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SIMULATION OF PRIMARY PRODUCTION

by

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PREFACE

During the last decades the application of simulation and systems analysis in agricultural research has increased considerably. The Department of Theoretical Production Ecology (TPE) and the Centre of Agrobiological Research (CABO) in Wageningen, the Netherlands, have contributed to this development and much of the insight, knowledge and methodology have been published in the series Simulation Monographs. One of these monographs describes a course taught by teachers of CABO and TPE in 1984: 'Modelling of agricultural production: weather, soils and crops'. Participants of the course were research workers in various developing countries. The course was sponsored and organized in close cooperation with the World Meteorological Organization (WMO) in Geneva, Switzerland.

As a result of this course, interest in simulation and systems analysis in agricultural research has increased in many developing countries. WMO asked CABO/TPE to give short courses on simulation of primary production in various countries. CABO/TPE is interested to teach such courses. The contents of the course is tailored to the level of beginners in this field and comprises various readers from books of the Simulation Monographs series. It is organized in such a way that after the course, participants have become acquainted with the approach and are able to use and develop elementary models on primary production under various circumstances. We hope that the participants will have a fruitful course and thank WMO for the initiative and willingness to sponsor.

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INSTRUCTIONS TO THE READER

The textbook of the roving seminar on 'Simulation of Primary Production of Crops and Natural Pastures and the resulting Carrying Capacity, using crop-, soil- and agrometeorological data', organized by WMO consists of 7 chapters. The first chapter is an introduction to crop modelling. Chapter 2 describes the most important plant physiological processes and two simple simulation models of potential crop production. Chapter 3 and 4 describe crop production as determined by respectively water availability and nutrient (N,P,K) availability. Chapter 5 lists the weather data which are needed in a simulation model of primary production. Chapter 5 explains a simulation model of potential crop production (L1.csm) and actual crop production as determined by water availability (L2.csm). A list of crop- and soil data to run these models is added. In appendices 1 and 2, numerical examples of equations used in the manual as well as answers to exercises are given.

To arrange the manual of the seminar, the following literature has been used (see also References):

(Chapter 2.3 of the manual).

(Chapter 1, 5 and 6 of the manual).

(Chapter 2.1, 2.2, 2.4 and 4 of the manual).

(Chapter 3 of the manual).

H.J.W. van Roermund
1 An introduction to crop growth modeling

1.1 Crop growth modeling

Growing a crop is complex. Some activities such as planting or seeding, are always needed, others such as irrigation, fertilization and spraying fungicides are optional. A farmer combines activities effectively because he has a concept or model of how the crop will react to its environment and to husbandry practices. In this sense farmers use multidisciplinary models. However, these mental models are somewhat crude and are difficult to improve or to communicate to others.

1.1.1 Descriptive and explanatory models

In developing an explicit crop growth model, a descriptive or an explanatory route may be followed.

Descriptive models.

Descriptive models reproduce the behaviour of a system at the same level as that of the real phenomenon (Figure 1). The regression equation derived from successively measured weights of a crop is an example of a descriptive model (Figure 2). This equation is helpful in quickly determining the weight of the crop at times where no observation was made. However, the growth rate of the crop follows another course when soil, crop husbandry practices or weather conditions are different. Large deviations can result from different weather patterns among years (Figure 3). Adapting the starting point of the regression equation and of the maximum value are possible in hindsight, but predicting these parameters for other fields and in other years is usually too inexact for specific production studies. In theory it is possible to perform many experiments and to derive the constants and equations required with
acceptable accuracy. However, in practice, a large number of variables influence growth patterns. Some, such as soil texture are more or less fixed; others, such as the properties of new cultivars and crop husbandry practices, constantly evolve. Thus, it is impossible to quantify all variables adequately through extensive field experimentation. Descriptive models are therefore of value only for situations where interpolation between observations is sought and there is no attempt to quantify the background of the shape of the biomass curve.

Explanatory models.

The second route to developing models is explanatory. In these models, the growth rates of distinct processes such as photosynthesis, leaf area expansion, and tiller induction are simulated. Crop growth is a consequence of these underlying processes (Figure 4). Each process must be quantified in relation to environmental factors, such as radiation and temperature, and to the crop status including leaf area, development stage, and nitrogen content. Growth rates can then be computed for any moment of the growing season, depending on the actual crop status, the soil, and current weather conditions. All important factors can be accounted for in this way, provided there is sufficient theory and data to quantify them. Models considered in this book are, as much as possible, of the explanatory type.

The behaviour of the model, i.e. the growth rate, for any moment can be explained from the basic physiological, physical, and chemical processes and from the effects of environmental factors on them. De Wit (1970) noted out that the hierarchical levels of explanatory processes and of explained behaviour are characterized
by time coefficients of different orders of magnitude, and that they are usually the subject of study in different scientific disciplines. The explanatory approach to modeling goes deeper at least one hierarchical level, and sometimes two or more, than the descriptive approach.

1.1.2 Simulation with explanatory models

Simulation models are relatively simple representations of systems in the world around us. 'Systems' may be defined as well delineated parts of reality. A system is identified by the user on the basis of objectives and on the intrinsic structure of reality. For an agronomist, such a system may be a crop of rice. Its elements, namely plant organs (such as leaf, stem and root) and processes (such as growth and transpiration), interact strongly. Weather is regarded as a driving variable because it exerts an important driving or regulating effect on the crop. The crop, on the other hand, has virtually no impact on the weather. In general driving variables influence the system and its behaviour, but the reverse is not true: the system does not influence its environment. 'Behaviour' is the course of all processes in a system together. An example is the growth of a rice crop during a season. A system is 'dynamic' when its states change over time, be it 'continuous' as when its behaviour and states change relatively slowly, or 'discrete' when changes occur fast and may be large (e.g. a tractor going from the state 'used' to 'not-used').

A model is 'dynamic' when it simulates the behaviour of a system. State variables in models represent quantities, which may be tangible, such as weight, or abstract, such as development stage.
Rate variables represent rates of change of state variables, such as the photosynthesis rate. 'Simulation' in this context is the study of a system and the computation of its behaviour within a dynamic model.

In explanatory simulation models of dynamic systems, such as those of crops, it is assumed that the rate of change can be approximated very well by considering the rates of processes to be constant during short time periods. This is the 'state variable approach'. In crop simulation time periods must be short compared to the duration of the growing season: often one day periods are chosen. The biomass formed in such a short time interval equals the multiple of growth rate and time period duration, and is added to the quantity of biomass already present. Computation of the rate is then repeated. The new rate is slightly different because environmental conditions or the internal status will have changed a little. Calculations of rate variables and updating of state variables are repeated until the entire growing season has been covered.

Fortunately, the number of processes of prime importance in simulating crop growth is limited, as is the amount of detail to quantify each. For example, computing the efficiency of synthesis of each biochemical compound in biomass is usually unnecessary; averages for classes of compounds are sufficient. It is unnecessary, and even counter productive, to include dynamic aspects of cell physiology in crop growth models. Explanatory models can be of practical use in spite of the fact that knowledge of the processes often does not reach the cellular level. It is indeed of limited importance whether processes at the explanatory
level are descriptive or explained at the deeper level, as long as their quantification is valid within the range of conditions for which the model is used. The more detail desired in the outcome of a model, the more detail the model itself must contain, and hence the more explanatory processes should be included.

1.1.3 Development of explanatory models

Large and complex explanatory models have been developed over the last decade in many places, including Wageningen in the Netherlands. Development has been relatively slow, because among other things, some essential topics were insufficiently understood. These large comprehensive models contain a wealth of information, but are rather unwieldy. Their use is limited to reassessing hypotheses, for sensitivity analyses and for reference and comparison with other models. These models are seldom used except by the group of persons that created them. This not only limits their usefulness, but also undermines the credibility of models and model builders.

