includes applications in risk analysis and scenario analysis such as land-use involving possible changes in the climate.

Operational problems are invariably linked to communicating the data to a central location where the models are used. These communication linkages may involve a courier, telegraph/telephone, teletype and/or other hardware connected with the computer. It is essential that these linkages are reliable so missing data can be kept to a minimum. In addition to communication linkages, the information requirement for the user of a model in problem application must consider the following: (a) data quantity, quality and availability; (b) reliability of the model, including timeliness; and (c) cost effectiveness of the system.

4.1.2 Homogeneity of Data

Thom (1966) defines homogeneity as a data series each sample of which is derived from a single population. This means that factors which could alter the natural variability of a location, such as station moves, instrument changes and physical changes in the environment, such as traffic or tree growth, must be considered. Heterogeneous data could lead to results that are misleading and erroneous. A major portion of model development and application should be allocated toward the basic data base development including a homogeneity analysis. In essence, results and methods can only be compared with each other if the data are from the same population.
There are several ways to check for homogeneity. Thom describes a non-parametric method. Another simple, practical way is to plot a time series of the variable (double-mass plotting). Data with a shift in the trend should be treated as suspect. Similarly, observations which are identical for a few days or months (e.g., precipitation) should be scrutinized carefully. A station history may be available. This should be used to describe moves, instrumentation changes and problems, observer(s) changes and dates, responsible agency, to include a few. For example, a sudden 10 degree change for the minimum temperature in the record may suggest a new observer problem or instrument problem. A knowledge of the climate and the variability of an area can also provide background information that can be used to discard or accept an unusual observation. Unusually large precipitation amounts can be analysed from written accounts in reports, newspapers and other journals if these events have economic or humanitarian impacts.

Data homogeneity does not only apply to meteorological variables. Crop production data should also be carefully examined. Geographical changes in reporting zones affecting the level of aggregation can occur. Other potential heterogeneity problems include units of measurement (e.g., per harvested or planted area); inclusion of grain for human consumption or for animal feed; or spring wheat or durum wheat, introduction of new varieties and hybrids or problems arising from statistical treatment of the original data (e.g. changes in the conversion from paddy to brown rice). These must all be consistent for the duration of the data base. Phenological periods should be identified with uniform morphological or biological characteristics.

4.1.3 Missing Data

This is a common problem. The solution is not easy and is often tedious. However, replacement of missing data can resolve other problems which may surface later, particularly those involving model development and operational use. For example, for crop model development daily data may be required for a specific period. Data missing during this period must be estimated or the model must be developed without data for this period. The extent of how much data should be replaced can only be resolved by judging the results. The question "Are the results reasonable and in line with expected results?" should be asked.

Three methods have been used to fill missing data: (a) The difference method is used to adjust temperatures for homogeneity; (b) The ratio method can be used to fill in or replace missing precipitation data. It is clear that the shorter the time period, the greater the error size of these estimated data. For example, a daily estimate of precipitation at a site is much more variable than an estimate for a month; (c) Isohyetal analysis, is probably the best way to estimate missing precipitation or temperature data. This method requires plotting all observations surrounding a station that has questionable or missing data. A subjective estimate is made based on topography and synoptic characteristics.

4.2 Spatial and Temporal Scale

Selecting the desired number of stations and the frequency of the meteorological reports from these stations will always need to be addressed by the user in view of the problem on hand. For example, the farmer will be interested in impacts on his farm or field size, where data requirements involve daily, monthly and seasonal values; the national policy maker is interested in large-scale features where information on seasonal effects is desired. Applications to land use evaluation may require regional scales involving a geographic section of a country. In this case, decadal or monthly data may suffice. The scaling requirements in turn affect the cost of providing the information. The cost increases exponentially as the spatial scale is reduced. Figure 4.1 shows the hypothetical cost of providing data when the density of station
Figure 4.1 - Hypothetical cost related to the temporal and spatial scale data requirements
network is increased. Similarly, the cost increases exponentially as the meteorological requirement spans from yearly to monthly to weekly to hourly frequency.

The most difficult variable to estimate is precipitation. Observations within a reporting network are only samples of the "real" rainfall, often highly variable over short distances. In crop/weather model application, the problem is to describe an amount which represents the depth of water over an xy plane such as that shown in Figure 4.2. The amount in this sub-set crop region can be estimated by one of several ways: (a) Averaging of those stations within and surrounding the area of interest where the stations can be weighted so more weight is given to the stations which represent a larger proportion of the crop acreage; (b) Establishing a polygon around each station with the amount in the polygon represented by the report of the station within the polygon with the estimate of the large area weighted by the polygon size; and (c) Using the isohyetal analysis method and interpolating the values visually. The last procedure is subjective and time-consuming, but provides the best estimate which can be produced by experienced meteorologists.

Compromises are also necessary when selecting weather stations. Generally only stations which are a part of a synoptic network and publish recent data should be selected. Sometimes, however, the location of the station may be unacceptable because the observations are influenced by local characteristics such as location of the station on a top of a hill or inside of a town.

Another question deals with the optimal time unit for weather data. With respect to physiological processes during yield formation, phenological periods would be the best practical subdivision of the growing season. However, weather data for such periods are rarely available. Also, phenological periods for large areas need to be estimated, because development of plants is not similar if the conditions in the whole area are not the same (different varieties, deviations in sowing time, fertilizing). Therefore, in most cases calendar time is used. The question is whether values for a month, decade or pentad should be used. According to Hanus (1969, 1978), the optimal length of the period of time depends on the length of the historical sample. Smaller time units increase the number of predictors in relation to the normally small sample size. In many cases monthly values led to sufficient results (Hanus, 1978).

For crop/weather model application, two different spatial scales may be distinguished:

(a) Models for a small site scale with uniform weather conditions (a single field or farm or a small production area with uniform conditions);

(b) Models for larger areas with great regional differences in the weather cycle or other production conditions (models on district, state or continental level).

To estimate yield of larger areas two different procedures are possible:

(a) Subdivision of the entire area into smaller regions with climatic conditions as similar as possible. For each region individual models are developed and yields of this region are estimated with weather data from one or more stations of that region. The individual results are aggregated to a weighted mean for the whole area. The weights (such as acreage) may be assigned according to potential productivity.

(b) Development of a model to estimate the mean yield for the entire area directly. In this case the weather data of several observation stations are correlated with the mean yield of the whole area.
Figure 4.2 - Conceptual description of the rainfall distribution problem in crop region $R$ described by a response surface represented by the observing stations.
The second procedure is usually easier because the statistics of yields are often based on political units (districts, countries, states) and not on natural uniform production regions. However, the disadvantage of this type of scale is the possible insensitivity of the models to a wide range of weather conditions in a large region.

To forecast yields for a political subregion with different natural conditions (districts in a state) the situation is basically the same as for the whole area, but on a lower level. One also needs observations of several stations to consider the regional differences in the weather cycle and the production conditions in each subregion. Therefore, the required number of weather stations is much higher than needed for forecasting the mean yield of the entire area directly. In a real-time operational scheme, the required amount of data may not be available.

4.3 Ground Observed Data

Three types of observed data required in model development and application are discussed in this section. They include crop, soil and meteorological data. For convenience, data dealing with pests are considered in the "crops" section. The extent to which these data are required will of course depend on the purpose of model application. In some cases, the necessary data may not be available. Therefore, the user either accepts less desirable data and supplements the analysis with other supporting information or decides that the task cannot be done.

These data sets may be either basic, supplemental or derived. Supplemental data may be required in some instances depending on the model application. Similarly, derived data which involve altering of basic observations may be the sole source of inputs into the modelling effort. Derived data can be used to minimize the collinearity problem associated with variables (e.g., temperature, precipitation) that are correlated with each other.

4.3.1 Crops

4.3.1.1 Yield and Production

Yield is defined as production of economic plant parts per unit land area. Since the area may change from year to year, production can be standardized by dividing it by area. Yield unit varies with different countries, but basically it involves the weight or number of the economic plant part per unit land area. Curiously, crop yield in the U.S. is reported as bushels per acre with the weight conversion factor varying for different crops. It is also important to recognize that the moisture content of a particular harvested crop may vary. In some countries, the harvested field moisture weight is not standardized. This leads to large variability in the data sets.

