THE EFFECT OF METEOROLOGICAL FACTORS ON CROP YIELDS AND METHODS OF FORECASTING THE YIELD
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— To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;
— To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;
— To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
— To promote activities in operational hydrology and to further close co-operation between Meteorological and Hydrological Services;
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FOREWORD

Recent world food problems have intensified interest in applying meteorological information as an aid to increase food production. In order to do this in as comprehensive a way as possible, it is necessary that the role of weather in agricultural production should be thoroughly studied. Over the years, research workers in many countries have been concerned with the establishment of relationships between the yield of agricultural crops and meteorological parameters. Although our knowledge regarding these relationships is far from complete, considerable progress has been made in this field and this Technical Note reviews the results of investigations into the effects of meteorological parameters on yields of seven crops.

The initiative for the preparation of this review came from the fifth session of the WMO Commission for Agricultural Meteorology, which established a Working Group on the Effect of Agrometeorological Factors on Crop Yields and Methods of Forecasting the Yield and proposed that the findings be published as a Technical Note. The Technical Note refers to crops other than grains, which are dealt with in the same detail in WMO Technical Note No. 151, "Crop-weather models and their use in yield assessment", by Dr. Wolfgang Baier.

I have pleasure in expressing the sincere thanks of WMO to the working group chairman, Dr. E. S. Ulanova, and to its other members, Messrs. J. Goudriaan, B. W. Kelly, M. Kurpelova, R. Pfau and B. Primault, for the time and effort they have devoted to this publication.

A. C. Wiin-Nielsen
Secretary-General
SUMMARY

The study of the effects of meteorological factors on crop yield and the development of methods of forecasting the yield have been the concern of agrometeorologists throughout the world. This report reviews studies on some commercial crops carried out in various countries.

The first five chapters summarize the results of investigations into effects of agrometeorological factors on crop yield and the methods used for forecasting potato, sugar beet, sunflower and cotton yields.

Chapters 6, 7 and 8 deal with studies relating to sugar-cane, coffee and cocoa yields with meteorological conditions.

The last chapter is devoted to mathematical modelling of plant growth and yield.

A list of references/bibliography is appended to the report.

RESUME

L'étude des effets des facteurs météorologiques sur le rendement des cultures et la mise au point de méthodes de prévision du rendement constituent une préoccupation de longue date des agrométéorologues du monde entier. Le présent rapport rend compte d'études portant sur certaines cultures commerciales qui ont été effectuées dans divers pays.

Les cinq premiers chapitres résument les résultats de recherches concernant les effets de facteurs agrométéorologiques sur le rendement des cultures et les méthodes utilisées pour prévoir le rendement des cultures de la pomme de terre, de la betterave sucrière, du tournesol et du coton.

Les chapitres 6, 7 et 8 traitent d'études sur les rapports qui existent entre le rendement de la canne à sucre, du café et du cacao, et les conditions météorologiques.

Le dernier chapitre est consacré à la modélisation mathématique de la croissance de la plante et du rendement.

Une liste bibliographique est annexée au rapport.
РЕЗЮМЕ

В течение длительного периода времени агрометеорологи во всем мире уделяют большое внимание вопросу изучения влияния метеорологических факторов на урожайность сельскохозяйственных культур и разработке методов прогнозирования урожая. В этом отчете рассматриваются исследования по некоторым коммерческим видам сельскохозяйственных культур, проводимых в различных странах.

В первых пяти главах приводятся результаты проводимых исследований по влиянию агрометеорологических факторов на урожайность сельскохозяйственных культур и на методы, используемые для прогнозирования урожайности картофеля, сахарной свеклы, подсолнечника и хлопка.

В главах 6, 7 и 8 подробно рассматривается влияние метеорологических условий на урожайность сахарного тростника, кофе и какао.

Последняя глава посвящена математическому моделированию роста растений и урожайности.

К отчету прикладывается список ссылок/библиографий.

RESUMEN

Desde hace mucho tiempo los agrometeorólogos de todo el mundo se han dedicado a estudiar los efectos que los factores meteorológicos ejercen en el rendimiento de los cultivos así como a desarrollar métodos de predicción de dichos rendimientos. En el presente informe se examinan los estudios realizados en varios países con respecto a algunos cultivos comerciales.

En los primeros cinco capítulos se resumen los resultados de las investigaciones hechas sobre los efectos de los factores agrometeorológicos en el rendimiento de los cultivos y también sobre los métodos utilizados para predecir el rendimiento de los cultivos de patatas, remolacha azucarera, girasol y algodón.

Los capítulos 6, 7 y 8 tratan de los estudios referentes a la relación que existe entre el rendimiento de la caña de azúcar, café y cacao y las condiciones meteorológicas.

El último capítulo está dedicado a los modelos matemáticos del crecimiento de las plantas y del rendimiento de los cultivos.

Como apéndice del informe figura una lista de referencias bibliográficas.
CHAPTER I

INTRODUCTION

By its Resolution 12 (CAGM-V), the fifth session of the WMO Commission for Agricultural Meteorology (Geneva, October 1971) set up a Working Group on the Effect of Agrometeorological Factors on Crop Yields and Methods of Forecasting the Yield (other than cereals). The terms of reference of the working group were: (a) to survey and summarize existing knowledge and data on the effect of meteorological factors on the yield of commercial crops other than cereals (for example: sunflower, potato, cotton, etc.) and on methods of forecasting the yields of such crops; (b) to present, whenever possible, evidence for the use of such methods of forecasting crop yields in areas other than the country or locality of origin. The Commission invited the following experts to serve on the working group: J. Goudriaan (Netherlands), B.W. Kelly (U.S.A.), M. Kurpelova (Czechoslovakia), R. Pfau (Federal Republic of Germany), B. Primault (Switzerland), E. S. Ulanova (U.S.S.R.) (chairman).

In adopting Resolution 12 (CAGM-V), the Commission pointed out that research on the influence of agrometeorological conditions on crop yields and on crop-yield prediction methods was of very great scientific and economic importance for agrometeorology and for agricultural production. The quantitative dependence of crop yields on meteorological conditions has already been established in many countries and, on the basis of these, it has been possible to make production and yield predictions at varying dates in advance of harvest. The working group has summarized the results of research work and dealt with mathematical models of plant growth and yield.
CHAPTER 2

THE POTATO

2.1 Meteorological factors affecting growth and yield

The potato is of great economic importance, not only as a food crop, but also for industrial products and fodder. Over the years, depending on the weather conditions, potato production varies within wide limits.

Most authors consider temperature, precipitation and soil moisture to be the important factors affecting growth and yield of potato crops. The temperature data used are frequently expressed as sums of temperatures, with a lower limit for potato development. Radiation and the temperature of the top-soil layer are the other factors used. Average or total monthly values are often employed since they are most easily obtained.

2.2 Methods of study

The methods of investigation can be divided into two groups:

(a) Experimental research

In the majority of cases, experimental research of the growth and development of the potato is based on the phytotron method with various combinations of temperature, air humidity, radiation and the length of the day. Some investigations are also made in greenhouses, in which case many of the factors are held at optimum (e.g. water, fertilizers).

(b) Statistical methods

Statistical methods are used involving climatological and phenological archives, as well as crop data. Correlation and regression analyses are employed. There is a recent tendency to construct crop-growth simulation models.

2.3 Influence of meteorological factors on yield and methods of yield prediction

Workers in a large number of countries are investigating the dependence of the crop yield on meteorological factors. Various quantitative methods are being worked out for estimating and predicting the yield.

The potato is one of the most complex crops as regards the establishment of sufficiently reliable links between agronometeorological conditions and tuber yield. The yield largely depends on harvesting efforts and farming factors, which are particularly difficult to take into account in prediction schemes. Nevertheless, meteorological factors play a fundamental role.

In Great Britain, experiments were carried out to determine standards for growth and assimilation as a function of temperature and radiation. It was shown that the commencement of tuber growth corresponds to the maximum of the assimilation curve, but tuber growth itself has its principal phase when assimilation and the upper leaf surface are beginning to decrease.
Three phases can be clearly distinguished in the growth of the tubers:

(a) A 10- to 14-day period of exponential growth after growth begins;
(b) A long period of linear growth (six to eight weeks);
(c) A final phase of slower growth with the dying-off of leaves at the same time.

In the second phase, two parameters can be observed which are interesting from the physiological viewpoint:

(i) Growth rate;
(ii) The time of the beginning of tuber growth.

To obtain plentiful crops, it is necessary to:

(a) Shift the growth curve to an earlier date, as well as advancing the commencement of growth to an earlier time;
(b) Improve growth rates;
(c) Lengthen the duration of the linear growth phase.

Research in a phytotron has led to the following results:

(a) The period of growth from planting to germination can be reduced by high temperatures; between 13.4°C and 22.9°C the time is reduced at the rate of one day per 0.5°C;

(b) The period of growth from germination to commencement of tuber formation is a function of the length of day, available light and temperature.

The influence of day length on tuber growth is insignificant. A 12-hour day in relation to an 18-hour day reduced the growth period by only three days. The effects of radiation and temperature are more significant, e.g. in constant conditions tubers formed one week earlier at 28°C than at 15°C. In a greenhouse experiment, it was observed that tubers began to form at an earlier date when the daily radiation was increased from 70 to 370 cal cm⁻² d⁻¹.

The fastest growth rate for an average amount of formed tubers was obtained when the temperature was about 20°C in the day and about 15°C at night.

Tuber growth rate is largely independent of the surface area of the leaves if, at the time of fastest growth, the plant has an upper leaf surface of 3 000 – 4 000 cm². A large degree of correlation exists between the tuber growth rate and meteorological parameters during the fortnight after tubers begin to develop.

In the U.S.S.R. the period after commencement of tuber formation is of decisive importance for yield; the temperature/humidity relationship determines the so-called "hydrothermal coefficient" (HTC):

\[ HTC = \frac{10 \cdot P}{\Sigma t} \]

where \( P \) is the sum of all precipitation (mm) during the period in question and \( \Sigma t \) is the sum of daily mean air temperatures (°C).

Optimum yields may be expected when, during the period of tuber formation, the mean temperature lies between 14°C and 18°C and the hydrothermal coefficient is greater than 1.
Yields fall if the mean temperature is higher than 18° - 19°C and the hydrothermic coefficient is 0.4 - 0.5. If the HTC is greater than 1, good results may be expected at much higher temperatures.

Popovskaya (1957), with reference to central regions of the European part of the U.S.S.R., elaborated a technique for predicting yield as a function of agrometeorological conditions during the period of tuber formation. This technique was based on the relationship between ten-day growth of tubers, air temperature and soil moisture.

Popovskaya, when analysing dynamics of tuber growth, singles out three basic sub-periods:

First sub-period: from commencement of tuber formation to commencement of intensive growth - coinciding, in the majority of cases, with the time from beginning of budding to beginning of flowering;

Second sub-period: characterized by tuber growth which attains highest values and remains at the same level for a lengthy period. This coincides with the time from flowering to beginning of wilting of the tops;

Third sub-period: commences when there is a rapid reduction in growth as a result of wilting. The sub-period may not occur in certain years because of late planting, favourable growing conditions or high agrotechnological level. Considerable growth may continue up to the occurrence of frosts or until harvest, if potato harvesting is carried out when the tops are still green in order to avoid large crop losses from frost.

The most important sub-period for crop development is the second, for which Popovskaya established the dependence of growth values on temperature and soil moisture. The least growth (irrespective of temperature) is observed with low soil moisture - less than 20 mm in the layer between 0 and 50 cm; greatest growth occurs with 60 - 70 mm in the top 50 cm of soil and a mean temperature of 16 - 18°C.

A comparison of data observed for potato growth in sandy and loamy soils revealed only slight differences, therefore relationships apply to both of these soils. However, for greater comparability it is better to express the correlation in relative units rather than absolute units.

Popovskaya expressed productive moisture content in the 50 cm soil layer as a percentage of the smallest field capacity, and potato growth as a percentage of growth in optimum conditions, i.e. soil moisture at 80 - 100% of field capacity and mean temperature of 16-18°C. If these conditions are modified, growth is reduced.

With low temperatures over a ten-day period (10-12°C), irrespective of favourable soil moisture, growth is reduced to 70-75% of optimum. Similarly, with temperature increases above optimum (18-19°C) there is also a decrease in growth. Many studies show that very high temperatures retard tuber formation.

Calculation of tuber growth has taken into account the weight of tops per hectare of crop. In favourable agrometeorological conditions high tuber growth rates were observed when top weight was not less than 18-20 t ha⁻¹.