In recent years, summary models have been derived from several comprehensive models. These models retain much of the scientific basis and quality of the comprehensive models, but are simpler and much easier to use.

Three phases in the development of explanatory models can be distinguished: the preliminary, the comprehensive and the summary phase. The model develops gradually from one phase into the next. Preliminary models can be defined as models with a structure that is simple because insights at the explanatory level are still vague. A comprehensive model represents a system in which essential
elements are thoroughly understood and it incorporates much of this knowledge. Summary models are abstracts of comprehensive models.

Summary and comprehensive models are currently found at the levels of crop production where weather or soil water limits growth. Models for lower production levels are predominantly in the preliminary and comprehensive phases. Models at different development stages vary considerably in their value for scientific research, education, and applications.

Much of the content of models considered in Chapters 2-6 is in the summary phase, though parts are still scarcely beyond the preliminary phase.

For more extensive introductory reading, see Brockington (1979), Dent and Blackie (1979), Loomis et al. (1979), Penning de Vries and Van Laar (1982), Penning de Vries, (1983), Van Keulen and Wolf (1986), or Rabbinge et al. (1988).
1.2 Models at different levels of crop production

1.2.1 Levels of crop production

Uses that can be made of different models are strongly related to the subject and the objective. De Wit proposed a classification of systems of crop production based on growth limiting factors (Penning de Vries and Van Laar, 1982). Four levels of plant production were distinguished. The systems of crop production at any of these levels can be seen as members of a broad class of systems. In order of decreasing yields, these levels are:

Production level 1

The crop has ample water and nutrients, so that its growth rate depends only on the current state of the crop and on current weather conditions, particularly radiation and temperature. With a full canopy, the growth rate of field crops is typically between 150 and 350 kg ha\(^{-1}\) d\(^{-1}\) of dry matter. This is called the 'potential growth rate' and the crop yield the 'potential yield'. Such growth conditions are realized on very intensive arable and grassland farms in Western Europe, and often in glasshouses.

Production level 2

The growth rate is limited only by water, for at least part of the growing season. This situation does not often occur spontaneously, but in semi-arid regions fertilization can result in crop growth at this production level. This may also occur in other climates under intensive cropping on light soils.

Production level 3
The growth rate of the crop is restricted by nitrogen shortage for at least part of the growing season, and by water shortage or bad weather for the remainder. This situation occurs frequently in agricultural systems all over the world. A nitrogen shortage occurs particularly when fertilizer is not intensively applied but is also common in the natural environment which cannot be avoided by even nitrogen-efficient plants.

Production level 4

Crop growth is restricted by low phosphorus and other minerals in the soil, for at least part of the growing season. The growth rates are 10 to 50 kg ha⁻¹ d⁻¹, and the growing season often lasts less than 100 days. This situation usually occurs in heavily exploited areas where no fertilizers are used.

Rarely do cases fit exactly into one of these production levels, but it is practical to reduce specific cases to one of these four categories. This focuses attention on the dynamics of the principal environmental factor and on the crop's response to it. Environmental factors that have no regulatory effect can then be neglected, because they do not determine the growth rate. The growth rate sets then the rate of absorption or efficiency of use of non-limiting factors. If, for example, plant growth is limited by nitrogen, there is little use in studying CO₂ assimilation or transpiration to understand the current growth rate. All emphasis should be placed on nitrogen availability, the nitrogen balance, and the plants response to nitrogen.

This analysis of plant production systems allows for considerable narrowing of the subject of study and permits more rapid research progress. Growth-reducing factors, such as diseases, insect pests,
and weeds, can occur at each of these production levels and give them, in a sense, an extra dimension. The fact that actual situations are often more complex does not contradict the general usefulness of this scheme of production levels as a basis for distinction between causes and consequences of plant growth.

Note that this use of 'production levels' has a crop physiological basis and is not related to descriptions of production systems based on crop ecology, such as the irrigated, rainfed lowland, deep water, and upland production systems in rice growing (IRRI, 1984).
Figure 1.1.1. A scheme to indicate how real world observations are brought into a descriptive model to compute the behaviour at the same level.

Figure 1.1.2. The course of the dry weight of a maize crop in The Netherlands in 1972. The crosses represent observations, the line the values of the regression equation \( BM = 12.0 \div (1.042 \cdot 0.04(-0.08 \cdot T)) \), where \( BM \) is the biomass in t ha\(^{-1}\), 12.0 is the maximum value of \( BM \), \( T \) is the time in days since emergence, and 1.0, 23.0 and 0.08 are constants.
Figure 1.1.3 The course of the dry weight of maize crops in The Netherlands in optimal conditions but in different years (from: Sibma, 1986)

Figure 1.1.4 A scheme to indicate how real world observations are analysed and brought into an explanatory model to simulate behaviour of the system.
2 POTENTIAL CROP PRODUCTION

2.1 Physiological principles

H.D.J. van Heemst

In agriculture, solar energy is conserved for future use via its fixation in biomass by the process of photosynthesis. In this process CO$_2$ from the air is converted into carbohydrates (CH$_2$O$_x$), according to the overall reaction:

$$\text{CO}_2 + \text{H}_2\text{O} + \text{sol}ar \text{ energy} \rightarrow \text{CH}_2\text{O}_x + \text{O}_2 \quad (1)$$

This process is also called CO$_2$ assimilation. Part of the carbohydrates produced is used as building material for structural plant dry matter, as cellulose, proteins, lignin and fats and part is used as a source of energy for plant processes. The release of energy from carbohydrates produced during the assimilation process is described by the equation:

$$\text{CH}_2\text{O}_x + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{chemical} \text{ energy} \quad (2)$$

This process is called respiration. About 40% of the weight of the carbohydrates formed during the assimilation process is lost by respiration. Subtraction of the rate of respiration from the assimilation rate gives the rate of increase in plant dry weight, i.e. the growth rate. In Figure 4, the time course of growth rate and total dry matter accumulation is in a schematic way presented for a summer wheat crop. The growth rates are obtained from the dry matter accumulation curve by determining at each point the slope of the curve.

With respect to the growth rate three phases may be distinguished: (i) during the first phase, the crop consists of individual plants that do not shade each other and the growth rate increases; (ii) in the second phase the crop covers the soil completely and the growth rate is constant; (iii) in the third phase the crop is maturing and the growth rate is decreasing.

In the first phase the major part of the assimilates is invested in leaf growth. This increase in leaf area is accompanied by a proportional increase in energy interception, because neighbouring plants are so small that mutual shading hardly plays a role. Individual plant weight increases by a constant proportion per day, thus leading to exponential growth. After a closed crop surface has been formed, more leaf growth does not lead to more light interception, hence the growth rate remains constant and total plant weight increases linearly. In the last phase leaf senescence leads to a decrease in the growth rate.

The major part of the total dry matter accumulation is achieved during the second phase. Total dry matter production of the crop is thus largely determined by the magnitude of the growth rate during the linear phase and the duration of that phase.
The duration of the period of linear growth is species and cultivar specific and, moreover, is influenced by environmental conditions (Section 2.2). The actual growth rate is predominantly influenced by environmental conditions, such as solar radiation and temperature, the supply of nutrients and water, and the occurrence of weeds, pests and diseases.

With an optimal supply of water and nutrients and in the absence of weeds, pests and diseases, the growth rate is determined by solar radiation and temperature and is referred to as the potential growth rate. Such conditions are supposed to prevail when discussing the basic processes of plant growth. A simple model for the calculation of potential dry matter production will be presented that may be applied to various crops at different locations.