Estimation of yield can be partitioned into three main methods:

(a) Judgements of experts, at the smallest regional level possible, without sampling and thereafter aggregating and evaluating the data to be national level;

(b) Judgements of experts as previously, but sampling representative areas at the national or regional levels;

(c) Direct measurements of yield from samples collected from the field. There are two sources of error related to items (a) and (b). They are:
(i) the error in the evaluation of yield which cannot be computed because it is an error of judgement, and

(ii) the error related to the field sampling. This error is not only very important but also is unknown if no consistent sampling procedure is followed,

(iii) the third procedure has the advantage of being more reliable than the other two methods. Unfortunately, this method is very difficult to apply on some crop species, as measurable representative samples are difficult to collect as for example, the case for hay and perennial plants and is extremely time-consuming.

4.3.1.2 Phenology

One of the most important observations required for effective crop modelling is phenological data. These data provide inputs for certain stages of the crop, observed through morphological and other visual changes. The first task is to determine which stages are important. Agronomists have provided charts of selected morphological stages for crops (Figure 4.3). Several attempts have been made to better identify these specific stages (Large, 1954; Hanway, 1963; Haun, 1973; Vanderlip and Reeves, 1972; Waldren and Flowerday, 1979; Fletchinger, 1945) in terms relevant to the physiological and biochemical changes in the crop cycle. Morphologically, these phases are unique, although at times it may be difficult to determine the specific date of the stage. It is the usual procedure to record the 50 per cent date. This means that samples from more than one area should be taken. The per cent of the crop reaching a particular stage may be observed. By fitting a curve, the 50 per cent date can be determined objectively. An example of the formats to record these pheno-

logical observations is presented in Figure 4.4. The recorded stages will differ with different plants. Maturity is another crop stage that requires homogeneity in observation. In maize, the black layer in the grain has been accepted as the maturity date. Physiological maturity requires the inspection of plant tissues. In the case of annual plants, the problem of phenological observation is not as simple as that for a perennial plant. The big difference in the vegetative stages of the annual plants depend greatly on the planting or sowing date while the perennial plants, once in place, respond in relation to the climatic variations of the season. Furthermore, according to the degree of the plant integration of the environment, two kinds of observations can be considered: the plants could be bunched or spaced. In the first case, it is difficult and time-consuming to perform individual observations (the case for cereal). The beginning phase, considering the whole population, is when the organic phase is initiated. The full phase occurs when the initiation reaches its maximum intensity; for example, when for a given day the appearance of this phase is more important than in any other day. The ending phase is when the process is losing its intensity.

In the second case where the plants are in rows, spaces between rows allow for individual observations. These may consist of counting the number of individual plants that have reached the given organic phase. Therefore, the beginning, full or the ending phase can be determined according to the per cent (20%, 50% or 80%) of the sample population showing the characteristic.

4.3.1.3 Sowing, Harvest Dates

The date of planting is a starting point for some model applications. For others it may be emergence date. Like other phenological stages, it is difficult to suggest a specific date since in general practice planting may be spread over a few weeks in a given area. A mean date is often used, but the variability of these data must also be considered. Data analysed in North Dakota, U.S.A., indicate that even in a crop reporting district the variability of planting and other growth stages is about two weeks (Hill et al., 1980).
Figure 4.3 – Generalized growth stages of wheat, barley, oats and rye
### MAIZE

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<th>Sprouting</th>
<th>Tillering</th>
<th>Incipient cobbing</th>
<th>Pollination</th>
<th>Earing</th>
<th>Ripeness</th>
<th>Harvest</th>
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### WHEAT

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Figure 4.4 - Forms for recording biological and phenological observations - After A. J. Pascale, 1972.
4.3.1.4 **Hazards**

Another useful source of data is description of the extent of crop damage from hazards. These events and the damage from them are usually not modelled. Field description affected by these events should be noted. Hail, flood, disease, insect infestation, wind damage, and excessive wilting are but a few of the common hazards noted in the field. These data are most useful from a standpoint of providing information on the historical extent of damage by these hazards and their possible use in operational production forecasting.

4.3.1.5 **Disease/Insect Infestation**

The development of pests and diseases is strongly influenced by short-term weather conditions. Therefore, time units of weather data for pest and disease models are shorter than for yield models. Regional differences in weather also have to be considered. Predictions can only be made for areas where the weather is uniform. The effect of weather on pests and diseases also depends on the initial conditions during a critical stage of crop growth. The density of the population at the beginning of a favourable period and specific conditions of the multiplication cycle of the individual pest or disease must be accounted for in models. Because models have to consider these aspects, they are mostly dynamic type models. Statistical models are seldom reliable in such predictions. Also, when the models consider the regional differences in the weather cycle they can only give rough information for crop protection measures because conditions in single fields may be very different (special conditions of the weather, microclimatic conditions inside of a plant canopy, different resistance of the planted varieties, different susceptibility with respect to fertilizing, etc.). Successful application therefore requires individual field treatment especially with respect to pest and disease incidence at any particular phenological stage of the crop.

If special conditions exist, it is necessary to use direct observations of pests and diseases at the fields for accurate predictions. Infestation by pests are often made by counting the damage done by the pest or in some cases by the number of pests (in the case of insects) caught in a special trap. The problem of sampling must be carefully considered. Because the development of pests and diseases depends on microclimatic conditions all models are based only on a site scale level but sometimes results are aggregated to a higher level. There is usually a difference in predicting pests and diseases population. Diseases are closer correlated to weather conditions because the reproduction rate is high and favourable weather conditions may increase the population density rapidly. On the other hand, diseases are omnipresent, and the reproduction cycle can start anytime when favourable conditions occur. The intensity of the disease is a microclimatic phenomenon and favourable conditions during inoculation time are very important. It may also involve a host or a vector, such as the aphid, and other environmental variables may need to be considered. Therefore, representation of the field environment relative to the potential damage by the pest should be considered. Qualitative descriptions such as light, moderate, or severe should be avoided whenever possible. Percentage of plants infested or pest disease density per plant are better quantitative ways of using the information in model development.

The reproduction of a pest population normally runs slower than diseases. Some pests only produce one generation during the growing season of an agricultural crop or within a whole year. The probable yield losses from pests, therefore, depend both on the population density at the beginning of the growing season and on weather conditions within it (Buhl and Schutte, 1971).
4.3.1.6 Supplemental

There are many kinds of supplemental data that can contribute to the development and application of models, each of which may be unique to the problem at hand; many are desirable in the development of mechanistic models and useful from the standpoint of analysing management strategies. These include, but are not limited to: (1) plant density, (2) leaf area index, (3) varietal characteristics, (4) dry matter production and distribution (leaves, stems, roots), (5) grain number, (6) grain weight, (7) tiller number, (8) vernalization requirements, and (9) maturity groups (e.g., soybeans). Other kinds of data include chemical composition, e.g. protein content, and sugar content. Winter kill or low temperature damage (percent of acreage damaged) is also useful. An index of lodging, water potential, and stomatal resistance are some of the data necessary to review and apply selected models. Management data are included in this section. Irrigation, and fertilizer application rate, are two of the most frequently used variables in model application.

It is obvious that these data sets require a pool of human and computer resources alluded to in the discussion of different types of models. In some cases, special equipment may be necessary.

4.3.1.7 Derived

These derived variables are distinguished from the basic and supplemental data by the manner in which they are secured. Modellers and users of these models faced with a deficient data base, have developed algorithms to produce the derived data. One example is leaf area index (LAI). This index may be modelled as a function of plant population, growth stage, water and temperature (Baker, 1982). Pollock and Kanemasu (1979) used Landsat satellite data to estimate LAI for wheat. This derived variable was subsequently introduced into a model to estimate winter wheat yield in Kansas.

Another example of a derived variable in the absence of fertilizer rates is the use of nitrogen sales as a surrogate for applied nitrogen. The problem with this variable is that inflationary adjustments are required with time.

One commonly used derived variable is based on the relationship between photosynthesis and respiration with light interception. These relationships are often based on field chamber or greenhouse carbon dioxide rate measurements.