Most research into yield dependence on meteorological factors is made by statistical methods.
In the U.S.S.R., Tsuberbiller (1969) expresses potato yield not in relative but in absolute values, i.e., as the increase in tuber weight in five-day periods. Calculations of anticipated crop may be made with the following equation:

\[ Q = q_0 + n \Delta g_{av} \]

where \( Q \) is the final tuber yield (t ha\(^{-1}\));
\( q_0 \) is the weight of the tubers (t ha\(^{-1}\)) developed in the initial period (before the start of the intensive tuber formation);
\( n \) is the number of five-day periods during intensive tuber formation;
\( \Delta g_{av} \) is the average increase in tuber weight over the five-day period.

Tsuberbiller proposed the following expressions for determining \( \Delta g \), the increase in tuber weight over the five-day period, as a function of agrometeorological conditions:

\[ \Delta g = \frac{acf(t,v_1)}{40000} \quad \Delta g = \frac{acf(t,v_2)}{40000} \]

where \( a \) is the increase in weight over the five-day period as observed in optimum agrometeorological conditions and normal plant density;
\( c \) is the density of plants (number of plants per hectare);
\( 40000 \) is the ratio of actual density to normal density; and
\( f(t,v) \) is an index of favourable agrometeorological conditions, determined by combining the five-day average soil temperature, \( t \), at a depth of 10 cm at 1300 LST with the quantity of productive moisture in the soil, \( v_1 \) or \( v_2 \), at 0 - 20 cm and 0 - 50 cm, respectively.

The length of the period of intensive tuber formation is one of the indices for producing a high yield. Another factor no less important is the average rate at which the tuber weight increases, which is determined essentially by agrometeorological conditions, by the level of agricultural technology, and by plant density. Tsuberbiller prepared tables for evaluating \( f(t,v) \) from data on soil temperatures and productive soil moisture.

Khudryakova (1961) obtained, for the Far East, the dependence of ten-day tuber growth on agrometeorological factors for different levels of agricultural technology. This regression equation for soil conditions (moisture content between 30 - 60 mm in the layer between 0 and 20 cm) is:

\[ y = 0.41x - 4.9; \quad r = 0.79 \]

where, for a ten-day period, \( y \) is the tuber growth (t ha\(^{-1}\));
\( x \) is the average air temperature (°C);
\( r \) is the correlation coefficient at 1300 LST.

For conditions of insufficient moisture (moisture content 10 - 30 mm) the regression equation is:

\[ y = -0.90x + 25.8; \quad r = -0.90 \]

Khudryakova also established fairly precise regression equations for the yield of early (a) and medium-riping (b) varieties based on total precipitation during July and July/August:
CHAPTER 2

\[ \log y = 4.55 - \log x; \quad r = -0.87 \]  \hspace{1cm} (a)

\[ \log y = 4.77 - \log x; \quad r = -0.82 \]  \hspace{1cm} (b)

where \( y \) is the weight of the tubers (centners\(^*\) per hectare (cent. ha\(^{-1}\))) at the start of harvesting and \( x \) is total precipitation for the period concerned. Yields could be estimated at least two months in advance. However, the equations are valid only for the level of agricultural technology applicable to the particular varieties studied.

For the Yabaikaliye region, Polevoj (1970) obtained quantitative data concerning the influence of weather over a 24-hour period on development of potato crops. He analysed data supplied by the network of hydrometeorological stations and strain-testing bases for three classifications found in this region: the early, early/medium and medium-ripening varieties. An initial rough estimate of expected yield \( (y_1) \) can be obtained from the average night-time air temperature \( (t_H) \) during the period between planting and germination:

\[ y_1 = -855.17 - 11.17t_H^2 + 221.13 \ t_H \]

Furthermore, the amount of the yield \( (y_2) \) can be determined after budding using mean day-time air temperature \( (t_g) \) and total night-time precipitation \( (O_H) \) over this period.

\[ y_2 = -727.14 + 0.68 \ y_1 - 2.77 \ t_g^2 + 92.43 \ t_g + 1.25 \ O_H; \quad r = 0.70 \]

A more precise method to estimate yield \( (y_3) \) is by temperature \( (t_g) \), precipitation \( (O_H) \) and length of the period between budding and end of vegetation \( (n_H) \).

The equation for the early/medium varieties of potato is:

\[ y_3 = -1791.00 + 0.86 \ y_2 - 5.60 \ t_g^2 + 195.66 \ t_g + 0.12 \ O_H + 2.23 \ n_H; \quad r = 0.84 \]

These equations enable predictions to be made of potato yield based on meteorological factors while assuming a high level of agricultural technology typical of strain-testing bases and experimental stations, as well as at farms with a similar level of technology.

Japanese researchers determined the following regression equation for estimating potato yield:

\[ y = -4897.5 + 389.996 \ x \]

where \( y = \) yield (g per 3.3 m\(^2\)); and

\( x = \) sum of the average maximum air temperature and the average minimum soil temperature (\(^\circ\)C) at a depth of 5 cm.

A slightly different equation for June is:

\[ y = 12303 + 358.21 \ (x_1 - 25.0) + 217.32 \ (x_2 - 44.22) \]

* 1 centner = 100 kilograms
where \( y \) is the yield (g per 3.3 \( \text{m}^2 \));

\[ x_1 \] is the average maximum air temperature (\( ^\circ \text{C} \)); and

\[ x_2 \] is the same as \( x \) in the previous equation, i.e. the sum of the average maximum air temperature and the average minimum soil temperature at a depth of 5 cm in June.

Results obtained by Tomaszewska (1922) deserve attention. She studied the effect of climatic conditions on crop yield and on dry matter content in the potato, and developed the following formulae for climatic conditions in Poland, without considering soil type:

\[ y = 335.80 - 0.417 \, x_1 - 0.374 \, x_2 - 0.249 \, x_3 + 0.133 \, x_4 + 0.316 \, x_5 \]

where \( y \) is yield (g ha\(^{-1}\));

\( x_1 \) is total precipitation (mm) for April-May;

\( x_2, x_3, x_4 \) are the sums of mean daily air temperature (\( ^\circ \text{C} \)) in August/September and April/May, respectively;

\( x_5 \) is total precipitation (mm) for September.

\[ U = 20.85 - 0.014 \, Z_1 - 0.007 \, Z_2 - 0.037 \, Z_3 - 0.005 \, Z_4 \]

where \( U \) is the percentage of dry matter in the potato;

\( Z_1, Z_2 \) are total precipitation (mm) in September and August, respectively;

\( Z_3 \) is the number of clear days in June and July; and

\( Z_4 \) is the sum of the mean 24-hour air temperature (\( ^\circ \text{C} \)) for August.

In Norway yields were classified on the basis of temperature and precipitation, using data from 84 field-test units in southern Norway. Late potato varieties developed the greatest tuber yield and amount of dry matter when the "temperature total" was 1 700-1 800 degree days (base 0\( ^\circ \text{C} \)) during the period from planting to harvesting, and when the average June-September temperature was 13.5 - 14\( ^\circ \text{C} \). For an early variety, the sum of temperatures was 1 400-1 500 degree days. Assuming these temperature conditions, the following "optimum" precipitation totals ensured the highest yield and the highest percentage of dry matter:

- May/June: 75 mm;
- July/August: 150 mm;
- August/September: 250 mm;
- June/September: 300 mm.

Excessive moisture reduced yield and dry matter content.

Frogner (1964) conducted statistical investigations into yield as a function of various meteorological factors, using four varieties cultivated for a number of years in southern Norway. He found the following optimum precipitation amounts (mm):

<table>
<thead>
<tr>
<th>Month</th>
<th>Optimum Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>35 - 65</td>
</tr>
<tr>
<td>July</td>
<td>120 - 150</td>
</tr>
<tr>
<td>August</td>
<td>75 - 105</td>
</tr>
<tr>
<td>September</td>
<td>40 - 70</td>
</tr>
<tr>
<td>June - September</td>
<td>270 - 390</td>
</tr>
</tbody>
</table>
An interesting correlation \( r = 0.66 \) was found by Rønssen (1970) between the number of tubers per unit area and the quantity of precipitation during the first month following planting.

In Finland, Yllö (1964) compared high and low yields over the years, and observed a fluctuation between 42.2 and 22.5 t ha\(^{-1}\). Good and bad yields obtained with the following summer temperatures (°C) were:

<table>
<thead>
<tr>
<th></th>
<th>June</th>
<th>July</th>
<th>August</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>14.7</td>
<td>16.3</td>
<td>14.1</td>
</tr>
<tr>
<td>Bad</td>
<td>13.0</td>
<td>16.8</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Precipitation of 68 mm for July produced a higher yield than a low value of 55 mm; corresponding figures for August were 79 and 62 mm, respectively.

In the Federal Republic of Germany, Tamm (1950), Baumann (1961), Brouwer and Martin (1962), Pfau (1964) et al. investigated the relationship between yield and weather. Brouwer found that a temperature not exceeding 16°C was essential during flowering.

Tamm and Baumann consider that a cool and rainy August favours increased yield. Hot, dry weather from the initial stage of growth up to about the time of flowering is conducive to an increase in yield, provided that temperatures during flowering remain lower than normal when precipitation is plentiful.

In general, temperatures should not be very high. 18°C seems to be the temperature for optimum growth. If the temperature is higher than 20°C, a reduction in growth occurs, while if it is higher than 28°C, growth ceases. Pfau (1964) made an attempt to investigate the problem of yield/weather dependence for the Federal Republic of Germany, using existing crop data supplied by more than 400 farming areas. As in the research by Yllö, he used statistical methods to compare years of high and low yields to determine optimum weather conditions.

If a late potato variety germinates at an average temperature of 10°C (upper 20 cm of soil), conditions favour the early appearance of sprouts and shoots \((x_1)\). A reversion to cold weather is unfavourable during the initial stage. The soil must be quite damp \((x_2)\) yet excess moisture is detrimental, especially a week before sprouting \((x_3)\), since it prevents aeration of the soil. After sprouting, young plants need an increase in temperature \((x_4)\), but marked variations in temperature are undesirable during the period between sprouting and flowering \((x_5)\).

For late varieties of potatoes, a small quantity of precipitation \((x_6)\) is needed during the period between sprouting and flowering. This condition is particularly important in the second half of the period \((x_7)\), although it is necessary to make allowance for evapotranspiration.

If the amount of precipitation is deficient in the final stage of growth, reduced yields should be expected. Up to the end of ripening precipitation must be sufficient and uniformly distributed \((x_8)\).

The eight weather factors affecting yield are:

\[x_1: 3.7 \text{ to } 4.6°C\]  
- Difference in the mean values of air temperature for the second and first halves of the period between planting and sprouting;
$x_2$: 1.4 to 1.8 mm d$^{-1}$ - Average daily precipitation in the period between planting and sprouting;

$x_3$: 0.1 to 1.0 mm d$^{-1}$ - Difference in the average daily precipitation for the first and second halves of the period between planting and sprouting;

$x_4$: 16.9$^\circ$ to 17.8$^\circ$C - Mean air temperature during the period between sprouting and flowering;

$x_5$: 0.7 to 1.6$^\circ$C - Difference in mean air temperature for the second and first halves of the period between sprouting and flowering;

$x_6$: 2.1 to 2.5 mm d$^{-1}$ - Average daily precipitation during the period between sprouting and flowering;

$x_7$: -0.3 to -1.2 mm d$^{-1}$ - Difference between average daily precipitation for the first and second halves of the period between sprouting and flowering;

$x_8$: 2.9 to 3.3 mm d$^{-1}$ - Average daily precipitation for the period between flowering and commencement of ripening of the crop.

Crop prediction is dealt with by means of discriminant analysis. Well-known and generally used test methods give the following discriminant function:

$$x = 232 \times_1 + 95 \times_2 + 915 \times_4 + 399 \times_6 + 886 \times_8$$

If $x < 3500$, the yield will be at least 25% higher than the standard value; if $x > 6100$, at least 25% lower; if $3500 < x < 4300$, 10-25% higher; and if $5300 < x < 6100$, 10-25% lower. A value of $x$ between 4300 and 5300 corresponds to the standard. This prediction can be given after flowering if, within the limits of long-term forecasting or climatology, it is possible to estimate the precipitation up to ripening of the crop.

K. Kudina (1966, 1967) studied the thermodynamic influence of climatic factors on potato yield and attempted to determine the reaction of some varieties of potato to a change in the internal energy $\Delta u$ of the sun’s energy/plant community system, expressed by $E_s \rightarrow E_{2s}$.