2.1.1 CO₂ assimilation of a single leaf

In the leaves of a plant the photosynthetically active radiation is absorbed by green chlorophyll and other pigments and is used for the reduction of CO₂. Not all radiation of the sun is photosynthetically active, but only the visible radiation in the wavelength range from 400 to 700 nm, which represents about 50% of the total global radiation (Figure 5).

The rate of CO₂ assimilation of a leaf can be measured by enclosing a leaf in a so-called leaf - chamber and analysing the CO₂ concentration of the incoming and the outgoing air, that passes the leaf at a known flow rate. When the assimilation rate is determined at various radiation intensities, a light response curve can be constructed as illustrated in Figure 6 for leaves of plant species referred to as C₃ and C₄ types. The main parameters characterizing these
Figure 5. Spectral distribution of total solar radiation (upper curve) and direct solar radiation (lower curve). Solar elevation is 30° and precipitable water in the atmosphere is 21 mm. (Source: Monteith, 1973)

Figure 6. Characteristic net CO₂ assimilation functions for individual leaves of C₁ and C₄ plant species.
curves are the initial light use efficiency, $E$, the respiration rate in the dark, $R_d$, and the maximum rate of net CO$_2$ assimilation at high light intensity, $F_m$. The latter ranges from 30–90 kg ha$^{-1}$ (leaf) h$^{-1}$ for $C_4$ type plants and from 15–50 kg ha$^{-1}$ (leaf) h$^{-1}$ for $C_3$ type plants, depending on environmental conditions. The gross rate of CO$_2$ assimilation, $F_m$, is the sum of the net rate and the concurrent dark respiration. The dark respiration is at normal temperatures roughly one-ninth of the maximum net assimilation rate.

The maximum net assimilation rate and the dark respiration rate are much more affected by temperature than the initial light use efficiency. The effect of temperature on the maximum assimilation rate is illustrated in Figure 7 for a $C_3$ and a $C_4$ type plant. However, these temperature responses were obtained with plants grown under controlled conditions at a temperature close to the optimum found in Figure 7. Under field conditions where plants are subjected to fluctuating temperature conditions, there appears to be adaptation of the photosynthetic apparatus. It was found that for such plants the maximum leaf assimilation rate was practically independent of temperature above about 13 $^\circ$C for $C_4$ species and above 8 $^\circ$C for $C_3$ species.

The difference in initial light use efficiency between the $C_3$ and $C_4$ types of photosynthesis is small, but the assimilation rate at light saturation is for the $C_4$ type plants generally higher. The names $C_3$ and $C_4$ refer to the length of the C skeleton of the first stable product in the photosynthetic process. Several characteristics of these two plant types are different (Gifford, 1974), such as: (i) the main carboxylating enzyme in the $C_4$ photosynthetic pathway has an affinity to CO$_2$ that is about twice as high as that in the $C_3$ photosynthetic pathway; (ii) in the $C_3$ type plants a respiratory process takes place in the light

![Figure 7. The relation between temperature and the maximum rate of CO$_2$ assimilation for a $C_3$ (a) and a $C_4$ (b) crop species.](image-url)
Figure 7A. The maximum rate of leaf photosynthesis as a function of leaf temperature for a potato (C$_3$) and for a sorgho (C$_4$) crop.

Figure 7B. The photosynthesis light response curve of sunflower leaves at 3 ambient CO$_2$ concentrations (from: Goudriaan and Van Lear, 1978b).
which results in a dependence of assimilation rate on the oxygen concentration in the ambient air, whereas that process is absent in C₃ species; (iii) under conditions where the CO₂ concentration in the intercellular space is regulated over a wide range of external CO₂ concentrations and light intensities through adaptation of stomatal aperture, the level at which the internal concentration is maintained in C₃ types is about half of that in C₄ types (Raschke, 1975; Goudriaan & van Laar, 1978b). This last characteristic will be discussed in detail in Section 3.3.

Examples of species having the C₃ type of assimilation, which prevail in the temperate zones, are small grains, including rice. Species that are of the C₄ type, which are more abundant in subtropical and tropical regions, are maize, sorghum, millet, sugar cane and most tropical grasses. Extensive lists of C₄ species have been compiled by Downton (1975) and Raghavendra & Das (1978).

2.1.2 Canopy CO₂ assimilation

The rate of CO₂ assimilation of a crop depends on incoming visible radiation in the same way as that of an individual leaf. Suppose for simplicity a crop with a horizontal layer of large leaves, forming a closed surface. This layer acts as one big leaf, and knowing the light intensity, the rate of CO₂ assimilation can be read from Figure 6, taking into account that 10% of the incoming visible radiation is reflected, 10% is transmitted through the leaves, 10% is absorbed by pigments not contributing to photosynthesis, and that only the remaining 70% is absorbed by the chloroplasts. At an incoming visible radiation intensity of 300 J m⁻² s⁻¹ this crop, if it was a C₃ species, would have a CO₂ assimilation rate of about 25 kg ha⁻¹ h⁻¹. Such a crop has a leaf area index (LAI) of one, because there is 1 m² of leaf area per m² of soil surface area. When another layer of such big leaves is situated under the first one, the crop has a LAI of 2, because there is 2 m² of leaf area per m² of soil surface area. The incoming radiation intensity in the second layer is equal to the light transmitted through the first layer, thus 10% of 300, or 30 J m⁻² s⁻¹, resulting in an additional assimilation rate of about 3 kg ha⁻¹ h⁻¹. The result is a small increase in assimilation rate for the two layer crop. Adding more layers under the second one will not substantially increase the assimilation rate of such a crop with layers of large horizontal leaves.

In reality, a crop does not consist of horizontal layers of large closely fitting leaves, but the leaves of a crop are spread in every direction and the light is therefore more evenly distributed over the leaves. The light extinction in a canopy can be experimentally determined by measuring the light intensity at different levels in the crop, while at the same time measuring the cumulative leaf area at the same levels. The result of such an experiment is presented in Figure 8, which depicts the relation between the relative light intensity and the cumulative LAI, counting the leaf area from the top of the canopy down-
Figure 8. Extinction of radiation in a crop canopy.

wards. The extinction of the light is exponential for an increasing number of leaf layers. For any LAI the proportion of absorbed radiation can be read from Figure 8. In combination with Figure 6 this yields an estimate of the assimilation rate of the crop. For an LAI of four, the CO₂ assimilation rate is about 39 kg ha⁻¹ h⁻¹, or about one and a half times that of the crop with layers of large horizontal leaves. The reason for this is that in a real crop the light intensity distribution over the leaves is more even and therefore more leaves are exposed to light intensities in the linear part of the light response curve.

The procedure just outlined is a schematized way of calculating the rate of CO₂ assimilation of a crop. Reality is more complicated, as the influence of direct and diffuse light, total leaf area, leaf angle distribution, leaf optical properties and solar height on the light distribution within the canopy have to be taken into account. The problem has been tackled with computer models (de Wit 1965; Duncan et al., 1967; Goudriaan, 1977) which calculate the assimilation rate of a canopy at any moment of a day in response to the incoming photosynthetically active radiation, which is dependent on solar height and the degree of cloudiness of the sky.