In essence, derived variables may become sub-models (sub-routines) of a larger programme. One recommendation provided by Hodges (1982) in evaluating process-oriented models is to modularize the various processes or sub-models by restricting the data flow in a programme so that each sub-routine (sub-model) has access to only those variables required. This restriction prevents unneeded variables from passing to another sub-routine and leading to unexpected changes in other parts of the programme. In statistical terms, it is desirable to minimize the errors of the sub-models that might lead to inflated or confounding effects in the yield estimation.

Aspects of a water-balance algorithm could also be included as desirable crop data. Rooting depth of different crops or cultivars plays a role in the amount of moisture extracted from the various layers of the soil. The depth of soil water extraction is also a function of soil texture and structure. These aspects will be discussed further in the following section.

4.3.2 Soil Data

The soil is a medium for roots that support the plants. The soil also stores water. It consists of organic matter, minerals, water and air. The capacity
of the soil to hold water depends on the soil structure, texture and organic matter content. The texture of the soil is determined by the particle size distribution of sand, silt and clay. The coarse textured soils include sand and loamy sand, while the fine textured soils include silty clay and clay. The soil depth refers to the thickness of the soil material that supports the plant for water and minerals.

Other terms related to soil moisture for which data are required include: bulk density, the density of the soil sample relative to the density of water. It is important in expressing the volumetric content of soil water by multiplying the per cent of water by dry weight. The per cent water by dry weight is determined by drying a soil sample at 105°C for 24 hours.

Another property of the soil profile is the permeability for water (hydraulic conductivity). The movement of water is a function of several factors, the major ones including soil structure and texture. Fine textured soils have slow permeability and coarse-textured soils have high permeability. In developing a soil moisture budget, it is important to consider this property of the soil.

In many applications of modelling, different characteristics of the soil environment are necessary. The soil-plant-atmosphere continuum is an interactive system and ignoring one facet may provide serious problems in reliably modelling the others. It should also be recognized that soil properties vary considerably. An area of field size will show large variability in its moisture retention. Therefore for forecasting grain yield in large land areas, it may be necessary to provide information on moisture content that considers this spatial variability. Unique problems associated with semi-arid and wet climates need to be known. For example, in the semi-arid region, soil problems may be associated with salt accumulation due to irrigation. In areas of excessive leaching, toxicity of selected elements, such as aluminium may be present.

In simplified regression models as well as mechanistic models, the major factor considered in modelling in soil water. From a practical viewpoint, moisture supply is the foremost factor in the operational mode. However, whenever the situation approaches more the optimum with respect to this factor, it is necessary to become aware of other limiting factors that will manifest themselves in crop production.

4.3.2.1 Soil Water

A user should become familiar with several terms related to soil water. Field water-holding capacity, the amount of water held in the soil after excess gravitational water has drained away, is usually associated with 0.3 to 0.5 atmosphere of tension or suction force. Permanent wilting refers to the moisture content at which the soil cannot supply water to the plant. By definition this is set at 15 atmospheres. This should not be confused with field observations of wilting of the plant. In some cases, the plant may wilt as a defense mechanism in response to the high atmospheric demand. This could occur even when there is ample water in the soil.

The amount of moisture between field capacity and the permanent wilting point is the available water. This amount differs with different soil types. Clay (heavy) soils contain more available water than sandy (light) soils. Commonly, the available water is separated into readily available (about 60 to 75% available) and available water. For coarse soils, readily available water is about 50 mm and for fine soils this is approximately 200 mm per one metre depth of soil. The available moisture is highly variable in the soil profile. However, for guidance, Table 4.1 provides information on the range of available water for soil with different textures.
### Representative Physical Properties of Soils

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Infiltration Capacity and Permeability cm/hour $I_f$</th>
<th>Total Porosity Space $%$</th>
<th>Bulk Density $\rho_b$</th>
<th>Field Capacity $%$</th>
<th>Permanent Wilting Capacity $%$</th>
<th>Total Available Moisture $%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy</td>
<td>5.1 (2.5-25.4)</td>
<td>38 (32-42)</td>
<td>1.65 (1.55-1.80)</td>
<td>9 (6-12)</td>
<td>4 (2-6)</td>
<td>5 (4.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>2.5 (7.3-7.6)</td>
<td>43 (40-47)</td>
<td>1.50 (1.40-1.60)</td>
<td>14 (10-18)</td>
<td>6 (4-8)</td>
<td>8 (6-10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loam</td>
<td>1.3 (0.8-2.0)</td>
<td>47 (43-49)</td>
<td>1.40 (1.35-1.50)</td>
<td>22 (18-26)</td>
<td>10 (8-12)</td>
<td>12 (10-14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay Loam</td>
<td>0.8 (0.3-1.5)</td>
<td>49 (47-51)</td>
<td>1.35 (1.30-1.40)</td>
<td>27 (23-31)</td>
<td>13 (11-15)</td>
<td>14 (12-16)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silty Clay</td>
<td>0.3 (0.02-0.5)</td>
<td>51 (49-53)</td>
<td>1.30 (1.25-1.35)</td>
<td>31 (27-35)</td>
<td>15 (13-17)</td>
<td>16 (14-18)</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>0.5 (0.1-1.0)</td>
<td>53 (51-55)</td>
<td>1.25 (1.20-1.30)</td>
<td>35 (31-39)</td>
<td>17 (15-19)</td>
<td>18 (16-20)</td>
</tr>
</tbody>
</table>

Note: Normal ranges are shown in parentheses.

1/ Modified from Israelsen and Hansen, 1962

2/ Intake rates vary greatly with soil structure and structural stability, even beyond the normal ranges as shown

3/ Readily available moisture is approximately 75% of the total available moisture
Various soil surveys have been published for the world, including the FAO/Unesco Soil Map of the World (Volume I, Legend; Volume II, North America; Volume III, Mexico and Central America; Volume IV, South America; Volume V, Europe; Volume VI, Africa; Volume VII, South Asia; Volume VIII, North and Central Asia; Volume IX, Southeast Asia and Volume X, Australasia). These reports include comparative studies of soil maps, field and laboratory work as well as sections on environmental conditions and land use suitability. Where available profile information and physical and chemical properties of the soils are described.

Several methods available to measure the amount of water in a soil sample are: (1) gravimetric, (2) electrical, (3) tensiometric, and (4) neutron scattering. Each of these methods has advantages and disadvantages. The World Meteorological Organization has previously published a guide for discussing these methods (WMO Technical Note No. 97).

In an operational system, it is impractical to measure soil moisture directly for model application. Therefore, other methods to acquire these data are needed. Several algorithms have been developed (Baier and Robertson, 1966; Palmer, 1965; Richardson and Ritchie, 1973; Brochet and Gerrier, 1975; Choisnel, 1977). The basic soil water balance model is based on the concept of supply and demand. The supply is precipitation and/or irrigation; the demand is evapotranspiration. The excess is runoff and drained water. The rate of soil water loss is a function of the intensity of the atmospheric demand, the soil type, and the degree of soil cover of the crop. Each algorithm differs in the required input data and the degree to which the physical processes are considered. They also differ in the method by which potential evapotranspiration and evapotranspiration are calculated. The number of soil layers from which moisture is extracted also differs. Baier and Robertson, for example, consider several layers in the soil profile. Palmer has only two, while Ritchie (1972) considers the entire root zone as one layer. The decision to use any method depends on available resources. Simple procedures have been developed by FAO (Frere and Popov, 1979). They used physically meaningful ways to calculate the inputs for operating a soil moisture budget.

A basic component of the soil water balance is the concept of potential evapotranspiration (PET). Several methods have been used in the past, but it is generally accepted that the combination equation of Penman (1948) provides the most reliable estimate of PET. However, data restrictions may not permit calculating PET by this method. Other methods such as Hargreaves (1982) or Thornthwaite (1948) have been applied. It is important to be aware of the limitations and advantages of each method, and to use the method within the framework of the data required for the spatial and temporal scales and the information desired.