The values of the parameter $\Delta u$ were determined from:

$$\Delta u = \frac{t_{av}}{t_s} - \frac{h_{sn}}{h_s} = \gamma_t - \gamma_{hs}$$

where $\gamma_{prod}$ is crop productivity in tons ha$^{-1}$;

$t_{av}$ is monthly mean air temperature;

$t_s$ is the sum of monthly mean air temperatures during the vegetative period;

$h_{sn}, h_s$ are precipitation amounts during the month and vegetative periods, respectively;

$\gamma_t, \gamma_{hs}$ are theoretical crop productivities as functions of temperature and precipitation, respectively.

Individual varieties (studied from the viewpoint of attaining maximum crop productivity) differ substantially in their climatic requirements and particularly for the times when precipitation is more important than temperature and vice-versa.
The maximum yield of each variety is sensitive to the distribution of minimum energy in certain months: July and August (very late varieties); and June (late, medium/late and medium/early varieties).

Results of multiple regression and correlation analyses of meteorological factors and average yield for Czechoslovakia by Čermák (1967) provided a base for crop-yield prediction. This consists of two parts: evaluations of the trend and of the departure from the trend. Both are combined, and the total may be positive (favourable weather) or negative (unfavourable weather). Trend value is evaluated by smoothing the time-series of potato crop yields into a straight line or curve, (parabola, hyperbola, exponent or logarithmic function).
CHAPTER 3
SUGAR BEET

3.1 Main biological characteristics and agrometeorological requirements

Sugar beet is an important plant both for industrial purposes and for use as fodder. Its cultivation calls for good-quality soil with sufficient humus and nutrient content. In low latitudes it grows at altitudes up to 1 000 m above mean sea-level, and in middle and high latitudes, up to 400 m above mean sea-level. It is best suited to a mild climate with uniform distribution of precipitation and sufficient soil moisture at the beginning of spring. Another important factor is temperature. Low temperatures in spring have a negative effect on growth, and consequently in the colder northern regions, with a shorter vegetative period, the plant produces less sugar and the roots are smaller in size. Too high a temperature also has an unfavourable influence, causing wilting, loss of leaf area, and loss of the assimilation system, resulting similarly in smaller roots with low sugar content.

Formation of leaf clusters is especially important, since sugar content in the root is in direct relation to the number of leaves. Sugar is formed in the leaf cells by assimilation, under the influence of light, from simple organic matter (CO₂ and H₂O). Depending on the meteorological factors, the sugar content may vary considerably. In normal humidity and temperature conditions, higher sugar contents are obtained (20 - 23%) with comparatively few non-sugars. If moisture is excessive and temperatures are lower, the sugar content is lower (14 - 18%); this is also true when moisture is insufficient, and the sugar beet consequently loses its leaves.

Growth of the root is affected not only by meteorological factors, but also to a considerable extent by the soil, which must be deep enough for the roots to be able to continue to penetrate.

Assuming normal moisture conditions, the main agrometeorological factor at the time of planting is temperature. Literature states that the sugar beet begins to germinate at a temperature of 4 - 5°C, but many authors consider that the active temperature is a 24-hour mean of 8°C. Seed may remain ungerminated in the soil at lower temperatures for roughly ten days without the quality of the shoots being affected.

In spring, frosts with temperatures below -3°C are detrimental to young shoots.

Adequate but not excessive soil moisture at the beginning of spring is critical to good germination and establishment of uniform stands. Precipitation of 150 to 300 mm during the autumn/winter period provides favourable soil-moisture conditions for shoots. Precipitation ≥300 mm makes it more difficult for the seeds to germinate and for the shoots to appear, particularly in heavy soils. In regions with autumn/winter precipitation of 100-150 mm, satisfactory soil-moisture conditions are obtained when the rainfall is ≥25 mm for a period of 20 days prior to sowing. With less rainfall, shoots are likely to appear later.

The agrometeorological indicator of the end of vegetation in Europe in autumn is when the sustained daily mean temperature is no longer about 10°C. At lower temperatures root-crop growth is slight. Sugar-beet yield can be reduced by high soil-moisture content.
3.2 Methods of investigating the effect of meteorological factors on crops and of predicting the yield

Investigations into the relationship between meteorological factors and yield of sugar beet at various stages of the vegetative cycle have progressed considerably in recent years. When studying the effects of these various factors on crop development, much difficulty is encountered because meteorological elements do not act separately, but are interrelated and vary in space and time. Atmospheric conditions do not act in an identical manner on leaf formation, root growth or sugar content. Consequently, study is complex and from many standpoints still in the development stage.

Three principal techniques are used for investigating the effect of meteorological factors on yield - the physiological (crop-growth simulation), the mathematical-statistical (empirical-statistical) and the compound methods (crop-weather analysis). The second is most widely used. For this, correlation and regression analysis are most frequently used, serving to express the relationship between yield and the main elements, temperature and precipitation.

Čermák (1967) used mathematical-statistical methods to obtain mean regional values for conditions prevailing in Czechoslovakia. He found that in autumn and winter months temperature and precipitation have no effect on yield. In May, precipitation has significant influence. The following quadratic regression equation was obtained for May:

$$y^1 = -148.39 + 4.915 x - 0.036115 x^2$$

Optimum precipitation ($x$) in May for the yield ($y^1$) is 70 mm. The following important indicators were determined from precipitation values in July and August:

$$y^1 = -47.66 + 0.5114 x \quad \text{(July)}$$

$$y^1 = -76.89 + 1.1334 x \quad \text{(August)}$$

Precipitation in August plays the most important role. For September, the regression is non-linear:

$$y^1 = -110.60 + 5.3935 x - 0.05108 x^2$$

and optimum precipitation is 50 mm. A good correlation was discovered between yield and precipitation values for August and September.

Temperature proved to have little influence on yield.

For climatic conditions in the Federal Republic of Germany, Weber et al. (1966) studied the influence on yield of precipitation, temperature, humidity, sunshine and water balance (difference between precipitation and evaporation over 21 ten-day periods from 1 March to 30 September 1948 - 1963). They determined the dependence of yield on several meteorological elements at isolated periods of time, and on the individual meteorological elements at various stages in the vegetative period. Time durations used were one-month and ten-day periods.

Results show that for high yield it is essential to have little precipitation but sufficient sunshine during the planting period. Under such conditions the soil is properly heated so that the appearance of shoots is accelerated. A mild, damp May is favourable to growth. In June, dry weather is favourable in stimulating downward growth of the roots; the sugar beet can then obtain more nourishment from
a greater depth and can withstand drought comparatively easily in the succeeding period of growth. In July, the sugar beet requires less precipitation but more sunshine; in August, it needs more precipitation, showing that the store of soil moisture has often already been used up. In September, meteorological factors have no particular impact on yield.

These studies confirm results obtained by others. Bachmann (1960), Baumann (1961) and Kampe (1951) state that, during the planting and sprouting period, sugar beet needs warm and sufficiently wet weather in order to accelerate germination under the influence of high soil temperatures. Kampe (1951) and Tamm (1950) maintain that dry, warm weather in May and June is favourable to the development of the root crop, which can grow during dry weather by penetrating to a greater depth.

Baumann, Kampe and Tamm also found that considerable precipitation during the period of basic growth (July/August) had a positive effect on yield.

Lüdecke (1960), Lüdecke and Nitsche (1956), Kampe (1951), Schnelle (1952) and Tamm (1950) noted that very active formation of sugar during September and October was due to a large amount of sunshine and low precipitation.

In Finland, Brummer (1961) used Fisher's multiple-regression method to analyse the effect of precipitation and temperature on yield. He staggered six plantings from mid-April to the end of May and discovered a good correlation between the time of planting and yield ($r = -0.67$). A decisive factor is the temperature after planting, which determines speed of germination and emergence. Temperature at the end of the vegetative period (September or October) is also important, since high temperatures increase development of the roots ($r = 0.67$). Precipitation had a much smaller influence on yield than temperature, and consequently irrigation is not very important.

In Japan, Takahashi (1968), using correlation equations, established the dependence of yield on meteorological factors at Obihiro, e.g. the average temperatures in July and the beginning of August ($z = 0.60$). Milder temperatures during July and August increase yield:

$$y = 7.951 - 0.204 \times x$$

where $x$ = average temperature from July to August;

$y$ = yield in kin tan$^{-1}$; the equation error $S_y$ being $\pm 0.457$ kin tan$^{-1}$.

Kudrna (1966) in Czechoslovakia concluded that the highest yield occurred with a maximum temperature of 16.5°C and maximum precipitation of 100-110 mm in August (i.e. during the period of intensive growth of the root).

Kudrna (1967) studied the maximum and minimum sugar-beet yields using the thermodynamic method to analyse the sun-energy/plant-energy association system $E_s \rightarrow E_{ras}$.

A criterion established for estimating the heat equilibrium level of the system is the parameter for its internal energy $\Delta u$:

$$\Delta u = u_2 - u_1$$

---

* 1 kin = 1.677 kg; 1 tan = 993 m$^2$. 
where \( u \) is the change in the system's internal energy when making the transition from one system state to the other and \( u_2, u_1 \) are values to the system's energy at the end and the beginning of the process respectively.

Solar energy (which introduces heat into the system) is needed for development of a specific yield \( (y_t) \). Precipitation uses up part of the heat (transpiration and evaporation) and thus represents a specific yield \( (y_h) \). The difference, \( \Delta u = y_t - y_h \), represents the overall quantity of energy entering the plant-association system.

A specific level of thermal equilibrium is created which is important for the functioning of living processes of plants.

If \( y_t \) and \( y_h \) represent specific quantities of potential energy, then the difference between the two values \( (\Delta u) \) represents either the available quantity of energy in the system for a specific yield, or the change in the total (internal) energy of the system \( (U) \). Then

\[
U = \frac{y_t}{t_c} \cdot t_{cn} - \frac{y_h}{h_s} \cdot h_{sn} = y \left[ \frac{t_{cn}}{t_c} - \frac{h_{sn}}{h_s} \right] = y_t - y_h
\]

where \( t_c, h_s \) are the sum of average monthly temperatures and precipitation values, respectively, over the plant's vegetation period, \( t_{cn} \) is average monthly temperature and \( h_{sn} \) is total precipitation during the month.

By means of this method dependence of maximum and minimum yields was studied under different thermodynamic conditions. It was found that the maximum yield could be obtained if temperature and precipitation attained their maximum values so as to produce a maximum difference \( -\Delta u \) min. Then, the so-called climatic equation for the critical period is:

\[
-u^8_{\min} = y^8_t_{\max} - y^8_{h8_{\max}}
\]

(Index 8 means August.)

Schmidt and Železný (1971), in Czechoslovakia, when investigating the relationship between atmospheric conditions and the weight of sugar-beet roots, used Selyaninov's hydrothermal coefficient (HTC) for the period from March to September. Large HTC values for the period April-May unfavourably affected root weight. Excessive precipitation during this period makes sowing and other agricultural work difficult, and at the same time shortens the vegetative period. However, a low HTC in May hampers the appearance of plant shoots and leads to a slower rate of increase in weight, particularly if June has variable precipitation and temperature. Corresponding figures for maximum root weight in June-September were 1.60 – 1.22; for minimum weight, 0.90 – 0.70.

The influence of meteorological factors on yield is often studied in connexion with other factors, such as soil, relief, etc. In Czechoslovakia, Kocúr and Džugan (1972) analysed the relationship between crop yield \( (y, \text{cent. ha}^{-1}) \) and precipitation during the critical period, June-September \( (x, \text{mm}) \) for separate types of soil in the lowlands of eastern Slovakia. They obtained these equations:

\begin{align*}
\text{Meadow-land (HP):} & \quad y = 154.60 + 0.7542 x \\
\text{Meadow-land glei (HP):} & \quad y = 51.007 + 2.554 x - 0.00691 x^2 \\
\text{Black soil degraded (CMd):} & \quad y = 65.10 + 0.7138 x
\end{align*}
For meadow-land soils (sandy/clay and clay) and for degraded black soil, the relationship is linear but for meadow-land glei soils, it is quadratic.

In the U.S.S.R., Holland, Czechoslovakia and Poland complex mathematical/statistical methods for investigating the effect of meteorological factors on yield have been devised concerning biological characteristics of the crop during the inter-phase phenological periods.

Kontorskhikova (1965) determined the dependence of yield on moisture supply from planting up to commencement of root growth, and also during the vegetative period for a zone in the U.S.S.R. with an inadequate moisture supply. Moisture conditions were characterized by the ratio of evapotranspiration from the sugar-beet field to the amount of evaporation at which optimum growth conditions occur. Kontorskhikova calculated evapotranspiration by nomograms from the productive soil moisture in a one-metre layer and from precipitation and air temperature.