In a schematized set up, two situations are considered: a completely clear sky and a completely cloudy sky. Integration of the instantaneous rates yields the daily total amount of CO₂ fixed. In Tables 1 and 2 these daily totals are presented as a function of geographical latitude for both completely clear and completely overcast days, under the assumption of zero respiration and an LAI of five, for two maximum rates of gross CO₂ assimilation of a single leaf at high light intensity, $F_a = 40$ kg ha⁻¹ (leaf) h⁻¹, typical for a C₃ type of plant,
Canopy photosynthesis
(kg CO₂ ha⁻¹ d⁻¹)

The courses of daily canopy photosynthesis throughout the year at 0, 20, 40 and 60 degrees northern latitude for a C₃ crop (PLEI=0.5, PLMX=40, dotted lines), and at 0 and 60 degrees for a C₄ crop (PLEI=0.4, PLMX=50., drawn lines), all at a leaf area of 5.

PLEI = E
PLMX = Fₘₙ

Canopy photosynthesis
(kg CO₂ ha⁻¹ d⁻¹)

The relation of canopy photosynthesis with area of leaves at two dates (January 16, the lower curves, and July 16) and for two values of PLEI (0.3 and 0.5). Other specifications: 50 degrees Northern latitude, at full light, and PLMX=40.
Table 1. Calculated gross CO\textsubscript{2} assimilation rate (kg ha\textsuperscript{-1} d\textsuperscript{-1}) of a closed canopy with a spherical leaf angle distribution, for clear (F\textsubscript{cl}) and overcast (F\textsubscript{oc}) days, and a maximum leaf CO\textsubscript{2} assimilation rate, F\textsubscript{m}, of 40 kg ha\textsuperscript{-1} h\textsuperscript{-1}.

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(Source: Goudriaan & Van Laar, 1978a)

and 70 kg ha\textsuperscript{-1} (leaf) h\textsuperscript{-1}, typical for a C\textsubscript{4} type of plant. On the basis of such tables, which for various maximum rates of CO\textsubscript{2} assimilation at high light intensity can be found in Goudriaan & Van Laar (1978a), potential crop assimilation can be calculated for any date, given the type of crop (C\textsubscript{4} or C\textsubscript{3}), the latitude of the location and the fraction of the time the sky is clouded.

Crop type determines which table is used; given the latitude and the date, the assimilation rate of a closed canopy for a clear and an overcast day is obtained by interpolation. The assimilation rate for partially overcast days is obtained from the formula:

\[
F_{ac} = f_o \cdot F_{oc} + (1 - f_o) \cdot F_{cl}
\]

\[\text{(3)}\]

where

- \(F_{ac}\) is the gross canopy CO\textsubscript{2} assimilation rate (kg ha\textsuperscript{-1} d\textsuperscript{-1})
- \(f_o\) is the fraction of the day the sky is overcast (1 - 0 for completely clear days, \(f_o\) is 1 for completely overcast days)
Table 2. Calculated gross CO₂ assimilation rate (kg ha⁻¹ d⁻¹) of a closed canopy with a spherical leaf angle distribution, for clear (Fₛ) and overcast (Fₒ) days, and a maximum leaf CO₂ assimilation rate, Fₘ, of 70 kg ha⁻¹ h⁻¹.

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(Source: Goudriaan & Van Laar, 1978a)

Fₒ is the gross CO₂ assimilation rate on completely overcast days (kg ha⁻¹ d⁻¹)

Fₛ is the gross CO₂ assimilation rate on a perfectly clear day (kg ha⁻¹ d⁻¹)

The fraction of the day the sky is overcast is obtained from the measured actual daily global irradiation and the daily global irradiation on a perfectly clear day, which is tabulated in Table 3.

Daily global irradiation on a completely overcast day may be approximated by multiplying the value for a perfectly clear day with 0.2. Thus:

\[ Fₒ = (Hₒ - Hₓ)/(Hₓ - 0.2 \cdot Hₓ) \]  \hspace{1cm} (4)

where

Hₓ is total global irradiation on a perfectly clear day (J m⁻² d⁻¹)

Hₒ is measured total global irradiation (J m⁻² d⁻¹)
If the canopy does not form a closed cover, as at the beginning and the end of the growth cycle, not all incoming radiation is intercepted, and CO₂ assimilation is reduced relative to that of a closed canopy. The reduction is estimated from the fraction of the incoming radiation intercepted by the crop, as discussed earlier:

\[ f_h = (1 - e^{-k_v \cdot LAI}) \]  

where

- \( f_h \) is the fraction of light intercepted by the crop
- \( k_v \) is the extinction coefficient for visible light, the value being between 0.5 and 0.8, depending on crop geometry

Exercise 1

Calculate the daily gross CO₂ assimilation for the middle of each month of the year for a completely clear and for a completely overcast sky at your own location, assuming a closed canopy, for both a C₃ and a C₄ type of crop.

Exercise 2

Repeat Exercise 1 assuming LAI = 1.5

The rate of CO₂ assimilation has been expressed so far in amounts of CO₂. The absorbed CO₂ is reduced in the crop to carbohydrates or sugars (CH₂O)ᵥ. To get an assimilation rate expressed in CH₂O, the rate in CO₂ is multiplied by 30/44 (the ratio of their molecular weights).

2.1.3 Respiration

The sugars produced in the assimilation process may be converted into structural dry matter, they may be accumulated and temporarily stored as reserves, or they may be used as a source of energy. The plant needs energy for two processes. On the one hand for maintenance of ionic gradients and resynthesis of degrading structural proteins; on the other hand for the conversion of primary photosynthetic products into structural plant material. In these processes CO₂ is produced, thus they are respiratory processes: the first one is
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<td>30.76</td>
<td>32.44</td>
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</table>

(Source: Goudriaan & Van Laar, 1978a)
called maintenance respiration, the second growth respiration.

Maintenance respiration

The proteins in the plant, especially in the leaves, consist mainly of enzymes, which have only a limited life span. They deteriorate at a relative rate of about 0.1 per day at a temperature of 20 °C, and have to be resynthesized. The rate of protein turnover is temperature dependent with a $Q_10$ of about 2 (Penning de Vries et al., 1979). This means that the rate of protein turnover doubles for temperature increases of 10 °C.

The concentration of ions in the vacuoles of plant cells is higher than in the surrounding tissue, which causes leakage of ions from the vacuoles. To maintain the desired internal concentration, the ions have to be taken up against a concentration gradient. That requires an active transport through cell membranes, which demands energy.

Although accurate data on maintenance requirements are scarce, reasonable estimates of the relative maintenance respiration rate can be made on the basis of the composition of the biomass present. Such estimates are given in Table 4 for four groups of crops, each group having approximately the same chemical composition.

Growth respiration

The conversion of primary photosynthates into structural plant material as cellulose, proteins, lignin and fats requires substrate for building materials and energy for synthesis of the end product, the transport of sugars and the uptake of nitrogen and minerals. Therefore, part of the sugars assimilated is respired to provide energy for the synthesis of new plant components. Another part is lost as refuse in the process of synthesis. The magnitude of growth respiration is determined by the composition of the end product formed. Thus the weight efficiency of conversion of primary photosynthates into structural plant material varies with the composition of that material. Fats and lignin are produced at high costs; structural carbohydrates and organic acids are relatively cheap. Proteins and nucleic acids form an intermediate group (Table 5).

<table>
<thead>
<tr>
<th>Crop group</th>
<th>$R_m$ (kg kg⁻¹ d⁻¹)</th>
<th>$E_s$ (kg kg⁻¹)</th>
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<td>cereals</td>
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<td>protein-rich seed crops</td>
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<td>oil-rich seed crops</td>
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</table>
Table 5. Efficiency of conversion, \( E_x \), of substrate (sugars) into plant constituents (kg kg\(^{-1}\)).