4.3.2.2 Soil Temperature

In the tropics, the variation of soil temperature with seasons is small (Figure 4.5). Soil temperature is highly correlated with sunshine, but the amount of variation is also a function of the specific heat, the thermal conductivity, moisture content and the kind and amount of cover at the soil surface. The World Meteorological Organization has suggested standard depth for measuring soil temperature (WMO No. 134). Because soil temperature is not routinely observed at many locations, air temperature has been used as a surrogate. Hackett et al. (1979), for example, used a potato model and altered the planting time to review the economic benefit by this alteration. Soil temperatures (surrogated by screen temperatures) impacted the development and productivity of the potato crop. In another application for the Asian Vegetable Research and Development Centre (AVRDC) in Taiwan, the model was run to determine the likely success of planting selected varieties.
Figure 4.5 - Mean monthly soil temperature at 50 cm at Nioka, Zaire and the relationship with sunshine, air temperature and rainfall. (After Smith et al., 1964.)
Daily variation in soil temperatures affects germination rate and development when the ground surface is visible from the top. With vegetative cover, soil temperatures follow the screen temperatures.

Other than direct measurement of soil temperature, there are several approaches to deriving this variable. Basic variables which have been used in statistical models include use of maximum and minimum temperatures, precipitation (snow and rain), number of rain days, and potential evapotranspiration. Since the previous day or month explains a major part of the variability of soil temperature, this has also been used. Also, solar and net radiation have been used to consider a thermal budget method of estimating soil temperature. Harmonic analysis with periodic sine function has been used to analyse the annual course of soil temperature (Kalma, 1971). It was concluded that wetting and drying of the soil are major factors determining the thermal regime of the soil. Further, the mean seasonal soil temperatures conform well to an annual sine curve. It has also been determined by a study at Purdue University (Newman, 1969) that the mean maximum, mean minimum and mean soil temperatures at 10 cm under sod can be estimated from one year of daily maximum and minimum temperature data. This suggests that for climatic analysis purposes, the mean soil temperatures at various depths are sufficiently stable and do not require several years of data.

Estimating diurnal temperature, however, is a more difficult problem. In the upper layer, the soil temperature is a function of the downward propagation of solar energy incident during daylight and the upward transfer of this energy at night. These in turn are a function of the thermal properties in the soil. Values of thermal conductivity \(k\) and volumetric heat capacity \(C\) need to be estimated or known. The thermal diffusivity \(D\) is defined as \(D = k/C\). Kersten (1949) provided a ready reference for various types of soils, given the moisture content and the bulk density.

Kalma (1971) suggests another objective method to evaluate the soil temperature by plotting the monthly maximum and minimum temperature as shown in Figure 4.6. In this manner, characteristics of the soil climate can be defined and used in relation to land-use studies.

Depth of soil temperature measurements should be standardized. Currently, the recommended depths are 5, 10, 20, 50 and 100 cm. The surface characteristics should also be described, i.e., is the site sodded, bare, rocky; is it surrounded by trees; is it on a slope with a specific aspect? The colour of the soil is also worth noting in the records. For crop/weather models however, soil temperature is generally not needed since the relations between soil temperature and such functions as root conductivity or root growth rate are not accurately known.

### Supplemental

Many other soil characteristics affect the utility of a model. These include the chemical nature. For example, alkali soils which have a high pH can affect plant growth by hampering moisture and fertilizer availability. Irrigation of these soils could present problems where the water table is high, salt would accumulate at the surface from evapotranspiration.

Drainage problems that affect the level of the water table can cause problems in crop productivity. Excess water leads to leaching of nutrients, and to poor aeration which restricts root growth.
Topography, including slope and aspects are also factors affecting the utility of models. These in turn may impact management of the land in terms of erosion control, fertilizer application and farm machinery operations.

The amount of fertilizer applied is a management factor. In some countries, artificial fertilizer is so expensive that little is added beyond the practice of following the land with crop rotation.

4.3.3 Meteorological Data

This section discusses various types of meteorological data that have been used in model application problems. Some of the limitations of each variable and examples of methods to calculate special types of variables are also discussed.

4.3.3.1 Air Temperatures

Instrument exposure to measure air temperature is an important factor that affects the utility of the data. The standard for observation is at the instrument shelter height approximately 1.6 metres above the ground. The temperature difference from crop height to the shelter height can be very large depending on cloud cover, wind and type and amount of plant canopy. Exposure on a steep slope, roof top, or in a depression should be avoided. In addition, the time when observations are reported, affects the mean maximum and mean minimum temperature. In the mid-latitudes, for
example, Schoorl and Dale (1977) showed that historical temperature data based on evening observations are apt to be more homogeneous (less biased) than those based on morning observations. In the tropics, changing observation times could also bias the data if precipitation occurs primarily at night or during the day.

4.3.3.2 Precipitation

This is one of the most important variables for many model applications. The major problem is that a sufficient number of sites are not usually available for an operational system. The spatial scale and data homogeneity issues have been discussed previously. The length of the period of record required for selected application varies, but is often limited by the length of the climatic record. For arid and semi-arid areas, a longer record period is usually necessary than for a humid climate, due to its greater variability.

Daily amounts, if available, are useful for crop yield modelling, pest severity and a soil moisture budget. Daily precipitation records are also useful in engineering problems related to storm and tile drainage system design in agricultural land.

In crop/weather modelling, it is not unusual to find that concomitant crop and weather data are not available. Most often only precipitation data are available. One method to maximize the information content from these data is to combine them with historical narrative reports. This is done in two steps. First, the precipitation data are normalized and ranked by:

(a) Finding the mean and standard deviation;
(b) Subtracting each observation from the mean and dividing by the standard deviation;
(c) Ranking the resultant values (scale 0 to 100);
(d) Plotting the ranked values for each period.

This standardization is a way of removing ill-conditioning effects of the varying origins of the scales of the variables. Subtracting the mean removes the correlation between the constant term (in a linear model). Dividing by the standard deviation scales the resultant value and provides a value that can lead to a more meaningful interpretation.

The second step is to relate the impact of these ranked values by comparing them with written or other available accounts describing the particular year. For example, Figure 4.7 shows the historical ranked values for Nepal. In 1982, the precipitation amount revealed a rank in the lower 5th percentile suggesting a very poor year. The value of 1982 was very similar to 1981. By researching the impact in 1981, some useful conclusions could be made for the 1982 crop year.

4.3.3.3 Global Solar Radiation

There are several methods for measuring the amount of solar energy received on the ground. Instruments have differed in their response to the spectrum of wave lengths of radiation. Costs related to measurement, and processing of radiation data have limited the utility of the network. The effects of pollution or aerosols have limited the use of these data. For example, Landsberg (1968) reported that city radiation can be reduced by 20 per cent or more by atmospheric pollution. Polyethylene film used in instruments can change transparency, leading to erroneous recordings. The radiation sensors colour characteristics can also deteriorate.
Figure 4.7 - Time series of yield moisture index (percentile ranking) in Nepal 1950-1982.
Because direct measurement records are rare, other methods such as cloud cover, per cent sunshine, water vapour, dust absorption, radiation at the top of the atmosphere, temperature, have been used. However, these relationships should not be transferred directly, since they are empirically derived. New coefficients should be developed whenever possible. When relative sunshine is estimated, these can be transformed into total radiation by using the usual Angstrom formula.

4.3.3.4 Wind

Wind data can rarely be extended to represent conditions over broad areas. Wind (km/day) is an input to estimating potential evapotranspiration by the Penman method. Land exposure including topography, storm tracks and crop surface have the greatest impact on the variability of wind. In arid and semi-arid climates, wind is an important factor in the energy and moisture balance of agricultural fields.

The kind and height of wind equipment, have not been standardized. It is obvious that the needs depend on the objectives for collecting the data. For micro-meteorology in agriculture, highly responsive instruments are needed to measure the momentum fluxes to calculate energy, moisture and carbon dioxide fluxes. Since many wind observing sites are at airport locations it is desirable to homogenize them for agricultural purposes. For a two metre height, an approximate conversion is made by the following relationship:

\[ \frac{V_2}{V_h} = \left( \frac{2}{h} \right)^{\frac{1}{n}} \]

where: \( V_2 \) = velocity (m/sec) at 2 metres,

\( V_h \) = velocity at h metres (between 7 and 300 metres), and

\( n \) = power adjustment (7 for dry-adiabatic and strong wind; 3 for intermediate stability and average wind; 2 for light wind and stable conditions).