The moisture requirement was determined from a biological curve which expresses the sugar beet's need for water. Quantitative dependence of yield (y) on the water supply (p) was obtained for the various vegetative periods and for different regions where sugar beet is planted.

For regions with sufficient water and where the decisive factor for crop development is temperature, Kontorskhikova worked out a method for determining root growth (z) over a ten-day period (expressed as % of the weight for the previous ten-day period) as a function of average air temperature (y, °C), and the total number of hours of sunshine (x). For non-black-soil regions the equation is:

\[ z = 0.13x + 4.6y - 41; \quad r = 0.81 \]

In the initial vegetative period, lack of heat in the non-black soil causes the sugar beet to grow slowly, and consequently the length of the period of intensive root growth is of particular importance: the longer the period, the greater will be the weight of the root crop. Kontorskhikova found a quantitative relationship between length of both periods and yield:

\[ y = 4.5n_1 - 1.4n_2 + 204; \quad r = 0.80 \]

where y is weight of roots (g) at the time in autumn when average air temperature for the ten-day period reaches 10°C;

n₁ is length of the period from sprouting to formation of a root weighing 100 g; and

n₂ is length of the period after this date in autumn until the temperature reaches 10°C.

Kontorskhikova also investigated effects of agrometeorological factors on sugar content of sugar beet in the black-soil region.

Assuming sufficient supply of moisture, the sugar content depends on photosynthetically active radiation as follows:

\[ y = 0.42\text{PAR} + 14; \quad r = 0.73 \]

\[ y = 0.08S_1 + 14; \quad r = 0.71 \]

where y is sugar content at the end of vegetation (%);
PAR is the photosynthetic active radiation in kcal cm\(^{-2}\) over the period of intensive sugar accumulation (from 1 August to 20 September);

\( S_1 \) is total direct solar radiation in kcal cm\(^{-2}\).

To use this relationship for predicting yield, a relationship was found between \( S_1 \) and the sum of active temperature (\( \Sigma t \)) over the period of sugar accumulation:

\[ S_1 = 0.08 \Sigma t - 65. \]

With poor water supplies, graphical relationships were obtained between sugar content, solar radiation and water supply or soil moisture. These graphs show that the greatest sugar content in the root (more than 18%) occurs when the water supply is between 30% and 80% of optimum, and when \( S_1 \) is more than 14 kcal cm\(^{-2}\) or PAR is greater than 8 kcal cm\(^{-2}\). In regions where the water supply is sufficient or excessive and when soil moisture in a one-metre soil layer is between 50 and 170 mm, \( S_1 \) and PAR decrease to 10 kcal cm\(^{-2}\) and 7 kcal cm\(^{-2}\) respectively, consequently decreasing sugar content by up to 15%.

Mikhajlova (1962, 1971) in the U.S.S.R. derived a prediction technique in which expected yield is calculated as a function of average root weight and soil-moisture content at the time of prediction. Corrections are then applied to allow for the effect of precipitation and temperature in the subsequent period of development.

The importance of mineral and organic fertilizers is estimated by special correlation graphs. Soil productivity is assessed indirectly, by constructing graphs of the dependences for groups of regions with the same types of soil. From air temperature in October, a rough estimate is made of losses in yield in the harvest period. Expected yield is calculated using seven to ten variables.

Kelschevskaia (1956, 1963) established complex agroclimactical indicators for growth of the sugar beet in the U.S.S.R. "New Lands". The relationship between yield and heat supply and the moisture coefficient may be expressed by the index:

\[ K = \frac{0.6 \Sigma r_1 + \Sigma r_2}{0.1 \Sigma t} \]

where \( \Sigma t \) is the sum of daily mean air temperatures;

\( \Sigma r_1, \Sigma r_2 \) are the precipitation amounts during non-vegetative and vegetative periods respectively.

Heat supply is determined from the sums of all daily mean air temperatures between the dates when the mean temperature passes through 7\(^\circ\)C in spring and 5\(^\circ\)C in autumn.

Kelschevskaia shows that if total temperatures are less than 1 600\(^\circ\)C (in any moisture condition) and precipitation is less than 250 mm (irrespective of heat supply), then yield is very low. Optimum total temperature is 3 500 to 4 000\(^\circ\)C and the total precipitation during vegetative and non-vegetative periods is 900-1 100 mm. She also determined the dependence of sugar content on moisture and the number of clear days during the period of sugar accumulation.

In Holland, Kuiper (1962) studied the influence of solar radiation intensity, temperature and soil moisture on growth, transpiration, and production of sugar-beet root. Dry root matter increased exponentially with the intensity of radiation and soil moisture. For weak radiation intensity the effect of soil moisture is insignificant. No dependence of dry matter increase was found with temperature.
In Poland, Metelski (1970) developed a method for predicting yield and sugar content. He concluded that:

(a) Prediction of commercial yield from rate of growth of roots, without taking climatic factors into account, should be fairly effective ($r = 0.80$ for 20 August and $r = 0.90$ for 10 October);

(b) Correlations between precipitation, temperature and yield are low for the whole period of growth compared with individual ten-day periods;

(c) Accuracy of prediction is affected more by precipitation than by temperature;

(d) There are no optimum precipitation or temperature values which would always correspond to a maximum yield;

(e) In those years which are exceptionally favourable or unfavourable for development of sugar-beet roots, it is possible to correct predictions by acknowledging that heavy roots grow comparatively slowly towards the end of the vegetative period;

(f) Planting density, leaf mass and leaf-to-root ratio all exercise a statistical influence on accuracy.

3.3 Methods of studying the effect of agrometeorological factors on yield and their practical use

The most important meteorological factors which influence development of agricultural crops are: precipitation, temperature, and sunshine. The sugar beet is no exception. Although it has been very successfully adapted to climatic conditions of many different regions, it is nevertheless still an exacting crop which is very sensitive to any change. Proof lies in the great variety of results obtained for different climatic regions during investigations of relations between yield and meteorological factors.

The distinctive conditions which apply for growing sugar beet in various climatic regions appear in correlation studies already presented (section 3.2). Thus in Central Europe (Czechoslovakia, Federal Republic of Germany) at the beginning of June, soil moisture is usually sufficient. However, just after planting, it is necessary to have light precipitation with enough sunshine to heat the soil to accelerate germination and shoot emergence. In summer (July and particularly August, when the root crop is experiencing its most intensive growth) the need for moisture again arises, since the soil moisture usually becomes insufficient. At the end of the vegetative period (September) a large amount of sunshine and light precipitation favourably influence sugar content. Temperature has little influence on yield.

In northern Europe (Finland), precipitation has a smaller influence on yield, while temperature plays a greater role. In order to obtain high efficiency and growth in Central Europe, irrigation must be considered, but not so in Finland.

In Japan (meteorological station, Obigiro), the temperature during summer is also very important for yield. Mild temperatures as well as high solar radiation are necessary to achieve good yields.

On the basis of the above information, one may conclude that the results of investigations made with mathematical/statistical methods cannot be applied universally, but only for those regions in which climatic conditions are similar to those
in the studies. The use of regression equations in different climatic regions necessitates elaboration of new correlation dependencies characterizing each climatic region.

Recently the compound method has been used for investigating the effect of agrometeorological factors on yield. This is applied, with the mathematical/statistical analysis, to the biologically based inter-phase phenological periods of plant growth.
CHAPTER 4

THE SUNFLOWER

4.1 General

The sunflower is a heat-loving plant. Sums of temperatures up to ripening required by the medium/late, medium and early varieties are 2 400, 2 100 and 1 800°C respectively. Sunflower shoots are able to withstand low temperatures to -6°C for short periods. Below this the growth point is damaged, leading to branching of the stalk. Older plants die at temperatures from -4 to -6°C.

4.2 Methods of predicting crop yield

Total moisture loss from sunflower fields over the vegetative period amounts to 550 - 650 mm (5 500 - 6 500 m³ ha⁻¹), under optimum moisture conditions. According to investigations made in the U.S.S.R. by Mel'nik (1972), the dependence of seed yield (y) for individual farms (cent. ha⁻¹) on total moisture consumption during the vegetative period (E; m³ ha⁻¹) may be expressed by the equation:

\[ y = 2.83 + 0.059 E; \quad r = 0.87 \pm 0.02 \]

the equation error \( S_y \) being ± 3.6 cent. ha⁻¹.

During the period between sprouting and the formation of racemes, sunflowers consume about 20% of the total moisture requirement of the vegetative period; between formation of the raceme and flowering, 50%; and between flowering and ripening, 30%. According to Miuskij (1965) the "Zhdanovsk" variety yield (y = cent. ha⁻¹) depends on the amount of precipitation between planting and formation of the racemes (x, mm) as follows:

\[ y = 11.1 + 0.1 x - 0.031 \cdot 10^{-7} \cdot x^4 \]

\( S_y = \pm 3.4 \text{ cent. ha}^{-1} \).

The yield for the variety VNIINK 6540 depends on the amount of precipitation falling during the period between sprouting and flowering and is described by the equation:

\[ y = 8.6 + 0.11 x - 0.0195 \cdot 10^{-7} \cdot x^4 \]

\( S_y = \pm 2.8 \text{ cent. ha}^{-1} \).

Mel'nik (1963) describes yield at the strain-testing stations (y, cent. ha⁻¹) as a function of moisture at the beginning of sowing and for individual inter-phase periods:

\[ y = f(x_1, x_2, x_3, x_4, x_5, x_6) \]

where \( x_1, \ldots x_6 \) are (1) total precipitation (mm) in the autumn/winter/spring period prior to sowing; (2) precipitation during the period from sowing to sprouting; (3) sprouting to raceme formation; (4) raceme formation to flowering; (5) flowering to date on which cumulative temperature is 500°C; and (6) from this date to the date of ripening.
The period from flowering to ripening has been broken down into two sub-periods since precipitation at the time of ripening has little influence on increase of yield, but sometimes has a reverse effect. The following equation has been obtained for this function and applies to the U.S.S.R. area where seed is grown on an industrial scale:

\[ y = 1.026 + 0.065 \times_1 + 0.054 \times_2 + 0.073 \times_3 + 0.054 \times_4 + 0.041 \times_5 - 0.032 \times_6 \]

From this equation the greatest contribution to yield is provided by \( \times_1 \) and \( \times_3 \). In this connexion, it should be stressed that \( \times_2 \) and \( \times_4 \) also affect development of the seed crop. These remarks must be considered when elaborating yield-prediction schemes.

Musluk studied the relationship in the Ukraine between seed yield and the moisture index:

\[ K = \frac{W + \Sigma x_2}{0.1 \Sigma t} \]

where \( W \) is soil moisture (mm) in a one-metre layer of soil at the beginning of sowing; \( \Sigma x_2 \) is the sum of daily precipitation over the vegetative period (mm); \( \Sigma t \) is the sum of daily mean air temperatures over the vegetative period (°C). The relationship between yield (\( y \)) and the moisture index (\( K \)) is described by:

\[ y = -15.3 + 22.86K \]

\( S_y = \pm 1.6 \) cent. ha\(^{-1} \).

An examination of this dependence indicates the existence of a sufficiently close link between hydrometeorological indices and yields and points towards the basic possibility of plotting prediction diagrams for yield.

The method of long-term agrometeorological prediction of average regional sunflower yields which was devised in the U.S.S.R. by Mel'nik (1972) is based on the relationship between yield and the moisture index:

\[ K_1 = \frac{0.6 \Sigma x_1 + \Sigma x_2}{0.1 \Sigma t} \]

where \( \Sigma x_1 \), \( \Sigma x_2 \) are total amounts of precipitation (mm) during the autumn/winter/spring period (up to date of sowing) and during the vegetative period, respectively, and \( \Sigma t \) is the sum of air temperature (°C) over the vegetative period.

An important advantage of the index is that it takes into account moisture in the autumn/winter/spring period, which plays a significant part in subsequent crop yield. Furthermore, \( K_1 \) takes into account the soil moisture not only in the one-metre soil layer, but in the entire volume occupied by the roots. Thus, according to Kruzhilin (1961), the sunflower draws from this layer 65-75% of its overall water requirements, while 22-35% is taken from the 100-200 cm layer.

In the black-soil area of northern Bulgaria, according to Dilkov (1967), the sunflower also draws a large amount of moisture (80 - 100 mm) from the 100 - 200 cm soil layer. The moisture from deeper levels is used by the plants during the normally drier second part of the vegetative period and sometimes largely determines yield.
Index $K_1$ takes into account indirectly, through its denominator, the evaporative part of the moisture balance, making it more universally applicable.