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<th>( E_x )</th>
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<tr>
<td>Carbohydrates</td>
<td>0.826</td>
</tr>
<tr>
<td>Nitrogenous compounds (normal mix of amino-acids, proteins and nucleic acids) from ( \text{NO}_3^- )</td>
<td>0.404</td>
</tr>
<tr>
<td></td>
<td>0.616</td>
</tr>
<tr>
<td>Organic acids</td>
<td>1.104</td>
</tr>
<tr>
<td>Lignin</td>
<td>0.465</td>
</tr>
<tr>
<td>Lipids</td>
<td>0.330</td>
</tr>
</tbody>
</table>

(Source: Penning de Vries, 1975)

For the same groups of crops distinguished above, the conversion efficiencies are tabulated in Table 4. At higher temperatures, the rate of conversion of primary photosynthates into structural plant material changes, but the conversion efficiency remains constant, because the biochemical pathway is not affected by temperature. Conversion of primary photosynthates into structural plant material occurs to a large extent at night. Low night temperatures may hamper this conversion to such an extent that not all the assimilates formed during the day can be converted into structural material. As a result, carbohydrates and starch accumulate in the plant and eventually this may affect the assimilation rate, either through a biochemical feedback or through physical damage to the chloroplasts. Under such conditions the assimilation rate is virtually determined by the capacity of the plant to convert the assimilation products.

2.1.4 Dry matter accumulation

On the basis of the processes presented in this section, the daily rate of increase in structural dry weight of a crop surface may be approximated by the formula

\[
\Delta W = E_x \cdot (F_{sr} - R_n \cdot W) \tag{6}
\]

where

- \( \Delta W \) is the rate of increase in structural dry weight (kg ha\(^{-1}\) d\(^{-1}\))
- \( E_x \) is the conversion efficiency of carbohydrate into dry matter (kg kg\(^{-1}\)); see Table 4
- \( F_{sr} \) is the gross rate of crop assimilation expressed in carbohydrates (kg ha\(^{-1}\) d\(^{-1}\))
$R_m$ is the relative maintenance respiration rate (kg kg\(^{-1}\) d\(^{-1}\)); Table 4

$W$ is the total dry weight of the live parts of the crop (kg ha\(^{-1}\))

In a temperate, humid climate e.g., in the Netherlands, the potential growth rate, as calculated by Equation 6, appears to be about 200 kg ha\(^{-1}\) d\(^{-1}\) during the growing season (Table 6). Experimental evidence confirming these estimates is given by Sibma (1968), who calculated growth curves for a number of field crops growing under near-optimal conditions, as shown in Figure 9. The main agricultural crops in the Netherlands all appear to have practically the same slope. That the C\(_4\) type crop maize shows the same slope is because in the Netherlands it is grown at the limit of its temperature range.

**Figure 9.** Growth rates of the main agricultural crops in the Netherlands under (near-) optimal growth conditions compared to growth rates of 200, 175 and 150 kg ha\(^{-1}\) d\(^{-1}\), respectively. 1. grass 2. wheat 3. oats + barley 3a. oats + peas 4. oats 5. peas 6. barley 7. potatoes 8. sugar beets 9. maize. (Source: Sibma, 1968)
Exercise 3
Calculate the potential growth rate per month of a C₃ crop for your own location, following the scheme presented in Table 6.
Estimate the fraction overcast from your own experience, if no data on radiation are available (heavy clouds: fₒ = 1; clear skies prevailing: fₒ = 0).

Table 6. Example of calculation scheme for the potential growth rate at De Bilt, the Netherlands (52°N) assuming the overall loss by respiration to be 40%.

<table>
<thead>
<tr>
<th>Month</th>
<th>Hₛ</th>
<th>Hₘ</th>
<th>fₒ</th>
<th>Fₙ₁</th>
<th>Fₙ₂</th>
<th>Fₚ₁</th>
<th>Fₚ₂</th>
<th>ΔW</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>16.92</td>
<td>30.43</td>
<td>0.55</td>
<td>829</td>
<td>339</td>
<td>560</td>
<td>382</td>
<td>229</td>
</tr>
<tr>
<td>June</td>
<td>18.60</td>
<td>33.78</td>
<td>0.56</td>
<td>906</td>
<td>374</td>
<td>608</td>
<td>414</td>
<td>249</td>
</tr>
<tr>
<td>July</td>
<td>16.45</td>
<td>32.50</td>
<td>0.62</td>
<td>877</td>
<td>361</td>
<td>557</td>
<td>380</td>
<td>228</td>
</tr>
<tr>
<td>August</td>
<td>14.57</td>
<td>26.86</td>
<td>0.57</td>
<td>747</td>
<td>301</td>
<td>493</td>
<td>336</td>
<td>202</td>
</tr>
</tbody>
</table>

Hₛ = long term average actual global radiation (10⁶ J m⁻² d⁻¹)
Hₘ = total global radiation on a clear day at 52° N.L. (10⁶ J m⁻² d⁻¹) (obtained by linear interpolation in Table 3)
fₒ = fraction of the day the sky is overcast (Equation 4)
Fₙ₁ = gross CO₂ assimilation rate on completely clear days (kg ha⁻¹ d⁻¹) (interpolation in Table 1 or 2)
Fₙ₂ = gross CO₂ assimilation rate on completely overcast days (kg ha⁻¹ d⁻¹) (interpolation in Table 1 or 2)
Fₚ₁ = actual gross canopy CO₂ assimilation rate (kg ha⁻¹ d⁻¹) (Equation 3)
Fₚ₂ = gross canopy assimilation rate in carbohydrates (30/44 x Fₚ₁)
ΔW = the potential growth rate (kg ha⁻¹ d⁻¹) (0.69 x Fₚ₂)
2.2 Crop phenology and dry matter distribution

H.D.J. van Heemst

2.2.1 Introduction

Figure 4 shows the time course of above ground dry matter accumulation of a summer wheat crop during its growth cycle. With respect to the growth rate, three growth stages can be distinguished (Section 2.1). However, a crop not only accumulates weight, it also passes through successive phenological development stages: after sowing or planting, a cereal crop first forms roots, leaves and stems during the pre–anthesis phase, subsequently it flowers, and the seeds set and fill and the crop matures in the post–anthesis phase. These phenological stages are schematically illustrated for a rice crop in Figure 10.

Recognizing the distinction between growth and development, growth is defined as the increase in weight or volume of the total plant or the various plant organs, and development is defined as the passing through consecutive phenological phases; it is characterized by the order and rate of appearance of vegetative and reproductive plant organs. The two processes, growth and development, are often strongly interrelated, which is probably the reason why the term development is used often when growth is meant.

Figure 10. Developmental phases of rice (Source: Doorenbos & Kassam, 1979)
The order of appearance of the various organs is a species characteristic, it may vary among species and is almost independent of the circumstances. The timing and rate of organ appearance, however, is dependent on environmental conditions and is, consequently, highly variable. Important events in the development of cereals are for instance, emergence, floral initiation, terminal spikelet formation, the moment of flowering (anthesis) and the beginning and end of grain filling. For tuber crops, the onset of tuber bulking is also such an event.