The errors introduced in estimating these winds can be as much as 20 per cent or more, but the error in PET estimation is not as large.

4.3.3.5 Pressure

One example of the use of pressure data sets was reported by Steyaert et al. (1978), to estimate large area crop yield for the U.S. and the Soviet Union. However, these data sets are not without problems. Williams and Van Loon (1976), for example, found large discrepancies between station and sea-level pressure data from the data sets compiled by NCAR (Jenne, 1975) and the U.K. Meteorological Office. Several methods are used to covert station pressure to sea level pressure (WMO 1964, 1968). One application of sea-level pressure extended the period of record to evaluate the variability of wheat yield in the spring and winter wheat region of the Soviet Union (Sakamoto et al., 1980).

4.3.3.6 Humidity

There are several ways to express humidity in the atmosphere, depending on the application. Some of the expressions include relative humidity, dew point temperature, actual and saturated vapour pressure. The instruments used to record these variables must be checked frequently.
Psychrometric tables are available to determine values of the above if two of the three variables are known at a specified pressure. Alternatively, equations have been developed to provide these estimates. Some examples are:

\[ v.p. = 6.11 \times \exp \left( \frac{176204.2621 + 5597.607915 \times T - 2.850772636 \times T^2}{125416.2 + 273 + T} \right) \]

\[ T = \text{temp} ^{\circ}F \]

\[ v.p. = \text{vapour pressure in millibars (after Trenchard and Artley, 1981).} \]

An approximation of the saturation vapour pressure over water as a function of temperature has been reported by Bosen (1960).

Average values of vapour pressure can be estimated from average air temperature and average relative humidity by the following formula:

\[ e = E_T \times \frac{R.H.}{100} \]

where \( e \) = average vapour pressure

\( E_T \) = saturation vapour pressure for the average temperature, and

\( R.H. \) = relative humidity.

In some cases relative humidity is presented for the specific hours either 6am or 7am or 3pm. In these cases the above formula is applied taking into account the saturation vapour pressure corresponding respectively to average minimum or maximum temperatures. In many humid tropical countries, vapour pressure of the lower atmosphere is conditioned by the minimum air temperature. Therefore this first approximation leads to values ± 2-3 mbs of the average vapour pressure calculated independently from observed data. This approximation should be checked for stations which have regular temperature and vapour pressure or relative humidity records.

4.3.3.7 Pan Evaporation

Use of pan evaporation data attracts controversy. Much of the quality of these data depends on the care of the observer. Different shapes, sizes and heights of measurement and exposures have been recorded. It is important to investigate these characteristics before using the data. Useful information on the evaporative demand of the environment can be obtained from these measurements.

Adective energy can increase evaporation by a considerable amount. This is particularly true in arid and semi-arid climates. On Lake Mead, Nevada, U.S.A., for example, advective energy increased the annual evaporation by 125 mm. In the agricultural land of the midwest, advection is an important factor in calculating evapotranspiration. The coefficient to convert pan evaporation to PET ranges from 0.60 to 0.80. In humid climate the coefficient is higher than in arid climate.

4.3.3.8 Supplemental Meteorological Data

Other kinds of data are useful for applications to agriculture. The wetting duration of vegetation is applicable for disease predictions. The number of hours (days) above and below a critical threshold variable is also useful. Snow depth, water equivalence, duration of snow cover, number of wet and dry days, freeze dates, and precipitation days above a threshold are all supplemental forms which can be secured from basic observations and have numerous applications.
4.3.3.9 Derived Meteorological Data

The purposes of using derived meteorological data are twofold. First, combining variables helps to minimize the collinearity problem. The statistical problem dealing with degrees of freedom is addressed, and the number of variables in models is reduced. Second, recognizing that meteorological variables do not act independently, the manipulation of the data into a derived variable seeks the most responsive interactive term that affects crop growth and development.

4.3.3.9.1 Potential Evapotranspiration

The concept of potential evapotranspiration has been used for many model applications. Since several methods have been reported elsewhere, they will be discussed primarily from their data requirement point of view.

A. Penman

Data Requirement

(1) Solar radiation (net radiation in water equivalence)
(2) Wind at 2 m (km/day) or (m/sec)
(3) Air temperature (°C)
(4) Humidity/vapour pressure
(5) Latitude, longitude, elevation of site.

Freer (1979) outlined a practical way to estimate PET with the Penman formula. He also provided easy to use tables to estimate the various required inputs. Although in theory this method has general applicability, data requirements may limit its use. The coefficients in the equations need to be corrected for different climatic conditions. The model also assumes that the eddy coefficient of heat and water vapour are equal. This is true only under neutral lapse conditions.

FAO calculates potential evapotranspiration according to the Penman method. The calculation of the total radiation is done according to the method discussed by Freer.

Some modifications have been made in the calculation of the wind functions to take into account the additional PET caused by advection in arid and semi-arid environments. The wind function used by Penman is:

\[0.26 (e_a - e_d) (1.00 + 0.54 U)\]

where \(e_a\) = saturation vapour pressure in mbs,
\(e_d\) = actual vapour pressure in mbs, and
\(U\) = wind speed at 2 m level expressed in m/sec.

The correction applied for minimum average temperatures greater than 5°C is:
Coefficient of $U$

<table>
<thead>
<tr>
<th>$U$</th>
<th>Difference between mean monthly maximum temperature and mean monthly minimum temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.54</td>
<td>$T_M - T_m \leq 12^\circ C$</td>
</tr>
<tr>
<td>0.61</td>
<td>$12^\circ C &lt; T_M - T_m \leq 13^\circ C$</td>
</tr>
<tr>
<td>0.68</td>
<td>$13^\circ C &lt; T_M - T_m \leq 14^\circ C$</td>
</tr>
<tr>
<td>0.75</td>
<td>$14^\circ C &lt; T_M - T_m \leq 15^\circ C$</td>
</tr>
<tr>
<td>0.82</td>
<td>$15^\circ C &lt; T_M - T_m \leq 16^\circ C$</td>
</tr>
<tr>
<td>0.89</td>
<td>$16^\circ C &lt; T_M - T_m$</td>
</tr>
</tbody>
</table>

B. Hargreaves (1977)

Data Requirements

(1) Solar radiation (RS)

(2) Mean monthly temperature (TMF) ($^\circ F$).

The equation is $PET = 0.0075 RS \times TMF$ where RS and PET are expressed in equivalent water evaporation. The use of this method has not been tested with daily data. Comparison of monthly values with Penman's and Hargreave's method in Latin America (Sanchez, 1982), show close similarity.

C. Jensen and Haise (1963)

Data Requirements

(1) Solar radiation (RS)

(2) Mean air temperature (T).

A variation of the Hargreaves formulation is reported by Jensen and Haise as follows:

$$PET = C_T (T - T_x) \cdot RS.$$  

$C_T$ is an air temperature coefficient for a given area and is a function of elevation and vapour pressure. $T_x$ is a constant for a given area. RS is expressed in water equivalence per day.

Other methods that use both radiation and temperature include Turc (1961) and Oliver (1961). The humidity of the air is also considered in these methods.

D. Solar – Thermal Units (Caprio, 1971)

Data Requirements

(1) Solar radiation (RS)

(2) Mean temperature ($^\circ F$).

Caprio derived the Solar Thermal Units (STU) as a surrogate for PET as follows:
PET = STU \times 10^{-5}

where \( STU = (RS \times (T_x - T) / 2) - 31.0 \). \( T_x \) and \( T \) are maximum and minimum temperatures, respectively. A threshold of 31°F is used. Any temperature effects below this level are ignored.

**E. Thornthwaite (1948)**

**Data Requirements**

1. Mean temperature
2. Latitude.

This empirical method should be used with caution. The largest error is found in arid climates where this method could underestimate PET by as much as 50 percent. (Sellers, 1964). In humid areas, this method has been found to compare favourably with and even exceed the Penman method for some months. The major advantage of this method is its requirement for the minimum data, of temperature and latitude. The method should not be used for daily data, but is best designed for monthly data.