Møl'nik (1972) established the dependence of yield ($y$, cent. ha$^{-1}$) on the moisture index ($K_1$) for strain-testing stations by means of a regression equation used for forecasting:

$$y = 23.44 \ (K_1 - 0.46)^{0.8}; \ \ r = 0.76 \pm 0.01$$

$S_y = \pm 3.2$ cent. ha$^{-1}$.

Other correlations are used to make the transition from crop estimates at the strain-testing stations to determine average regional values.
CHAPTER 5

COTTON

5.1 Introduction

Cotton is another heat-loving plant and has a long vegetative period. The main meteorological factors which determine development, growth and yield are light, heat and moisture.

In areas where cotton is grown, sunshine is available throughout the vegetative period. Where irrigation is necessary, moisture for the roots is provided throughout the vegetative period in accordance with the plant's requirements. However, since the temperature is variable during this period, particularly in spring and autumn, it is the main meteorological element determining the growth of cotton.

Other meteorological elements such as humidity, wind and cloudiness increase or decrease the effects of light, heat and moisture.

Throughout the entire vegetative period, cotton has varying requirements for temperature and soil moisture. Because of this, the effects of the main meteorological factors on development during the individual phases of growth are examined separately for each period. To begin with, research carried out in the U.S.S.R. will be described.

5.2 Period between sowing and germination

The first signs of activity in cotton seeds are observed at temperatures of 9 - 10°C. Sowing should therefore be started when the daily mean air temperature reaches 10°C, at which time the soil temperature at the depth where seeds are planted is 11 - 12°C.

The speed with which seeds germinate and shoots appear is greatly affected by soil moisture. Sabina (1965) established that 5 mm of productive soil moisture in a layer 0 - 5 cm deep (planting depth) is the lower limit for seedling emergence.

Even in optimum conditions of air temperature and available soil moisture, the soil crust lying over seeds restrains emergence and may damage or kill them. Consequently, heavy rain during germination and emergence is undesirable, since it causes a crust to form, the thickness of which depends on the amount and intensity of precipitation.

Causes of crust formation are unfavourable soil conditions, incorrect irrigation and weather conditions. Hardness of the crust often depends on the rate of rainfall. The faster the rate, the harder the crust, so that downpours are more likely to form a crust than steady rain. A light drizzle during warm weather does not have any harmful effect.

Precipitation of 10 - 15 mm per 24 hours favours crust formation, thus causing seedlings to be very sparse; precipitation of more than 20 mm per 24 hours produces an even thicker crust and greater sparseness.
The more slowly the soil dries out, the easier it is for the cotton shoots to emerge out of the surface. High air temperature and wind speed accelerate crust formation.

Cotton seedlings are very vulnerable to frost and perish at soil surface temperatures of -0.1 to -0.5°C.

5.3 Period between germination and bud formation

Warm weather, with a mean daily temperature of 14 - 19°C, is required for normal development of the cotton plant between germination and bud formation.

Mean temperatures of 26 - 27°C retard plant development while those of 29°C and above, especially associated with low relative humidity (dry wind phenomena), may lead to loss of buds.

Low temperatures and excessive soil moisture during this period are also detrimental, since they favour the occurrence of root decay and suctorial pests (aphids, thrips).

5.4 Period between bud formation and flowering

Mean daily air temperatures of between 24 and 29°C favour the development of the cotton plant but those of 30°C and above during the day may cause overheating of plant tissue and loss of turgor.

Cotton should be watered when the moisture content in the top 50 cm of the soil falls to 65-70% of field capacity, which corresponds to 60-75 mm of productive moisture.

Total loss of moisture from a cotton field is composed of evaporation and plant transpiration, and depends on the plant mass, shadiness of the soil surface, soil moisture and air temperature. Values of average daily loss as a function of the soil-moisture content in the 0 - 50 cm layer and mean daily air temperature (see Sabinina, 1965) are shown in Table I for loam soils, with deeply located groundwater.

<table>
<thead>
<tr>
<th>Mean daily air temperature (°C)</th>
<th>Productive soil moisture (mm) in a 0-50 cm layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>20 - 21</td>
<td>0.1  - 0.2</td>
</tr>
<tr>
<td>22 - 23</td>
<td>0.3  - 0.5</td>
</tr>
<tr>
<td>24 - 25</td>
<td>0.6  - 0.8</td>
</tr>
<tr>
<td>26 - 27</td>
<td>0.7  - 0.9</td>
</tr>
<tr>
<td>28 - 29</td>
<td>1.0  - 1.2</td>
</tr>
</tbody>
</table>

5.5 Period from flowering to opening of first bolls

Volosyuk (1971) and Karaul'shchikova (1962) established that maximum boll growth is observed when mean air temperature is 27°C over a ten-day period. Boll accumulation rate decreases as this temperature increases or decreases.
Apart from temperature, the number of developing bolls depends also on soil moisture. If the latter falls to 60% of field capacity, intensive bud-shedding occurs together with some loss of flowers. Small boll inceptions fall off.

During this period, when the cotton-plant develops a large above-ground mass and a strong, deep root system, soil moisture is consumed from a one-metre layer. Consumption values, as a function of temperature and initial soil moisture, are shown in Table II for regions with deep accumulations of groundwater.

### Table II

<table>
<thead>
<tr>
<th>Mean daily air temperature (°C)</th>
<th>Productive soil moisture (mm) in a 0-100 cm layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>21-22</td>
<td>1.0-1.2</td>
</tr>
<tr>
<td>23-24</td>
<td>1.5-1.8</td>
</tr>
<tr>
<td>25-26</td>
<td>2.2-2.3</td>
</tr>
<tr>
<td>27-28</td>
<td>2.7-3.0</td>
</tr>
<tr>
<td>29-30</td>
<td>3.2-3.5</td>
</tr>
<tr>
<td>31-32</td>
<td>3.8-4.0</td>
</tr>
</tbody>
</table>

5.6 **Period from opening of first bolls to end of harvest**

Formed bolls of the cotton plant emerge after the bracts have dried out and burst open. High temperatures and dry air accelerate the process. If cotton fields are dense or contain high levels of nitrogen-based fertilizer, the opening of bolls occurs at a slower rate since there is a strongly developed vegetative mass that causes higher air humidity and lower temperature. Bolls also open later if plants are growing in very moist conditions (soil moisture more than 70% of field capacity).

According to Platonova (1963), the opening of each successive boll of Soviet varieties requires a total daily average vapour pressure deficit of 60-80 hPa.

Opening is also accelerated after defoliation, the best average daily temperature conditions being at 17°C.

Precipitation during opening and harvesting delays opening, increases fibre humidity and degrades its quality. Furthermore, if the soil has become sodden as a result of rain, it is difficult to use harvesting machines.

Platonova (1973) found that favourable conditions for operating mechanical cotton-pickers exist when the mean daily vapour pressure deficit is 8 hPa or above. The machines cannot operate when the deficit is 3 hPa or below.

5.7 **Methods of predicting plant yield**

For long-term predictions of average regional yield, Platonova (1968, 1971) considers the number and weight of bolls at the end of vegetation as well as plant density, variety and time of sawing.
Her method for predicting the number of bolls is based on the relationship between the average rate of accumulation of bolls and the mean air temperature over the period of growth and ripening. Table III shows the relationship.

TABLE III

<table>
<thead>
<tr>
<th>10-day mean air temperature (°C)</th>
<th>Number of bolls formed over a ten-day period (average per plant) as a function of air temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Medium varieties</td>
</tr>
<tr>
<td></td>
<td>Late varieties</td>
</tr>
<tr>
<td>19</td>
<td>0.85</td>
</tr>
<tr>
<td>20</td>
<td>1.20</td>
</tr>
<tr>
<td>21</td>
<td>1.55</td>
</tr>
<tr>
<td>22</td>
<td>1.0</td>
</tr>
<tr>
<td>23</td>
<td>1.2</td>
</tr>
<tr>
<td>24</td>
<td>1.4</td>
</tr>
<tr>
<td>25</td>
<td>1.6</td>
</tr>
<tr>
<td>26</td>
<td>1.8</td>
</tr>
<tr>
<td>27</td>
<td>2.0</td>
</tr>
<tr>
<td>28</td>
<td>1.6</td>
</tr>
<tr>
<td>29</td>
<td>1.4</td>
</tr>
<tr>
<td>30</td>
<td>1.1</td>
</tr>
<tr>
<td>31</td>
<td>1.55</td>
</tr>
<tr>
<td>32</td>
<td>1.20</td>
</tr>
</tbody>
</table>

The method for predicting the average weight of wool from one boll is based on the relationship between weight of wool from one boll \((y, g)\) and the sums of active air temperatures over the vegetative period \((x, °C)\). The regression equation is:

\[ y = 0.0018 x - 1.17 \quad r = 0.91 \pm 0.03 \]

\( s_y = 0.3 \text{ g} \quad (s_y \text{ is the equation error}) \)

Since it is necessary to predict yield even before the cotton-plants flower, it is essential to forecast the time at which they will flower en masse. This is estimated from the sums of effective air temperatures above 10°C between sowing and flowering. For early-maturing varieties, this figure is 900°C; for medium varieties, 1 000°C; and for late varieties, 1 050°C.

Prediction information concerning the average weight of cotton-wool from one boll \((v, g)\), the average number of bolls on the plant at the end of vegetative \((n)\), and also factual information concerning the number of plants per ha \((g)\), enable the potential yields \((u_p)\) to be calculated in cent. ha\(^{-1}\).

\[ u_p = (vn) \text{ g} \]

To determine the farm yield \((u_f)\) it is necessary to multiply the potential yield by a specific coefficient, i.e.

\[ u_f = ku_p \]
where \( k \) is calculated from equations obtained for each region. For example, for the Sydar'insk region:

\[
k = -0.002 \, u_p + 0.516; \quad r = -0.87 \pm 0.08
\]

\[
S_y = \pm 0.01.
\]

For the Tashkent region:

\[
k = -0.011 \, u_p + 1.058; \quad r = -0.91 \pm 0.06
\]

\[
S_y = 0.04.
\]

Sobinina (1967) and Kovalenko and Sabinina (1968), in predicting average regional yield \((u, \text{ cent. ha}^{-1})\) of cotton in the Uzbek S.S.R., include plant density \((x, 1000 \text{ ha}^{-1})\), average number of bolls per plant \((y)\) and the difference in the sum of effective air temperatures (above 10°C) \((z)\) at 10 July minus 1000°C in the first forecast, and at 31 August minus 1880°C in the final prediction. Thus, for the Fergansk valley region, the equation is:

\[
u = 0.31 \, x + 2.14 \, y + 0.01 \, z - 16.8 \quad r = \pm 0.84
\]

\[
S_y = \pm 1.6 \text{ cent. ha}^{-1}.
\]

Vlasovuk (1971) proposed similar equations for predicting the regional yield in the Turkmen S.S.R. However, in these he calculated the sum of effective temperatures (above 10°C) from the date of flowering to the date of the first autumn frost.

The relation is:

\[
u = 0.28 \, x + 2.69 \, y - 0.005 \, z - 10.61
\]

The multiple correlation coefficient \( r = 0.74 \pm 0.03 \); the equation error \( S_y = \pm 3.6 \text{ cent. ha}^{-1} \).

Prediction for fine-fibred varieties is calculated by means of:

\[
u = 0.0691 \, x + 0.8280 \, y + 0.0156 \, z - 26.7621; \quad r = 0.84 \pm 0.05
\]

\[
S_y = \pm 2.8 \text{ cent. ha}^{-1}.
\]

For predicting yield, Rachkulik and Sitnikova (1966) proposed the use of the albedo of the soil/plant system together with certain parameters of the soil layer. They showed, in particular, that with a crop between 0 and 34 cent. ha\(^{-1}\) there is a direct relationship between the albedo of the cotton field during the period of maximum growth of leaf surface \((R_{n,p})\) and yield \((m)\); this relation can be written approximately as:

\[
R_{n,p} = R_n + bm
\]

where \( R_n \) is the albedo of the soil under the cotton plant and \( b \) is a constant.