The major environmental conditions influencing phenological development are temperature and day length. Many plant species or cultivars need a period of low temperature to induce flowering, for example winter wheat, winter rye and sugar - beet. The process taking place during this period is called vernalization or hardening. Summer crops in temperate climates and tropical crops do not need a period of low temperature to induce flowering. For winter crops the low temperature requirements first must be satisfied. For all crops, higher temperatures generally shorten the length of a given phenological phase. Van Dobben (1979) collected data on the length of the period from emergence to anthesis for a number of crop species, grown at various constant temperatures (Figure 11). The shape of the curves relating the number of days to anthesis to temperature suggests a constant product of days and temperature. This product is the temperature sum or the so called Thermal Unit (TU, expressed in units of day degrees). The most common method of obtaining TU values for the duration of a phenological phase is to add average daily temperatures above a threshold value. The range of threshold temperatures

![Figure 11. The influence of temperature on the length of the pre-anthesis phase for various field crops. (•) rye; (○) wheat; (△) flax; (□) maize; (×) peas. (Source: van Dobben, 1979)
varies between 0 and 10 °C for different species or varieties (Table 7). Sometimes an optimum temperature exists. In that case, temperatures exceeding the optimum, are replaced in the calculation by the optimum temperature itself.

Therefore the higher the temperature, the shorter the length of the total growing period of a crop or, in other words, the higher its rate of development. If development is expressed on a numerical scale, that ranges from 0 to 2, with 0 being emergence, 1 anthesis and 2 maturity, then the development rate is defined as that part of the scale that is accumulated per unit time. Generally a grain crop does not flower in the middle of its growing period. Consequently, the development rate during the pre-anthesis phase differs from the development rate during the post-anthesis phase at the same temperature. If, for example, the time lapse between emergence and anthesis for a certain crop variety in a specific environment is 50 days and between anthesis and maturity 25 days, then the average development rate during the pre-anthesis phase is 1/50 or 0.02 d⁻¹, and during the post-anthesis phase it is 1/25 or 0.04 d⁻¹. The numerical values between 0 and 2, obtained by adding the daily development rates are defined as the development stage.

Exercise 4
Transform the graphs for wheat and maize in Figure 11 into curves of development rate versus temperature. What do you notice about the curves?

For some species or cultivars the effect of temperature on development rate is modified by the influence of the length of the day, or, in fact, the length of the dark period. This effect is called photoperiodism. With regard to this mechanism, plants may be classified into three groups: (i) day-neutral plants, for which development rate is insensitive to day length; (ii) long-day

<table>
<thead>
<tr>
<th>Crop</th>
<th>T₀ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>10</td>
</tr>
<tr>
<td>Soybean</td>
<td>10</td>
</tr>
<tr>
<td>Sorghum</td>
<td>7-10</td>
</tr>
<tr>
<td>Pea</td>
<td>4</td>
</tr>
<tr>
<td>Chickpea</td>
<td>4</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.5</td>
</tr>
<tr>
<td>Rice</td>
<td>0-10</td>
</tr>
</tbody>
</table>
plants, for which anthesis is induced by the occurrence of long days (and therefore short nights); (iii) short-day plants, for which anthesis is induced by the occurrence of short days (and therefore long nights). The reaction to day length may be an important characteristic when a new species or cultivar is introduced in a region, even when it originates from a region at about the same latitude and — consequently — the same photoperiod. The reason is that the growing seasons at the two locations may not coincide due to differences in rainfall pattern. The effects of day length are not treated quantitatively here, because we assume that in each region species with the proper day-length reaction are cultivated.

Although the basic processes governing phenological development and biomass production act independently, both phenomena are strongly interrelated. If the rate of development is high, total biomass production will be low, because the period of linear growth will be short (Section 2.1). Moreover, crops are generally not grown for total biomass, but for their storage organs, such as tubers, grains or pods. These storage organs grow only during the latter part of the growth cycle, after roots, leaves and stems have been produced. A short growing period, resulting in a low vegetative biomass, especially of leaves responsible for light interception, leads inevitably to a poor crop. On the other hand, too much biomass invested in vegetative organs may lead to a relatively low production of storage organs, because in that case the maintenance requirements are high. Therefore, not only total biomass production is of interest, but also its distribution over the various plant parts. The actual proportion of leaves, stems, roots and storage organs in the total biomass at a certain moment depends on the preceding growth rates, which are governed by the weather and the leaf area index in the past, and the partitioning of that dry matter increase over the various plant parts. A fixed distribution pattern, for instance partitioning factors defined as a function of development stage, does not necessarily lead to a constant ratio of various organs. A simple example will illustrate this.

Suppose there is at a certain moment a crop in the field, that comprises 1000 kg ha⁻¹ leaves and 400 kg ha⁻¹ stems. During the following 10 days, the average growth rate is 200 kg ha⁻¹ d⁻¹; the partitioning factors for leaf and stem being 0.6 and 0.4, respectively. In the subsequent 10 day period, the growth rate is only 100 kg ha⁻¹ d⁻¹ because of a much lower energy availability, and the partitioning factors have changed to 0.3 and 0.7 for leaf and stem, respectively. At the end of the second period the weight of leaves is 1000 + 0.6 x 200 x 10 + 0.3 x 100 x 10 = 2500 kg ha⁻¹ and the weight of stems is 400 + 0.4 x 200 x 10 + 0.7 x 100 x 10 = 1900 kg ha⁻¹. This results in a leaf–stem ratio of 1.32. Now suppose the growth rate in the first period to be 100 kg ha⁻¹ d⁻¹ and in the second period 200 kg ha⁻¹ d⁻¹. Assume too, an identical distribution pattern. Then the weight of leaves at the end of the second period is 1000 + 0.6 x 100 x 10 + 0.3 x 200 x 10 = 2200 kg ha⁻¹ and the weight of stems 400 + 0.4 x 100 x 10 + 0.7 x 200 x 10 = 2200 kg ha⁻¹.
Then the leaf - stem ratio is 1.00.

In this example the development pattern and the time course of partitioning factors were assumed to be identical. However, development is not identical each year, as it responds to differences in environmental conditions. It is therefore not possible to relate the distribution pattern to crop age. Usually the partitioning of the current assimilate supply over the various plant parts is expressed in a distribution pattern in dependence of the development stage of the crop. Such configurations are characteristic for each crop. The effects of environmental conditions other than temperature on the distribution pattern are often very small, especially in the potential production situation; they are therefore not taken into consideration here.

In the next part of this section the partitioning of newly formed dry matter over the various plant organs is treated in relation to the development stage of the crop. Examples will be given for the crops rice, maize and cassava.

2.2.2 Development and dry matter distribution in maize

For maize, the total growing period from emergence to maturity varies from 80 to 110 days for short duration varieties, and from 110 to 140 days for medium duration varieties, when average daily temperatures are above 20 °C. Under cooler conditions, maize is mostly grown as a forage crop because the associated extended length of the growing period does not permit timely maturation, due to the low temperatures, especially towards the end of the growing season.

Maize is considered to be either day-neutral or a short-day plant. The flower has separate male and female parts. The male flowers are in the tassel at the top of the plant; the female flowers are in cobs at nodes along the middle of the stem (Figure 13). The pre-anthesis period ends at silking. The

Figure 13. Developmental phases for maize. (Source: Doorenbos & Kassam, 1979)
duration of the interval between emergence and silking is affected by both
genetic factors and environmental conditions. For most common cultivars,
the time from silking to maturity under normal environmental conditions is
identical, an average 30 – 55 days.

The most frequently used method for determining the temperature require-
ment from emergence to silking is a direct summation of average daily tempe-
raturess, taking into account a base temperature of 10 °C. Mederski et al.
(1973) established TU values of 625, 640, and 755 d °C for the period between
emergence and silking, and 650, 655, and 635 d °C for the post – silking
period for the varieties Ohio 401, DeKalb XL45 and Pioneer 3306, respecti-
vely. The latter values may vary with the definition of maturity. In this case, it is
defined as the moment that a black layer develops at the base of the kernel,
which marks the end of the period of effective grain filling. Similar to rice, the
TU value for the post – silking period is almost identical for the three varieties
at 650 d °C. The average duration of that period at 20 °C is 650/(20 – 10) =
65 days; at 25 °C it becomes 650/(25 – 10) = 43 days (the base temperature is
10 °C). The corresponding development rates are 1/65, or 0.0154 d ° 1, and
1/43, or 0.0233 d ° 1, respectively.