**F. Blaney and Criddle (1966)**

**Data Requirements**

1. Mean temperature (°F)
2. Crop coefficient (consumptive use coefficients)
3. Daylength.

Like Thornthwaite's method, this procedure is empirically derived. Crop coefficients, related to the monthly consumptive use, need to be determined for a local area. If generalizations are satisfactory, the method is practical from a data requirement view.

\[
PET = K \times f
\]

where \( K \) = monthly consumptive use coefficient that varies with growth stage and temperature

\[
f = T \times p / 100
\]

\( T \) = monthly mean temperature (°F), and

\( p \) = per cent of daylight hours per year.

**G. Trenchard and Artley (1981)**

**Data Requirements**

Maximum and minimum temperature.

Trenchard and Artley used maximum (TX) and minimum (TN) temperatures to estimate pan evaporation by converting the temperature to vapour pressure equivalents and regressing in a simple linear regression model with:
\[ E = 0.2163 + 0.3473 \text{ Vapour (TX) - 0.2644 Vapour (TN)} \]

where \( E \) is pan evaporation in inches.

Trenchard and Artley also use this equation to estimate daily soil moisture. The daily soil moisture content for a profile containing (8 inches) 200 mm of water holding capacity can be monitored as follows:

\[ S_i = S_{i-1} + P_i - (E_i \times S_{i-1}/\text{CAP}) \]

where \( S_i \) = moisture contents on day \( i \),

\( P_i \) = precipitation on day \( i \),

\( E_i \) = pan evaporation on day \( i \),

CAP = soil profile moisture capacity, and

\( 0 \leq S_i \leq \text{CAP} \).

H. Brochet and Gerbier (1977)

Data Requirements

Global solar radiation, Piche Evaporation or maximum and minimum temperature.

Brochet and Gerbier propose two expressions to calculate potential evapotranspiration using global radiation known at a large scale and local measurements of Piche evaporation or maximum and minimum temperature, for a decade (10 days).

First expression:

\[ \text{PET}_1 = m \cdot Rg + n \cdot Ep \]

Second expression:

\[ \text{PET}_2 = m \cdot Rg + p \cdot F (T, \bar{T}_n + \bar{E}) \]

Where:

\( \text{PET} \) = potential evapotranspiration in mm

\( Rg \) = global solar radiation

\( T \) = mean temperature: (max + min) \( \frac{1}{2} \)

\( T_n \) = minimum temperature

\( m, n, p \) are adjusted coefficients depending on the location

\( Ep \) = Piche evaporation

\( F \) = a function (values of \( F \) are given by tables)

\( \bar{E} \) = coefficient given on maps.

4.3.3.9.2 Temperature Indices for Plant Development

Robertson (1983) described several applications of temperature derived indices. He suggests with good reason that the terms "heat-unit" and "growing degree days" are misnomers since there is no quantity of heat (in the physical sense) involved and temperature affects biochemical reactions that control development, not growth.
A. Temperature Remainder Index Model (TRIM)

The daily rate of development $R_a'$ is assumed to be related to a linear function of daily mean temperature ($T_a$) for a specific phenological period by:

$$R_a = a + b T_a$$  \hspace{1cm} (1)

$$= b (T_a - T_o)$$  \hspace{1cm} (2)

$$= b (T_a - T_o)$$  \hspace{1cm} (3)

In equation (3), $T_o = -\frac{a}{b}$ where $T_o$ is the "apparent" threshold temperature. In the example of the observations in Table 4.2, the regression equation to calculate this threshold temperature is determined as:

$$R_a = \frac{1}{N} = .00228 (T_a - 6.34)$$

B. Curvilinear Temperature Model

To describe the curvilinear pattern of biological responses such as shown in Figure 4.8, quadratic equations have been used to express the rate of development with temperature (Brown, 1960; Robertson, 1968; Williams, 1974; Holt et al., 1975; Major et al., 1975; Brochet et al., 1977). For a phenological period, the form of the equation is:

$$R_a = a_o + a_1 T_a + a_2 T_a^2$$  \hspace{1cm} (4)

Equation (4) can be expressed in the temperature remainder index form as

$$R_a = a_1 (T_a - T_o) + a_2 (T_a - T_o)^2$$  \hspace{1cm} (5)

The threshold temperature $T_o$, is determined by

$$T_o = \frac{a_1 - (a_1^2 - 4 a_o a_2)^{1/2}}{2a_2}$$  \hspace{1cm} (6)

so that the optimum temperature ($T_{op}$) is determined by

$$T_{op} = -a_1/2a_2$$  \hspace{1cm} (7)

C. Temperature - Daylength Model

To consider the variation of the duration from emergence to maturity for a range of latitude, Nutttonson (1948) introduced daylength to consider the average photo-period. Robertson (1983) noted that although the average daylength was suitable for long-day crops under certain circumstances, for short-day crops the dark period length rather than the light period length should be used.

Variation of the above that included photoperiod was reported by Robertson (1953). Accumulation of hours of daylight above a threshold for wheat and of hours of darkness above a threshold for millet explained the changes in length of the phenological period and rate of development better than the TRIM.
Figure 4.8 – Schematic diagram showing the influence of temperature on biological activities (see Robertson, 1983).
Table 4.2 - Rate of development and duration as affected by temperature for the period heading to maturity for wheat in Canada (after Robertson, 1983).

For the phenological period heading to maturity:

<table>
<thead>
<tr>
<th>Station</th>
<th>Duration days</th>
<th>Average rate of development 1/day</th>
<th>Average of the daily mean temperatures degrees C. Ta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marrow</td>
<td>31</td>
<td>.0323</td>
<td>21.1</td>
</tr>
<tr>
<td>Ottawa</td>
<td>29</td>
<td>.0345</td>
<td>20.6</td>
</tr>
<tr>
<td>Normandin</td>
<td>54</td>
<td>.0185</td>
<td>15.0</td>
</tr>
<tr>
<td>Swift Current</td>
<td>41</td>
<td>.0244</td>
<td>19.1</td>
</tr>
<tr>
<td>Lacomoc</td>
<td>59</td>
<td>.0169</td>
<td>14.7</td>
</tr>
<tr>
<td>Beaverlodge</td>
<td>54</td>
<td>.0185</td>
<td>13.9</td>
</tr>
<tr>
<td>Fort Vermilion</td>
<td>48</td>
<td>.0208</td>
<td>15.3</td>
</tr>
<tr>
<td>Fort Simpson</td>
<td>38</td>
<td>.0263</td>
<td>16.4</td>
</tr>
</tbody>
</table>

D. Tri-Quadratic Model

Robertson (1968) proposed a tri-quadratic model involving quadratic functions of daily maximum and minimum temperatures and daylength. For a specific phenological period,

\[
S = \left[ a_1 \left( L - a_o \right) + a_2 \left( L - a_o \right)^2 \right] \cdot \left[ b_1 \left( T_1 - b_o \right) + b_2 \left( T_1 - b_o \right)^2 \right] \\
\left[ b_3 \left( T_2 - b_o \right) + b_4 \left( T_2 - b_o \right)^2 \right]
\]

where: \( S \) = fraction of total development in the phenological period,
\( L \) = daylength (astronomical sunrise to sunset),
\( T_1 \) = daily maximum temperature,
\( T_2 \) = daily minimum temperature,
\( a_o \) = threshold value for photoperiod,
\( b_o \) = threshold value for temperature, and
\( a_1, b_1, b_2, b_3 \) and \( b_4 \) are coefficients.
The model is known as the Biometeorological Time Scale (BMTS). One weakness that Robertson (1983) points out is that the lower threshold temperature is common to both the maximum and minimum temperatures.

A variation of the BMTS was applied by Major et al. (1975b). Ravelo and Decker (1981) used soil moisture, mean temperature and daylength to estimate phenological periods and yield for soybeans.

E. Vernalization Model

Requirement of a cold treatment is called vernalization. For some crops the sensitive period is the period after germination and prior to floral bud development. One example of this model is the work of Bidabe (1967). This model is an exponential model taking into account requirements of cold and warm treatment for the bloom of apple trees.