Muminov et al. (1971) examined the dependence of yield on productivity, i.e. the number of bolls per \( 10 \text{ m}^2 \). They also investigated the influence on average regional yield \((y)\) caused by the amount of irrigation water received by the cotton plant during the vegetative period \((x)\). Equations were obtained for various groups of regions of the Uzbek S.S.R. For example, for the Fergansk, Andizhansk, Samarkand and Kashkadar'insk regions they found that:
\[ y = 1.80 x + 6.0; \quad r = 0.79 \pm 0.049 \]

\[ S_y, \text{ the equation error, } = \pm 2.3 \text{ cent. ha}^{-1}. \]

Abdulaev et al. (1967) established the relationship between the yield \( (y) \) and maximum leaf area \( (x; \text{thousand m}^2 \text{ ha}^{-1}) \)
\[ y = 0.94 x + 3.4; \quad r = 0.78 \pm 0.05 \]

\[ S_y = \pm 3.6 \text{ cent. ha}^{-1}. \]

The equation is valid for a maximum leaf area within the limits of 14 000 and 41 000 m\(^2\) ha\(^{-1}\).

The same authors propose calculating biological \( (y_b, \text{ g ha}^{-1}) \) and farm \( (y_f, \text{ g ha}^{-1}) \) yields of cotton-wool from the consumption of soil moisture \( (x, \text{mm}) \) during the period between planting and frost.

\[ y_b = -0.00046 x^2 + 0.57 x - 131.9; \quad r = 0.69 \pm 0.054 \]

\[ S_{y_b} = \pm 6.5 \text{ cent. ha}^{-1}. \]

\[ y_f = -0.00038 x^2 + 0.47 x - 111.5; \quad r = 0.75 \pm 0.05 \]

\[ S_{y_f} = \pm 3.6 \text{ cent. ha}^{-1}. \]

The dependence of \( y_b \) and \( y_f \) on moisture consumption \( (E) \) and the sum of effective air temperatures above \( 10^\circ C (T) \) during the period between flowering and opening of the first balls is:

\[ y_b = 0.52E + 0.77T - 665.3; \quad r = 0.74 \pm 0.045 \]

\[ S_{y_b} = \pm 6.3 \text{ cent. ha}^{-1}; \]

\[ y_f = 0.31E + 0.046T - 390.7; \quad r = 0.77 \pm 0.041 \]

\[ S_{y_f} = \pm 3.2 \text{ cent. ha}^{-1}. \]

Dependence of the yield \( (y_f, \text{ g ha}^{-1}) \) on maximum surface area of the leaves \( (x, \text{thousand m}^2 \text{ ha}^{-1}) \), the soil moisture consumption \( (E, \text{mm}) \) for the one-metre soil layer during the period between flowering and opening of the first balls before the first autumn frost is expressed by:

\[ y_f = 0.79 x + 0.12 E + 0.01 T - 23.6; \quad r = 0.89 \pm 0.012 \]

\[ S_{y_f} = \pm 2.9 \text{ cent. ha}^{-1}. \]

\( (S_{y_b} \text{ and } S_{y_f} \text{ are equation errors}). \)

Production of cotton in the Sudan Gezira depends on intensity and distribution of rainfall. Correlation relations were obtained between yield \( (y) \) and rainfall \( (mm) \) during the previous season \( (x_2) \) and during the period preceding sowing \( (x_1) \), i.e. 1 July to 15 August (for average data over past several years). Regression equations were obtained for different periods of years, e.g. for data observed between 1935 and 1955:

\[ y = 6.117 + 0.00659 x_1 - 0.00899 x_2. \]
In Egypt, Hosny et al. (1965) studied the effect of meteorological factors on the number of cotton-flowers formed. From experiments carried out in 1961, 1962 and 1963, the following conclusions were reached:

(a) The closest relationship obtained was that between absolute air humidity and flowering of the plant. A decrease (increase) in absolute humidity by one millimetre from its 1962 level on any day during a three-week period before flowering decreased (increased) the number of flowers per ten plants by 1.08 in 1961, and by 0.88 in 1963.

(b) Mean night-time air temperature three weeks before flowering was the next important factor. Results showed that the average night-time temperature in 1962 was optimum for flowering. A 1°C increase in 1961 over the average for 1962 reduced the number of flowers during the main flowering period by 0.76 per ten plants, while a 1°C reduction in 1963 increased the number by 0.48 per ten plants.

(c) Mean day-time air temperature is less important than absolute humidity or night-time temperatures for formation of flowers.

(d) Maximum amount of green matter is formed 21 days before flowering. Climatic factors do not affect flowering directly, but indirectly by their influence on the area of the plant on which the flowers form.

A formula was also determined for Egypt for the dependence of cotton yield on maximum and minimum air temperatures and the vapour-pressure deficit:

$$\Delta M = 0.333 \Delta L$$

where $\Delta M$ = deviation between cotton yield and average yield for 20 years;
$\Delta L$ = the sum of deviations from normal values of maximum and minimum air temperatures and the vapour-pressure deficit.

In India a study for different regions used Fisher's method to determine the influence of rain on yield during the growth period. For the Kollambar region, optimum values for cotton yield were 250 mm of rainfall with maximum and minimum temperatures of about 30 and 20°C, and with 550 hours of sunshine during the vegetative phase.
CHAPTER 6

SUGAR CANE

6.1 Introduction

Sugar cane is a tropical crop grown mostly between the latitudes 35°N and 35°S. It is often of significant economic importance to countries in this zone. Commercial production ranges over widely varying ecological conditions, notably elevation, precipitation, temperature and sunshine. The growing season may extend over two years or be as short as nine to ten months in frost-prone areas.

6.2 India

Gangopadhyaya and Sarker (1963, 1964) stated that the relationship between crop yield and weather is not simple and cannot be expressed only by a linear correlation of two factors. The curve, as one of the characteristics of the relationship of the crop and weather, may represent the corresponding optimum of one or several meteorological factors, on which this characteristic depends. The linear regressions of several factors may express these relationships.

Thus, the authors clearly reveal the complexity of the problem encountered in determining the weight of each meteo-element in the attempt to find formulae for crop prediction. On the one hand, the weight of each independent variable may change as the plants develop and, on the other, the maximum weight varies throughout the vegetative period.

These authors worked out a technique for predicting yield. This method of statistical analysis is a simple partial linear regression. A graphical method makes it possible to analyse the importance of each of the meteo-elements for crop development - specifically the average maximum temperature during stalk growth, which affects sugar cane production.

This simple numerical prediction technique, comparing meteorological factors with yield for years, is really based on accidental factors and is not sufficiently reliable.

Therefore certain additional corrections must be made to include meteorological parameters for other periods of development. Graphs may be used to show the quantity of crop expected, giving adjustments to the predictions calculated numerically. Meteorological parameters are not usually expressed in absolute values, but as deviations from mean values of the previous year. Mean values must always take into account phenological periods, and not calendar dates.

Calculations depend on rainfall, average minimum temperature and duration of solar radiation at times of tillering and growth of stalk.

Prediction of yield can be made one and a half or two months before harvest.

Actual relationships derived by Sarker (1965) are not presented, but the general formula is:

\[ x_1 = f_3(x_3) + f_2(x_2) + f_4(x_4) + f_5(x_5) + f'_2(x'_2) + f'_4(x'_4) + f'_5(x'_5) \]
where \( x_1 \) = yield per unit area in kg ha\(^{-1}\);
\( f_3(x_3), f_2(x_2), f_4(x_4), f_5(x_5) \) are values of mean maximum temperature, mean minimum temperature, rainfall and duration of solar radiation, respectively, during tillering;
\( f_2(x_2), f_4(x_4), f_5(x_5) \) are the same meteorological parameters, but for the corresponding period of stalk growth.

Sarker’s method, while having complex regression equations, is simple to use in practice. Observation of the meteorological parameters is easy. Comparison of sums of their corresponding averages by vegetative period can be made by any technician. Calculation of all values, with the aid of graphs, can be done by using simple algebraic rules.

The method was developed for India with a typical monsoon climate; therefore it should not be applied to other regions without careful study of their climatic conditions. It is obvious that weather-crop relationships will not be the same for other regions cultivating sugar cane.

6.3 Barbados

Hudson (1964, 1968) used the partial correlation method to investigate the effect of meteorological elements on development of sugar cane and on sugar formation in leaves and stalks. He determined the quantity of moisture required for favourable development.

Smith (1972) showed rainfall to be an important factor in the development of sugar cane in Barbados, where rainfall can vary considerably from month to month. Furthermore, the Barbados climate, like that of India, has a wet and dry season. The relative importance of above-average precipitation depends on whether there has been a preceding moisture deficit.

Comparison of rainfall measurements over a number of years with the average monthly total provides data for each monthly assessment. Three-month rainfall assessments can then be used to predict probable yield. However, the relationship between precipitation and yield is not a linear function.

Leak (1929) obtained an equation for the dependence of yield on rainfall during different periods:

\[
y = 0.026 P + 0.055 D + 540 Q + 4.12
\]

where \( y \) = yield; and
\( P, D \) and \( Q \) are, respectively, rainfall amounts during the rainy season preceding planting; during the dry season at time of planting; and during the rainy season corresponding to maximum growth.

Rouse (1966) gave another approximation based solely on the soil-moisture deficit:

\[
y = 43 - 1.34 x
\]

where \( y \) = yield;
\( x \) = soil-moisture deficit.
Thus, in Barbados, the decisive factor for yield is rainfall. If rainfall is less than average, the harvest is poor; but if it is excessive, the harvest cannot be fully collected.

6.4 Mauritius

The Mauritius Research Institute publishes a large number of documents concerning sugar cane yield, since it is the island’s main crop. Fluctuations in yield have immediate effects on the well-being of the entire population.

Mauritius is in a region of steady winds, the varying directions of which have a fundamental effect on variations in the meteorological factors, e.g., the precipitation on one side of the island is greater than on the other, depending on wind direction.

Halais (1954, 1956, 1968) studied the dependence of productivity on rainfall with a partial correlation method. He concluded that Mauritius is very favourable for growth of sugar cane, because it experiences neither very heavy rain nor excessively low temperatures, and only slight differences between minimum and maximum temperatures.

The island has three regions (north, centre, south) with different climatology, differing particularly with regard to rainfall. Three equations are applicable:

North: \[ y = 11.20 - 0.219 (x_1 - 1.29) + 1.013 (x_2 - 9.23) \]
South: \[ y = 10.43 - 0.107 (x_1 - 3.33) + 0.317 (x_2 - 6.57) \]
Centre: \[ y = 11.18 - 0.074 (x_1 - 3.51) + 0.870 (x_2 - 5.79) \]

where \( y \) is the average quantity of sugar in cane collected on 15 August (in per cent);
\( x_1 \) is the total quantity of excess rain during June and July (mm);
\( x_2 \) is the average difference between minimum and maximum temperatures for June and July.

If the area cultivated in each region is known, then the sugar production may be estimated several months in advance.

6.5 Conclusions

During vegetative growth there are two stages of sugar-cane development:

(a) An initial stage, tillering, during which weather conditions must be as favourable as possible to guarantee the largest number of stalks and the greatest possible yield. Since side stalks are also collected, the succeeding period of initial stalk growth is important;

(b) A second stage, flowering, when sugar starts to accumulate in the stalks. If flowering is prolific, the amount of sugar decreases considerably.

The various authors, in particular Panje et al. (1968), conclude that some meteorological factors, especially insufficient radiation, have a restraining influence on the flowering of sugar cane. Dull weather at the time of flowering is therefore a sign of increased accumulation of sugar, and is also a condition favourable to plant growth.
CHAPTER 7

COFFEE

7.1 Introduction

Coffee is one of the most widely used commodities. Its cultivation is of
great importance to many countries and it is the most important economic factor in
some of them, not only in its native areas (Turkey or North Africa) but also in most
tropical and sub-tropical regions.

Despite the great economic significance of this crop, it is rare to come
across studies based on meteorological data for determining the growth rate of the
plant and the yield that may be expected.

In Ethiopia, prediction is based on the soil water balance; and in Kenya,
on the rainfall during the early part of the flowering period and on the temperature
during flower-bud development. In Angola, workers are studying the effects of tem-
perature and solar radiation on the absorption of CO$_2$ by the leaves and on photo-
synthesis.

7.2 Main research

Bierhuizen et al. (1969) have shown that each degree above 20°C leads to an
increase of 20 p.p.m. in the CO$_2$ concentration and a reduction of about 7% in gross
coffee production, thus enabling forecasts of coffee production to be made.

The small number of studies published contain analyses of the relationship
between yield and meteorological factors; however, they do not give formulae for
making numerical calculations.

Many researchers point to a direct influence of temperature and radiation
on the overall plant growth.

Investigations into the effects of radiation show that coffee, compared
with other plants, reacts to it in several substantially different ways. The shrub
does not grow proportionally to direct or scattered radiation received, but reaches
its maximum height in rather shady conditions. Studies by Murray and Nichols (1966)
particularly stress this phenomenon. By far the largest leaves are usually those
which have received less light; the smallest, those which have received the most.
The latter are also subject to yellowing, indicating that chlorophyll is destroyed
by strong radiation.