Exercise 5
A maize variety is grown at a location (air temperature given in Table 8), for
which a TU value of 760 d °C has been established for the period between
emergence and silking, and one of 660 d °C between silking and maturity. For
both periods a threshold value of 10 °C may be taken into account. The crop
emerged 1 June.
Calculate the dates on which development stages 0.2, 0.4, 0.6, 0.8, 1.0, 1.5,
and 2.0 are reached.
What are these dates if emergence takes place on 15 June.
Calculate the average development rates for the pre – silking and post – silk-
ing periods for both emergence dates.

Exercise 6
A maize crop is harvested periodically at ten – day intervals. The harvested
plants are separated into leaves and stems. The dry weights of the plant parts
are given below:

<table>
<thead>
<tr>
<th>Date</th>
<th>Leaf weight (kg ha °)</th>
<th>Stem weight (kg ha °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 June</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>20 June</td>
<td>1400</td>
<td>300</td>
</tr>
<tr>
<td>30 June</td>
<td>2800</td>
<td>800</td>
</tr>
<tr>
<td>10 July</td>
<td>4500</td>
<td>2000</td>
</tr>
<tr>
<td>20 July</td>
<td>5700</td>
<td>3800</td>
</tr>
</tbody>
</table>

Emergence date is 1 June; silking date is 5 August.
Draw a graph of the fraction of the weight increment allocated to the leaves as
a function of the development stage of the crop. Assume a constant tempera-
ture regime.
Table 8. Average air temperatures (°C) to be used in Exercise 5

<table>
<thead>
<tr>
<th>Date</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>20</td>
<td>24</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>22</td>
<td>26</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>21</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>19</td>
<td>26</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>18</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
<td>18</td>
<td>24</td>
<td>30</td>
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<td>7</td>
<td>16</td>
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<td>8</td>
<td>13</td>
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<td>33</td>
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</tbody>
</table>

Figure 14. Partitioning factors for plant parts of maize in the course of development.

The distribution pattern for maize (Figure 14) is constructed from experimental data in the same way as is done for a part of the pre-silking period in Exercise 6.
2.3 Introduction of CSMP by an elementary simulation program

L.J.M. Basstanie and H.H. van Laar

2.3.1 Introduction

The scientific approach toward studying ecological and physiological phenomena often results in their being described by mathematical expressions. A great deal of these phenomena behave in a 'dynamic' fashion which means the 'state' of the ecological system changes with time. With knowledge of the processes within the system one can develop a mathematical model to study the dynamic behaviour of the system.

De Wit & Goudriaan (1978), Ferrari (1978) and Brockington (1979) have written introductory textbooks on simulation of ecological processes. Although the main topic of this book is modelling of growth processes and related phenomena, those textbooks are useful for their complementary explanations and illustrations.

In this section we introduce the simulation language CSMP (Continuous Simulation Modeling Program) (IBM, 1975), which is used throughout this book. Basic principles of its use are demonstrated by construction of a simple program for the simulation of crop dry-matter production (Subsection 2.3.2). In its first form the program calculates photosynthesis, respiration, dry-matter distribution, and leaf area index during a growth season, assuming a constant environment. Subsequently the program is modified to account for a varying environment and its effect on some of the processes (Subsection 2.3.3). Starting from this basic level has the advantage that the reader who is not familiar with growth modelling and programming in CSMP can find handholds in such a simple program. Gradually, as processes are treated in more detail in the following sections, more elaborate modelling techniques and their programming in CSMP will be discussed.

Subject of this section is also the internal structure of a CSMP program with special attention to the sorting mechanism (Subsection 2.3.4). Finally some basic CSMP programming knowledge is summarized (Subsection 2.3.5) to provide sufficient information for a good comprehension of the following sections. In Section some of these aspects will be elaborated. The CSMP manual (IBM, 1975) may be useful for those with some programming experience.

2.3.2 An elementary simulation program for dry-matter production

In a first approximation dry-matter production of a crop can be simulated based on the simple model depicted in Figure 16. Gross CO₂ assimilation feeds a pool of carbohydrates that supplies material for growth and respiration. Part of
this pool is needed for maintenance of the crop, a process usually defined as maintenance respiration. The substrate for growth is also taken from this pool, and the conversion into shoot and root biomass involves a loss of carbohydrates, defined as synthesis respiration. The relational diagram of such a system has been presented.

Because we would like to describe this model and use it for simulation of growth on a day-to-day basis, one simplification of the relational diagram has to be made: we will assume that all carbohydrates from photosynthesis are consumed by growth and maintenance processes within one day. As a result, we can omit the pool of carbohydrates as a separate variable from the model. In Section this simplification will be explained more extensively.

The relational diagram reveals the kind of quantitative information that should be available. A standard value for the gross photosynthetic rate (GRA) of a green and completely closed canopy, well supplied with water and nutrients is in terms of glucose production on the order of 400 kg ha\(^{-1}\) d\(^{-1}\) on clear summer days. When the canopy is not fully closed the actual value of the gross photosynthetic rate (GASS) is a fraction of GRA. This fraction corresponds with the fraction of absorbed visible radiation, calculated with an exponential extinction of radiation as function of the leaf area index (LAI, an area fraction of leaves to ground surface, in m\(^{2}\)m\(^{-2}\)). A value of 0.7 for the extinction coefficient results in a fraction \(1 - \exp(-0.7 \cdot \text{LAI})\) of absorbed visible light.

Maintenance respiration (MRES), expressed in glucose, is related to the total dry matter weight (TDW), a proportionality factor of 0.015 kg kg\(^{-1}\) d\(^{-1}\) is a fair estimation. As for growth, a conversion factor (EC, in kilogram of dry matter per kilogram of glucose) of 0.7 quantifies reasonably well the efficiency of synthesis of structural material from the carbohydrates, the remainder being lost as respiration. Dry matter is distributed between shoot (WSH) and root (WRT), both in kg ha\(^{-1}\); fixed fractions of respectively 0.7 and 0.3 have been chosen for the purpose of this example.

With this information the equations characterizing the model can be written.
By using a simulation language, such as CSMP, these equations can be easily coded into a small set of statements comprehensible to reader and computer. Figure 17 represents the actual computer program of the simple model that is developed above. A computer program is normally the last stage in the construction of a 'working version' of a simulation model. When the program is submitted to a computer, the output gives a picture of the behaviour of the model. Numerical values of state variables are computed starting from their initial value at simulation time zero until the end of the simulation period. For defined time intervals, a list of calculated values of variables in which one is interested can be printed.