Beginning from 1 October, a cold action \((A_c)\) is first calculated for selected stages, \(p\) by this formula:

\[
A_c = \sum_{j=1}^{P} Q_{10}^{-T/10}
\]

When \(A_c\) reaches a certain threshold, then a warm action \((A_w)\) is calculated by this formula:

\[
A_w = \sum_{j=p+1}^{Q_{10} + T/10}
\]

where,

- \(Q_{10}\) is a characteristic constant of the variety of apple, and
- \(T\) is the mean daily temperature.

The date when \(A_w\) reaches a certain threshold corresponds to the flowering stage.

4.3.3.9.3 Moisture Stress Indices

As discussed by Robertson (1983), the rate of growth is influenced mainly by moisture stress in the plant tissues, temperature and light intensity. Various forms of the moisture stress indices have been developed for crop-weather relationship studies. In these indices the concept of potential evapotranspiration is critical.

A. Palmer Drought Index (PDI)

This index is a hydrological accounting approach developed by Palmer (1965). The severity of the index is based on what is climatically appropriate for a given area. Therefore, if an area is accustomed to 250 mm of precipitation a year, this is considered normal, whereas if this area received three or four times this amount per year this situation might be considered abnormally wet. Similarly, an area with a normal 760 mm of precipitation receiving 250 mm may be considered a drought situation.
Basic data input are monthly temperature and precipitation. The index values range from extremely wet through normal to extreme drought condition. Potential evapotranspiration was determined from Thornthwaite's method although other methods can be used as well.

B. Z-Index

Sakamoto (1978) used this index as independent variable to estimate wheat yield in Australia. Unlike the PDI, the Z-index responds more rapidly to the month to month moisture anomaly. The disadvantage of this index is the requirement for a long-period of record, between 20 to 30 years.

C. Crop Moisture Index (CMI)

Palmer (1968) developed this index to consider the week to week changes in the moisture situation in the U.S. The CMI is the algebraic sum of the evapotranspiration anomaly index and the wetness index.

D. Moisture Availability Index (MAI)

The Moisture Availability Index is defined by Hargreaves (1982) as:

\[ MAI = PD / PET \]

where PD is dependable precipitation, defined as the 75 per cent probability of precipitation occurrence, i.e., that amount expected to be equalled or exceeded 75 per cent of the time. With a long period of record (preferably 30 years), the probability of occurrence in per cent can be rapidly determined by the following equation (Thom, 1966):

\[ F = m / (n + 1) \]

where \( m \) is the ranked order of the data set, \( n \) is the total number of data points and \( F \) is frequency.

E. Crop Moisture Ratio (CMR)

In the tropical zones where temperature fluctuations are not very large, it is possible to estimate PET using normal temperatures (e.g., Thornthwaite) and/or normal sunshine or radiation (e.g., Hargreaves). For an operational system, only reported precipitation is required for the CMR, which is defined as a Precipitation/Potential Evapotranspiration ratio.

F. ET/ETP Ratio (Yao, 1969; Van Keulen, 1975)

This index is defined as the ratio of actual evapotranspiration (ET) to potential evapotranspiration (ETP). Since the crop reacts to its relative moisture deficit, this ratio has been used as an index of crop moisture stress.

G. Yield Moisture Index (NOAA/CEAS, 1979)

This index makes minimal assumption on soil moisture and potential evapotranspiration. It is defined by:

\[ YMI_j = \sum_{i=1}^{n} P_i K_i \]

where: \( YMI_j \) = index for jth crop (e.g. wheat, maize, etc.),
\[ P_i = \text{precipitation for the } i^{th} \text{ growth stage with } P_i \text{ less than field capacity of the soil,} \]
\[ KC_{ij} = \text{crop coefficient for the } i^{th} \text{ growth stage and } j^{th} \text{ crop, planting (i=1), vegetative (i=2), flowering (i=3).} \]

The crop coefficient is a measure of the water requirements at different growth stages.

**H. Soil Moisture Index (Ravelo and Decker, 1979)**

This index is defined as the ratio of observed plant available soil moisture to the maximum available soil moisture (difference of field capacity and wilting point).

4.4 **Simulated Data**

Given only the maximum and minimum temperatures for the day it is sometimes desirable to determine the integrated energy for the day, i.e., what are the representative or average day-time and night-time temperatures or the duration above/below a specified threshold. Following are some examples of how this could be determined.

4.4.1 **Estimation of Average Day-time and Night-Time Temperatures**

A. It is assumed that the diurnal temperature follows two cosine curves with different periods. One curve is applied to the period 13 hours to 24 + \( t_0 \) hours and another to the period \( t \) to 13 hours (Figure 4.9). Both curves reach their minimum and maximum at points at which the temperature reaches the minimum and maximum (P. Petricevic, 1977).

Their equations are shown below:

\[
T_2(t) = \frac{T_{\text{MAX}} + T_{\text{MIN}}}{2} + \frac{T_{\text{MAX}} - T_{\text{MIN}}}{2} \cos \left( \frac{180^\circ}{13 - t_0} (t - t_0) \right)
\]

for \( t_0 \leq t \leq 13 \), and

\[
T_2(t) = \frac{T_{\text{MAX}} + T_{\text{MIN}}}{2} + \frac{T_{\text{MAX}} - T_{\text{MIN}}}{2} \cos \left( \frac{180^\circ}{11 + t_0} (t - 13) \right)
\]

for \( 13 \leq t \leq 24 + t_0 \)

Average day-time temperature \( T_D \) and average night-time temperature \( T_N \) will be given by the following expression:

\[
T_D = \frac{1}{24 - 2t_0} \left[ \frac{T_{\text{MAX}} + T_{\text{MIN}}}{2} (13 - t_0) + \int_{13}^{24 - t_0} T_2(t) \, dt \right]
\]

\[
T_N = \frac{1}{2 t_0} \left[ \int_{24 + t_0}^{24 - t_0} T_2(t) \, dt \right]
\]
After solving the integrals and simplifying obtained expressions the following formulas are obtained:

$$T_D = \frac{\text{TMAX} + \text{TMIN} + \frac{\text{TMAX} - \text{TMIN}}{4/L} \cdot \frac{11 + t_o}{12 - t_o}}{\frac{\text{TMIN} + \text{TMAX} - \frac{\text{TMAX} - \text{TMIN}}{4/L} \cdot \frac{11 + t_o}{12 - t_o}}{t_o}}$$

where \( \alpha = \frac{11 - t_o}{11 + t_o} \times 180^\circ \) degrees or \( \frac{11 - t_o}{11 + t_o} : 3.14159 \) radians

Example for \( t_o = 7 \), TMAX = 35, TMIN = 12, the following is obtained

\( T_D = 27.74 \)

and \( T_N = 20.47 \)

A simple procedure developed by de Wit et al. (1978) may be used to simulate mean temperatures from daily maximum and minimum records.

B. Representative day-time and night-time temperatures are needed to estimate photosynthesis and respiration. Simple regression functions were used by Hodges, et al. (1979), to estimate these variables. For average night-time, \( T_N = (T_{\text{max}} + 2T_{\text{min}})/3 \). \( T_{\text{max}} \) and \( T_{\text{min}} \) are the maximum and minimum daily temperatures. Similarly, for average day-time temperature, \( T_D = (2T_{\text{max}} + T_{\text{min}})/3 \) where \( T_{\text{min}} \) is the previous day's minimum temperature.

![Diurnal Temperature Trend](image)

TMIN: minimum temperature occurs at sunrise-time \( t_o \)
TMAX: maximum temperature occurs at 13 o’clock
TD: average daytime temperature
TN: average night time temperature
daytime: period between \( t_o \) and 24-\( t_o \)
night time: period between times 24-\( t_o \) and 24 + \( t_o \)
t: time is expressed in decimal hours.

Figure 4.9 – The typical diurnal temperature trend. (After Petricevic, 1977.)
4.4.2 Duration Above/Below Threshold Temperature

Figure 4.10 shows graphically a model that can be used to estimate the number of hours above a threshold temperature $T_0$ in a day. As shown, the temperature curve for a day is assumed to be described by a triangle given the maximum ($T_1$) and minimum ($T_2$) temperatures. The height of the triangle describes the temperature range; the number of degree hours is described by the area of the triangle, or the area of the rectangle with base 24 hours and height $T_2 - T_1$.