A retardation in the growth of the cocoa plant caused by excessive
radiation can be avoided by addition of fertilizers, particularly mineral fertilizers;
but this is not true for coffee. Of course, fertilizers must be properly balanced,
particularly as regards nitrogen and phosphorus. The largest coffee yield results
when radiation is 70-80% of the maximum.

As far as coffee production is concerned, dimensions of the beans affect
the total weight of the yield, but not its quality. Smaller beans are more highly
priced than large ones, so that it is not sufficient to base an evaluation of the
crop’s economic worth simply on the yield. An index reflecting quality of the
harvest must be added and this depends on the size of the husk, which reflects the size of the bean within (Cannell and Huxley, 1970; Cannell, 1971). About 20 weeks after flowering the entire energy of the plant is directed either towards production of oil and other extracts, which determine aroma and flavour, or towards production of alkaloids, e.g. caffeine. Yield can be determined from the rainfall during the period 10-17 weeks before flowering. Cannell, however, did not give quantitative indices for relating these phenomena.
CHAPTER 8

COCOA

8.1 Origin and economic importance

According to Pound, Chessman and Baker (see Burgos and Reyes, 1965), cocoa originated from the forests of the Amazon, and particularly from the eastern slopes of the Cordillera. At present cocoa is cultivated in many countries of the tropical zone, and is important for their economies.

Workers in Ghana have developed a method to predict cocoa yield by means of meteorological data. In Indonesia a method has been devised to predict yield based on plant age but not meteorological factors.

8.2 Influence of light

Cocoa is often cultivated under the tops of higher trees which create shade in the tropical woods. Even during the first centuries of its cultivation, this was thought to be necessary for proper growth. In Africa, large trees in forests are used for shade after they have been thinned to provide room for cocoa plants.

Studies at the beginning of this century pointed out the influence of light on growth rate, which is maximum when 50% of the available light is used. These studies were made with soils which degrade very rapidly because organic matter mineralizes very quickly in the tropics. As a result, the basic soils are poor in nitrates, which contain nitrogen, alkali and assimilable phosphorus.

Murray (1958, 1965, 1966) experimented with cocoa on poor and rich soils. If the nutrient content was sufficient, naturally or through application of fertilizers, the effect of shade on yield was not at all apparent. He found that with proper levels of fertility cocoa can fully utilize all of the light it receives. Alvim (1965, 1966 a, 1966 b) demonstrated that cocoa development depended on light conditions when assuming sufficient moisture.

8.3 Importance of rainfall

In the tropical countries of its origin, cocoa is seldom exposed to the effects of drought, since precipitation is plentiful and frequent. Bean pods are produced continuously and can be harvested throughout the year. Extension of this crop to regions with different climates (the plains of Central America, or the central interior of the African continent) requires consideration of not only light conditions, but also water supply. In regions with very distinct rainy and dry seasons, the harvest has serious fluctuations.

Toxopeus and Wessel (1970) pointed out the importance of moisture in development of cocoa pods and beans. Extreme lack of moisture during general plant development retards flowering and there is a subsequent reduction in bean yield. The weight of collected and cleaned beans is largely dependent on rainfall during the first month of pod development, i.e. immediately after flowering.
Ali (1969) showed that the sum of precipitation amounts for the three months preceding harvest determined the quality of the beans collected. Moisture does not play as important a part when cocoa is grown in the shade rather than in the open.

According to Alvim (1969) cocoa-plant roots should develop in loose soil and the plants should not be overcrowded, since roots with freedom to spread and penetrate have a greater capacity for absorption of available moisture and minerals.

8.4 Numerical methods

In Ghana, formulae have been developed to enable calculations of expected cocoa yield by means of meteorological data. Results indicated that maximum yield occurred four to five months after peak rainfall. An inverse relationship was established between the number of sunspots and yearly yield. Using average monthly data, a good relationship was obtained between yield and various weather factors:

\[ y = 254.55 R - 25.69; \quad r = 0.86 \]
\[ y = 6.6 TD - 85.0; \quad r = 0.83 \]
\[ y = 8.9 H - 718.3; \quad r = 0.72 \]

where \( y \) is the cocoa yield (number of pods per unit area);
\( R \) is 24-hour rainfall (inches);
\( TD \) is the average difference between the daily maximum and minimum temperatures (°F);
\( H \) is the average monthly relative humidity (%).
CHAPTER 9

CROP-WEATHER RELATIONSHIPS AND MODELS

9.1 Mathematical modelling (crop-growth simulation) of plant growth and yield

In previous chapters we examined mostly statistical relationships between yield and agronomical factors for specific commodities. In this chapter, we give details of work done in connexion with mathematical modelling (crop-growth simulation).

With the statistical approach, it is difficult, if not impossible, to explain the reasons why yield has a close correlation with any particular factor. On the other hand, crop-growth simulation modelling attempts to define plant growth and crop yield as functions of physical, chemical and physiological factors and their interdependencies, i.e. causes and effects. The latter make it possible to explain why certain factors are important for yield while others are not. Frequently the path from low-level relationships (physical, physiological, etc.) to high-level relationships is so complicated that modelling is essential.

Modelling does not replace the statistical approach - each complements the other - but it may identify factors which have statistical importance.

The modelling technique may also include experiments on problems which are important, but have not been studied sufficiently. Modelling, in effect, is a means of studying and verifying any hypothesis. If the hypothesis is true and no important factor has been left out, the final result should be close to reality. In this case, modelling would have a greater value for prediction than statistical formulae. For example, it is possible to calculate the frequency of eclipses statistically, but astronomical physics provide reasons for their occurrence and means for predicting them accurately.

However, if the hypotheses provide an incomplete or distorted view of processes which actually occur, the statistical approach is more reliable for predicting certain factors. This is more or less the situation in agriculture, and it must be borne in mind when assessing modelling methods. As better knowledge is acquired of the main processes, reliability of prediction technique will also increase. Nevertheless, any modelling system presupposes certain simplifications of the true picture of the process under study.

9.2 Studies in the Netherlands

In this section, models for processes of growth and yield are described. At first, a variant is examined for plants growing in a properly watered and fertilized plot, but without including effects of disease, soil fertility, economics or poor farm management, i.e. factors which are needed to obtain a practical model of yield.

A situation with restricted water supply will be considered because the evaporation process requires considerable attention. The main processes taking place in plants and their environment are very closely interrelated and are examined below.
9.2.1 **Main processes occurring in plants**

The main processes occurring in plants are: production of dry matter; distribution of dry matter; and water balance.

9.2.1.1 **Production of dry matter**

Accumulation of dry matter in the plant is computed by preparing models of the processes of photosynthesis and energy exchange, as well as of the nutritional environment necessary for plant growth and the continuation of these processes. The total photosynthesis is estimated by calculating the amount of photosynthesis and the specific surface area for the leaves in each layer of foliage. The amount in each layer depends on light intensity, CO₂ concentration and resistance diffusion of CO₂ from the atmosphere.

Coefficients for attenuation and reflection of radiation are calculated from the distribution of leaf angle, the leaf scattering coefficients and the direction of incident light. Intensity in each layer is calculated from radiation measurements. Reflected radiation is also considered. An exponential loss of intensity with depth is assumed; at the same time, corrections are applied for differences between direct and diffuse light radiation, and between leaves in sunlight and in shade. CO₂ concentration is assumed to be constant throughout the depth of foliage. Resistance to CO₂ diffusion depends on steady turbulent conditions above the foliage, as affected by wind speed, stability of the atmosphere, stability of the laminar layer around the leaves, stomatal resistance and internal resistance. The stomatal resistance is a function of absorbed radiation and the water condition of the crop. The internal resistance is a function of leaf age and temperature.

Respiration is the sum of the respiration required for normal existence and that required for growth. Normal respiration is proportional to the amount of protein and increases as mean temperature of the crop increases. Respiration for growth is the result of keeping reserves for the plant's structural matter. It is therefore proportional to the growth rate and chemical composition of the plant material.

9.2.1.2 **Distribution of dry matter**

Dry matter reserves can be determined from the contribution of photosynthesis on the one hand and the absorption of reserves from growth and respiration on the other. Growth rates of sprouts and roots depend on the temperature of organs, so that there is an indirect influence of temperature on growth respiration. These growth rates are also proportional to the amount of reserves. If there is a shortage of water, the growth of shoots is retarded; therefore, more reserves accumulate and root growth increases. By this mechanism, the plant adapts itself in relation between the weights of shoots and roots.

The root system may be classified into young and old roots. The penetrability of old roots is 30% that of the young. The rate at which the young change into old depends on soil temperature; however, numerous difficulties have been encountered in establishing a model of morphogenesis. The rate at which small grains develop depends, generally, on the temperature and length of day. Consequently, it is not too complicated to establish a model for the vegetative and generative stages. Increase in leaf area compared with growth of dry matter is difficult to represent during the vegetative stage. During the generative stage the leaves do not grow, but their ageing is difficult to track down.
9.2.1.3 Water balance

The water balance of a plant is determined from the difference between transpiration and water absorbed from the soil. Transpiration of a crop is the sum of transpiration amounts for individual leaves. This follows from the equation of leaf energy balance, which includes absorbed radiation energy and loss of sensible and latent heat in transpiration.

The ratio of the last two factors is also regulated by stomatal resistance, resistance of the laminar layer around the leaves, and temperature and humidity of the surrounding air. An estimate is also made of leaf temperature, since it has an influence on internal or mesophyll resistance and consequently on photosynthesis. The leaf temperature of each layer is averaged and the average plant temperature is determined to evaluate the growth rate and intensity of respiration. For certain processes it is preferable to use the temperature of the growth point rather than the average plant temperature.

Stomata are the means by which the plant regulates transpiration. Stomatal resistance is influenced by absorbed radiation, the water deficit and carbon dioxide inside the stomatal cavity. However, the regulating mechanism of stomata is still a matter of discussion. When transpiration exceeds water transfer from the soil, the water deficit increases, the plant wilts, and the stomata close. In this way, the intensity of transpiration adapts to the amount of water absorbed from the soil. Meanwhile, the roots will grow more rapidly, so that absorption of soil moisture tends to adapt to the loss by evaporation. As water supply to the plant decreases, absorption of soil moisture will increase. Absorption of soil moisture is a function of the number of roots, their conductivity and the difference between the water potential of the soil and that of the plant. Conductivity depends on soil temperature, age of the roots and their morphology. The effect of a water deficit on intensity of photosynthesis is shown by an increase in stomatal resistance which may eventually render carbon dioxide diffusion difficult.

If this phenomenon is correctly formulated and modelled, the main relations reflect the reaction of the plant to the surrounding conditions. There is no need to differentiate between climatic regions, since the model itself will indicate which factors limit growth under various conditions. In a wet climate with low temperature and radiation, the model will show a close correlation between radiation and yield (Sibma, 1970). In a hot, arid climate, the model will show a close correlation between yield and total rainfall. Thus the basic model is independent of the climatic region and type of plant. Variables introduced into the model to reflect main reactions of the plant with its climatic conditions will be different in each case.

9.2.2 Measurements

As was stated in the previous chapter, tissue temperature has an influence on practically all of the processes which occur in the plant. Other important factors are radiation from the plant's organs, air temperature and humidity, and wind speed. Soil condition is also very important. All of these must be known in the environment where the plant grows and may therefore differ from the standard meteorological conditions. For example, grass modifies conditions because of mutual shading and by slowing down wind speed, hence transpiration and heat loss are reduced.

Microclimatological conditions may be modelled from standard meteorological conditions, which require the following observational data:
Global solar radiation or radiation balance (daily, hourly, instantaneous). It is desirable that global solar radiation and radiation balance should be measured with good-quality standard radiometers, over a standard surface;

- Daily minimum and maximum air temperatures;

- Daily air humidity, measured with an Assmann psychrometer;

- Wind speed, measured at a height of one or two metres above the foliage. A normal cup-type anemometer is very convenient for this purpose. Because there is a very great difference between wind speed at night and during the day, it is preferable to break the data down into two 12-hour periods to show average values. The height at which measurements are made above the plant foliage, as well as the height of the foliage, should also be indicated.

Attempts to obtain values of parameters above the plant foliage by means of measurements from meteorological stations located at a distance from the plot are rather risky but sometimes inevitable. In flat regions this would be more reliable than in mountain areas, where such practices should not be used.

9.2.3 Radiation

To calculate transpiration and temperature of the leaves, it is necessary to know total absorbed radiation; to calculate photosynthesis, the absorbed visible radiation should be known. The coefficients for extinction and reflection, which depend on the angle of incidence and the wavelength region, may be calculated using Goudriaan's method (1973). Optical characteristics are fairly uniform within the three wavelength regions - namely, the visible, the near-infra-red and the infra-red. With this information the radiation absorbed at various levels of plant foliage can be calculated for the three wavelength regions. Distribution of intensity of direct radiation, which is influenced by the position of the leaves, may be estimated by De Wit's method (1965).

9.2.4 Wind and turbulence

Wind speed affects the thickness of the laminar layer around the leaves. The layer resistance is defined as the leaf thickness divided by the product of the thermal conductivity and the values of water vapour and carbon dioxide. Photosynthesis and transpiration depend little on this resistance. Another barrier lies between the air at leaf level and the atmosphere above. Goudriaan and Waggoner (1972) gave a physically acceptable interpretation of this kind of resistance. To obtain a model of the yield, it is of course important to simplify the approach, so that only one resistance is examined in the space between the plant's foliage and the measurement height. The value of this resistance can be calculated by means of the Thornthwaite-Holtzmann formula, corrected by the Richardson number.

9.2.5 Transpiration

Once stomatal resistance, stability of the boundary layer, resistance to air turbulence, air temperature and humidity have been determined, the transpiration and temperature of leaves at various foliage levels can then be calculated by this formula:

\[ EHL = \frac{SA + VPD \cdot \frac{\rho C}{R}}{V \cdot \frac{(R + R_s)}{R_a + \lambda}} \]
where EML is the loss of latent heat per unit area of the leaves, S is absorbed radiant energy, \( \lambda \) is the slope of the saturated vapour pressure/air temperature curves, \( \rho \) is the volumetric heat capacity of air (Jm\(^{-3}\)K\(^{-1}\)), VPD is the vapour pressure deficit in hPa, \( R_a \) is the resistance of the boundary layer and the turbulence of the air, \( R_s \) is stomatal resistance and \( V \) is the psychrometer constant. This Penman-type formula was obtained by analysing the heat transfer and the vapour and radiation balance, assuming that the leaf is in a thermally stable state.

The different transpiration intensities calculated in this way are summed to obtain the plant's total transpiration. Together with the radiation balance, this enables an estimate of the leaf temperature to be made for use in calculating the photosynthesis, respiration and growth rates.

9.2.6 Root system and soil

The plant's water absorption is calculated from the difference between the water potential of plant and soil, multiplied by conductivity of the root system. It is assumed that the water potential of the soil is very low, 100 hPa, equivalent to the field moisture capacity. Even in this case, a plant water deficit may occur during periods of high radiation because conductivity of the root system is limited. This conductivity is proportional to the weight of the roots, and allowance should be made for old roots that are not easily penetrated by water. Conductivity also depends on soil temperature which, at a depth of about 15 cm, is assumed to lag about four hours behind air temperature. Soil temperature may also be calculated by the method of De Wit and van Keulen (1972).

9.2.7 Preparing a model of yield for arid conditions

De Wit (1958) showed by experiment that yield is proportional to transpiration under steady conditions, when water is the limiting factor. The relationship between the weight of evaporated water and the production of dry matter is termed the transpiration coefficient, the value of which depends on crop condition and environment, and which may also be determined theoretically by means of the model discussed above.

Van Keulen (1974) worked out a method to use this model, with data on weather conditions and state of the crop, in order to obtain average values of the transpiration coefficient for ten-day periods. If it is assumed that the coefficient does not vary when there is a water shortage, the production of dry matter is equal to actual transpiration of the crop divided by the transpiration coefficient. Actual transpiration is the potential transpiration multiplied by the corresponding coefficient, which depends on the soil water deficit and on root structure. Potential transpiration of a crop is part of the potential evapotranspiration as calculated by the Penman formula. It is equal to part of the total radiation energy absorbed by the foliage, and is determined in the same manner as the transpiration coefficient. An additional amount consists of energy absorbed by the soil surface, while the remainder of the potential total evaporation is assumed to be the potential evaporation of the soil. This water is used for production of the dry matter. The real evaporation from the soil will then be the reduced value of potential evaporation (as calculated earlier), depending on the magnitude of the soil water deficiency.

9.2.8 Estimation and prediction

Modelling may be designed for various time-scales, and parts of a model may provide separate estimates. It is possible to evaluate how the model estimates final crop value (for the end of the season) during the growth period, and how it imitates the 24-hour patterns of photosynthesis and transpiration processes. Hence it is
possible to evaluate the correctness of assumptions formulated and incorporated into the model, both for photosynthesis and for accumulation of dry matter.

Various methods have been described in greater detail by Goudriaan (1973), Van Keulen and Louverse (1974). The 24-hour pattern of photosynthesis and transpiration is measured by means of the "covered" method, by enclosing plants in the field in a special transparent chamber. By providing circulation in this chamber, the intensity of photosynthesis and transpiration can be determined by measuring the CO₂ and water-vapour contents in the air entering and leaving.

9.3 Studies in the Soviet Union

In the last 15 years workers in the Soviet Union have achieved considerable success in studying processes of energy and mass exchange in the plant environment, and in establishing from this a theory for the production process of agrophytocenosis.

The following are directly associated with the development of agrometeorology:

(a) Mathematical modelling of processes of heat-mass exchange in crop plantations;
(b) Mathematical modelling of agrometeorological aspects of the production process;
(c) The work done in connexion with creating an overall dynamic model for "weather/crop yield".

The most significant results obtained in the U.S.S.R. in connexion with mathematical modelling of the heat-mass processes in crop plantations are given below.

A mathematical model has been devised for the radiation régime of plant foliage, based on an equation for the transfer of radiant energy in the foliage assumed to be horizontally homogeneous, anisotropic, turbid medium. Approximate solutions have been found for this equation, so that upward and downward fluxes of photosynthetically active, total and near-infra-red radiation can be calculated (Ross and Nilson, 1966).

Simplified and semi-empirical formulae have also been derived for calculating vertical radiation fluxes (Tooming, 1974; Ross, 1975).

For the first time the correct form for writing the closed system of equations has been found, enabling calculations of the characteristics of air motion in growing plants. The equation of motion includes terms which describe resistances of the leaves and stalks, which are proportional to the square of local wind speed. The equation for the balance of turbulent energy contains a term which corresponds to effects arising from fluctuations when the mean flux interacts with the plant elements (Menzhulin, 1974).

A stationary model has been worked out for the meteorological régime in foliage (Budyko, 1972; Menzhulin, 1974) and the basis of this model consists of equations for turbulent heat conductivity and turbulent diffusion of water vapour. Source terms in these equations describe heat and moisture exchanges between elements of the phyto-mass and ambient air. To close this system, an equation is introduced for the thermal balance of these elements. Boundary conditions are at levels Z = H and Z = 0, in the vertical direction where H is the canopy height.
Analytical solutions of the system have been obtained for a number of important individual cases, and the system has been investigated by means of numerical experiments.

Recently, a non-stationary variation of the problem of calculating the meteorological régime in crops has been formulated and studied (Sirotenko and Boiko, 1977). That model is not confined to calculating the heat- and moisture-exchange processes in the air layer near the ground, but also includes the volume of soil occupied by the roots. It enables indices of the water/heat régime (required for practical purposes) to be calculated for applications to periods of up to ten days.

With regard to mathematical modelling of agrometeorological aspects in the production process, the most important results are discussed below.

From studies with mathematical models of the radiation régime of foliage, a statistical model has been evolved for photosynthesis and productivity of foliage. Attention has been mainly devoted to estimating the effect of geometric structure of the foliage on photosynthesis and the effect of leaf orientation on total photosynthesis (Ross, 1975). A general ecological principle has been formulated to the effect that during the period of vegetative growth, adaptation of the plant community in the external environment is directed at achieving maximum productivity (Tooming, 1974).

A general theory has been proposed for total photosynthesis in the foliage, considering radiation factors and variations in the concentration of carbon dioxide at various levels. A non-linear differential equation has been obtained which links the CO₂ concentration in the foliage with a number of parameters which affect it (Budyko and Gandin, 1972).

The creation of a dynamic model for the production process of agrophytocenosis is a large and complex problem, the solution of which calls for the synthesis of all existing knowledge in phytocenosis biophysics. Work on creating such a model is only just beginning. The successes so far achieved and the difficulties have been examined by Ross (1975).

Achievements in developing a theory already enable a simplified semi-empirical variant of the model to be constructed for the production process for use in agrometeorology - the complex dynamic "weather/yield" model. A major difference is that this is the first time that it has been possible to evolve a closed system of differential equations which, when integrated, provide a means of calculating the mathematical expressions for the dynamics of leaf biomass, stalks, roots and reproductive organs of the plant community (Sirotenko and Boiko, 1977).

The model has a number of basic equations, broken down into two closely interrelated subsystems, and a large number of additional relations. The first subsystem (the meteorological block) consists of equations for turbulent thermal conductivity and for turbulent diffusion of water vapour in the interfolial space of plant foliage and an equation for thermal balance of leaves and stalks. The heat- and moisture-transport processes in the volume of soil occupied by roots are described by quasi-linear equations for thermal conductivity and moisture transport. Absorption of moisture by roots is described by a special term in the moisture-transport equation. Integration of the above system of equations enables calculations to be made for the hydrometeorological elements inside the plant foliage and in the volume of soil occupied by roots. To do this, values of the standard meteorological parameters above the plantation and the physical properties of the soil are used.

Structure of the plantation is assumed to be given (leaf and root areas, and their
locations in space). During growth and development of the plantation structure the weather conditions change, so that calculations in the meteorological block are repeated at equal intervals of time. Data obtained from the meteorological block are then introduced into the second (biological) block, which consists of six equations, the main one being the equation for balance of the phyto-mass in the plantation:

$$\frac{dM}{dt} = \frac{1}{c} \int_{0}^{H} \Phi(z, t) \, dz - \left( R_o \, \phi \, M + R_R \, \frac{dM}{dt} \right)$$  \hspace{1cm} (1)

where $M$ is total dry biomass per unit area; $t$ is time; $\xi$ is a gas exchange coefficient; $H$ is the height of the plantation; $\Phi(z, t)$ is a function of leaf photosynthesis, which reflects the dependence of photosynthesis on the following external factors: intensity of absorbed PAR, $\text{CO}_2$ concentration, leaf temperature and soil moisture potential in the volume occupied by the roots. The term in brackets describes the process of respiration, consisting of respiration for preservation of life (proportional to $M$) and for growth (proportional to $dM/dt$). $R_o$ and $R_R$ are coefficients; $\phi$ is a temperature coefficient.

The second equation is for $\text{CO}_2$ balance:

$$\int_{0}^{H} \Phi(z, t) \, dz - \xi \left( \phi_1 \, R_0 \, M_1 + R_R \, \frac{dM_1}{dt} \right) = F_o - F_H$$  \hspace{1cm} (2)

where $M_1$ is the total dry above-ground biomass of the plantation; $\phi_1$ is the temperature coefficient for this biomass; $F_H$ and $F_o$ are the $\text{CO}_2$ fluxes through the upper and lower boundaries of the plantation, respectively.

The remaining four equations are all of the same type:

$$\frac{dm_p}{dt} = a_p(t) \frac{dM}{dt}$$  \hspace{1cm} (3)

where $m_p$ represents $m_r$, $m_s$ and $m_r$, the biomass of the leaves, stalks, and reproductive organs, respectively, and $a_p(t)$ are the corresponding growth functions of a specific crop, assumed to be known.

Integration of systems (1) to (3) with pre-set initial conditions enables the $m_p(t)$ functions to be obtained for the dynamics of biomass of individual organs of the plantation. Value of $m_s(t)$, for $t$ corresponding to time of waxy ripeness, represents the value of biological yield, the final result of the calculations.

After overcoming difficulties caused by lack of experimental data for determining parameters, the dynamic "weather/yield" models will serve as a basis for devising operational schemes suitable for agrometeorological calculations on a large scale.

9.4 Conclusions

Crop yields depend on agrometeorological factors, a complicated multi-factor non-linear relationship, and on state of the crop linked to technology. Extension of weather and crop relationships from one climatic region to another is limited due to a lack of absolute knowledge about these relationships - in particular, knowledge of interrelationships of climate, varieties, soils and field management.
Nevertheless, statistical relationships between crop yields and the main agrometeorological factors are of significant value and are used for developing crop-yield forecasting methods in many countries.

Undoubtedly, these relationships are of scientific importance too, since they help to define what may be expected in crop growth, development and yield under usual conditions in given producing areas as well as defining limiting factors.
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