4.4.3 Generating Synthetic Data

It is realistic that a long-term meteorological data series is often not available for a particular site. However, there may be other stations in the approximate vicinity that can be used to derive another series with the same properties as the observed series. This generation of a synthetic sequence of weather data can be accomplished if the stochastic structure of meteorological variables is defined. Richardson (1981, 1982) presents an approach that may be used to generate long samples of daily precipitation, maximum temperature, minimum temperature and solar radiation. Precipitation is generated separately by using a Markov chain exponential model. Others have suggested the two-parameter gamma distribution (Buishand, 1978) or the three-parameter mixed exponential distribution (Woolheiser and Pegrám, 1979). Richardson chose the Markov chain exponential model because of its simplicity, although the gamma and mixed exponential better describe the precipitation distribution.

Maximum and minimum temperatures and solar radiation are generated by a continuous multivariate stochastic model.

![Diagram](image)

**Figure 4.10** - The use of a triangle to show the relationship of the number of hours above a threshold temperature $T_0$, given the maximum ($T_1$) and minimum ($T_2$) temperatures.
4.4.4 Gridded Data

It may be desirable to provide a gridded estimate based on reports within a specified area and neighbouring stations. Various objective methods have been used to estimate precipitation at a grid point. Regardless of the chosen method, the accuracy depends to a large extent on the density of the reporting network. These procedures only allow an objective and systematic way to portray data at a grid level; they do not improve the accuracy of the network. Some of the procedures previously employed include polynomial fitting (Endlich and Mancuso, 1968), successive correlation (Barnes, 1973) and statistical interpolation (Eddy, 1973). The variables themselves influence the network density need. Temperature, for example, is not as variable as precipitation or wind. The reporting network could be enhanced with satellite imagery, used to refine the quantity as well as the spatial distribution of precipitation.

4.5 Remotely Sensed Data

The operational satellites for which data are readily available to the prospective user are:

(a) Landsat, with the MultiSpectral Scanner (MSS) and, on Landsat D, the Thematic Mapper (TM);

(b) The NOAA series of polar orbiting satellites with the Advanced Very High Resolution Radiometer (AVHRR) and other meteorological sensors; and

(c) The Meteorological Satellite series of geosynchronous satellites with a variety of meteorological sensors such as (GOES).

As compared to conventional methods of collecting data related to agriculture, satellites offer the major advantage of providing data of the same type and quality worldwide. For a particular application, however, one must consider the source and extent of satellite data very carefully. The NOAA-7 AVHRR, for example, provides digital and imagery data of the entire globe twice daily at a resolution of about 1 km (the smallest element of scene for which data is acquired is about 1 km x 1 km). The GOES sensors have similar resolution and acquire data several times a day, but only for the approximately one-third of the earth under the satellite. The Landsat sensors, on the other hand, have a much higher resolution - about 80 m for MSS and about 30 m for TM. This provides much more detailed data of even individual fields, but at the cost of coverage once every 18 days. The cost and effort of processing the high resolution data are also vastly increased.

Some of the more promising applications of satellite data in crop condition assessment and in crop yield or production estimation are described in the following sections.

4.5.1 Environmental Data from Satellites

The following meteorological parameters offer the potential of being estimated from environmental satellite data. They are important in modelling crop development and yield. Satellite-derived parameters should be most useful in regions where conventional data sources are not satisfactory.

A. Temperature

Surface temperature is readily measured by sensors operating in the thermal infra-red spectral region. The geographical distribution of the temperature field is smooth enough that available surface measurements can accurately calibrate the satellite
data. Accurate daily estimates of maximum, minimum, or average air temperatures from satellites appear feasible.

B. Incident Solar Radiation

Frequent observations of cloud cover amount and type from geosynchronous satellites can give a fairly accurate estimate of incident solar radiation over a large area. The satellite observations are readily calibrated by surface observations. Daily estimates of solar radiation from satellite appear feasible. (See Figure 4.11.)

SOLAR RADIATION COMPARISON
SATELLITE DERIVED VS OBSERVED GROUND
COLUMBIA, MISSOURI
JULY-NOVEMBER 1980

Figure 4.11 - (After Sakamoto personal communication, 1982.)

C. Precipitation

The meteorological parameter most desired from satellite observations is precipitation. Unfortunately, it appears to be the most difficult to obtain. Estimation of precipitation from satellite data requires the relation of cloud amount and type from satellite observations, to rainfall amount and distribution. This relation is not well established in the temperate regions. Furthermore, precipitation is so variable geographically that surface observations cannot easily be used to calibrate satellite data. Precipitation estimates on a daily or even weekly basis from satellite data do not appear feasible in the near future, but research is progressing.

4.5.2 Vegetative Data from Satellite

The Landsat MSS and TM, and the NOAA-7 AVHRR sensors measure radiation from surface scenes in spectral bands in the visible and the near infra-red. Advantage of the unique spectrum of chlorophyll in green vegetation - low reflectivity in the visible wavelengths, very high reflectivity in the near infra-red - can be taken to
measure the amount and health of green vegetation. As noted in Figure 4.12 below, clouds, snow, soil and water all have relatively flat spectra in the visible (Vis) and infra-red (IR). The numerical value of (IR - Vis) is small for all of these features. Vegetation, even when severely stressed, shows a much larger value of (IR - Vis) which increases with the health, vigour, or density of the green vegetation. Crop vigour is closely related to its condition and ultimately to the yield. Monitoring of the (IR - Vis) difference over the growing seasons in major global crop regions should soon provide information on crop conditions as the crops progress towards maturity.

![Reflectivity vs Wavelength](image)

**Figure 4.12** - Reflecting response of various material in relationship to the wavelength.

### 4.6 References


____ and____, 1977. Une methode operationelle pratique de calcul de l'evapo-
transpiration potentielle. (A convenient operational method to calculate potential

(Agrrometeorological study of soft winter wheat.) Monographie de la Meteorologie

Brown, D. M., 1960. Soybean ecology I: Development-temperature relationships from


of Hydrology, 36:295-308.

and potential evapotranspiration. Montana Agricultural Experiment Station, Montana
State University, Bozeman. Cir. 251. 10 pp.

Choisnel, E., 1977. Le bilan d'énergie et le bilan hydrique de sol. (Energy balance
and soil moisture budget.) La Meteorologie, (6)11:101-159.

Meteorological Society of Japan, 51:450-457.

Endlich, R. M. and R. L. Mancuso, 1968. Objective analysis of environmental condi-

Fleckinger, J., 1945. Notations phenologique et representations graphiques du
developpement des bourgeois floraux du poirier. (Phenological notations and graphic
representations of the development of pear floral buds.) Compte rendu du Congres de
l'Association Francaise pour l'Avancement des Sciences, 73:91-98.

Frere, M., 1979. A method for the practical application of the Penman formula for the
estimation of potential evapotranspiration and evaporation from a free water surface.
FAO, Rome.

Plant Production and Protection Paper No. 17. FAO, Rome. 65 pp. (in English, French
and Spanish).

of potatoes. III. Some implications for potato production and research. Field Crops
Research, 2:349-364.


Petriccovic, P., 1977. Estimation of day and night temperatures from minimum and maximum temperatures and daylength (private communication FAO, Rome).


Trenchard, M. H. and J. A. Artley, 1981. Application of thermal model for pan evaporation to the hydrology of a defined medium, the sponge. AGRISTARS (FC-L1-04192, JSC-17440) Lyndon B. Johnson Space Center, Houston, Texas 77058.


CHAPTER 5

OTHER BIBLIOGRAPHY


Rasmidatta, V., R. Achutuni, L. Steyaert and C. M. Sakamoto, 1981. A maize/weather yield model for Thailand. Agrometeorological Analysis Sub-Division, Thai Meteorological Department, Bangkok; Atmospheric Science Department, University of Missouri-Columbia; and Center for Environmental Assessment Services. 22 pp.