We will discuss the program of Figure 17 line by line. It is useful to start by identifying the program with a TITLE statement:

**TITLE DRY MATTER PRODUCTION**

Subsequently the structure of the model is defined. The goal of the simulation is the total dry matter weight (TDW), which is the sum of the dry matter weight of the shoots (WSH) and the roots (WRT):

\[ TDW = WSH + WRT \]

WSH and WRT are state variables in the model that change according to their characteristic growth rates GSH and GRT. Integration of these growth rates gives the actual values of WSH and WRT at any moment. CSMP provides the INTGRL function (Table 2) as a means to integrate numerically a specified rate in time:

\[ WSH = \text{INTGRL}(WSHI, GSH) \]
\[ WRT = \text{INTGRL}(WRTI, GRT) \]

Initial conditions (WSHI, WRTI) and relevant rates (GSH, GRT) have to be specified as arguments of the INTGRL function and are placed between brackets. At time zero, WSH equals WSHI and the current value of WSH at any time is found by integrating GSH. A similar reasoning is valid for WRT. At the beginning of the growth season, shoot and root dry weight can be estimated at 50 kg ha\(^{-1}\). In an **INCON** statement we can assign numerical values to these **INITIAL CONDITIONS**:

**INCON WSHI = 50., WRTI = 50.**

The growth rates GSH and GRT are calculated as

\[ GSH = 0.7 \times GTW \]
\[ GRT = 0.3 \times GTW \]

in which GTW is the net rate of total dry matter increase (kg ha\(^{-1}\) d\(^{-1}\)). As illustrated in Figure 16, we can express GTW as

\[ GTW = (\text{GASS - MRES}) \times \text{EG} \]
Table 2. Some CSMP III functions. From: IBM (1975).

<table>
<thead>
<tr>
<th>CSMP III Function</th>
<th>Equivalent Mathematical Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrator</td>
<td>( y(t) = \int_{t_0}^{t_1} x , dt + y(t_0) )</td>
</tr>
<tr>
<td>where IC = ( y_{t_0} )</td>
<td>( t_0 ) where ( t_0 ) start time</td>
</tr>
<tr>
<td></td>
<td>( t_1 ) time</td>
</tr>
<tr>
<td>Arbitrary function generator (linear interpolation)</td>
<td>( y = f(x) )</td>
</tr>
<tr>
<td>Y=AFGEN(FUNCT,X)</td>
<td></td>
</tr>
<tr>
<td>Arbitrary function generator (sigmoidic interpolation)</td>
<td>( y = f(x) )</td>
</tr>
<tr>
<td>Y=HLFGEN(FUNCT,X)</td>
<td></td>
</tr>
<tr>
<td>Modulo function</td>
<td>( y = x \mod n ) where ( n ) is an integer value such that ( 0 \leq y &lt; n )</td>
</tr>
<tr>
<td>Y=AMOD(X,P)</td>
<td></td>
</tr>
<tr>
<td>Limiter</td>
<td>( y = \begin{cases} D_1 &amp; x &lt; P \ D_2 &amp; x &gt; P \ D_3 &amp; x = P \end{cases} )</td>
</tr>
<tr>
<td>Y=LIMIT(P1,P2,X)</td>
<td></td>
</tr>
<tr>
<td>Not</td>
<td>( y = \begin{cases} 1 &amp; x = 0 \ 0 &amp; x &gt; 0 \end{cases} )</td>
</tr>
<tr>
<td>Y=NOT(X)</td>
<td></td>
</tr>
<tr>
<td>Input Switch Relay</td>
<td>( y = x_3 ) if ( x_1 = 0 )</td>
</tr>
<tr>
<td>Y=INSW(X1,X2,X3)</td>
<td>( y = x_3 ) if ( x_1 = 0 )</td>
</tr>
</tbody>
</table>

The maintenance respiration is supposed to be 1.5 percent of the total dry matter per day:

\[ \text{MRES} = (\text{WSH} + \text{WRT}) \times 0.015 \]

The equation representing the relation of the gross photosynthetic rate and green surface has an exponential form:

\[ \text{GASS} = \text{GRA} \times (1 - \exp(0.7 \times \text{LAI})) \]

The leaf area index (LAI) is here assumed to be proportional to the shoot dry matter (WSH) to a maximum of 5 ha ha\(^{-1}\). The AMINI function (Table 3) can be used to achieve this:

\[ \text{LAI} = \text{AMINI} (\text{WSH}/500, 5) \]

The AMINI function takes the minimum value of its arguments separated by comma's.
TITLE  DRY MATTER PRODUCTION
*Each line is explained in the text (chapter 2.3)

INITIAL
INCON  WSHI = 50., WRTI = 50.

DYNAMIC
TDW = WSH + WRT
WSH = INTEGR(WSHI, GSH)
WRT = INTEGR(WRTI, GRT)
GSH = 0.7 * GTW
GRT = 0.3 * GTW
GTW = (GASS - MAINT) * EG
GASS = GRA * (1. - EXP(-0.7 * LAI))
MRES = (WSH + WRT) * 0.015
LAI = AMIN(WSH/500., 5.)
PARAM  EG=0.7, GRA=400.

TIMER  FINTIM=100., DELT=1., PRDEL=5., OUTDEL=5.

METHOD RECT
PRINT TDW, WSH, WRT, GTW

OUTPUT TDW

END

STOP

ENDJOB

For explanation see also:
* GTW: equation 6, page 24
* Reduction factor (1. - EXP(-0.7*LAI)): equation 5, page 21
* Relative maintenance respiration (0.015): table 4, page 23
* Specific leaf area: 1/500 = 0.0020 ha.kg-1
* Conversion efficiency (EG): table 4, page 24
The parameters \( EG \) and \( GRA \) have to be specified to complete the numerical information for the program. The PARAMeter statement is used to assign values to variables used as parameters:

\[
\text{PARAM } EG = 0.7, \text{ GRA } = 400.
\]

So far the structure of the model has been transformed into a simulation program that can be executed. Only timing, output format and an appropriate integration method must still be specified. A TIMER statement gives the time of finishing the simulation (FINTIM), the printed output interval (PRDEL) and plotted output interval (OUTDEL), and the size of the time step for integration (DELT):

\[
\text{TIMER } \text{FINTIM} = 100., \text{ DELT} = 1., \text{ PRDEL} = 5., \text{ OUTDEL} = 5.
\]

All TIMER variables are expressed in days, as this is the basic unit of time in this program. A numerical integration method is selected from a set of available
Table 3. Some FORTRAN functions, which can be used in CSMP III statements. From: IBM (1975).

<table>
<thead>
<tr>
<th>FORTRAN Functions</th>
<th>Equivalent Mathematical Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponential</td>
<td>$y \cdot \exp(x)$</td>
</tr>
<tr>
<td>Trigonometric $\sin$</td>
<td>$y \cdot \sin(x)$</td>
</tr>
<tr>
<td>Trigonometric $\cos$</td>
<td>$y \cdot \cos(x)$</td>
</tr>
<tr>
<td>Square root</td>
<td>$y \cdot \sqrt{x}$</td>
</tr>
<tr>
<td>Largest value</td>
<td>$y \cdot \max(x_1, x_2)$</td>
</tr>
<tr>
<td>Smallest value</td>
<td>$y \cdot \min(x_1, x_2)$</td>
</tr>
</tbody>
</table>

For instance, to perform the simulation using the rectangular method after Euler, the next statement has to be used:

**METHOD RECT**

Printed output of the variables is obtained by means of:

**PRINT TDW, WSH, WRT, GTW**

Plotted out can be obtained by:

**OUTPUT TDW**

The END statement defines the end of the simulation model and the STOP statement the end of the simulation program.

**END**

**STOP**

**ENDJOB**

The ENDJOB statement finishes the computer job. Figure 17 shows a complete listing of the example model and the output after execution.
Exercise 11
Run the program.

During a simulation run all statements defining the structure of the model are executed several times, the number of which equals FINTIM divided by DELT, when using the rectangular method. DELT, equivalent to $\Delta t$ in Section 2.1, plays a critical role since it indicates the size of the time interval for integration. For a CSMP statement with an integral function like:

$$WSH = \text{INTGRL}(WSH_1, GSH)$$

the equivalent numerical expression when using a rectangular integration method,

$$WSH_{\text{now}} = WSH_{\text{previous}} + GSH \cdot \text{DELT}$$

From this equation it is clear that the rectangular integration method implicates a constant growth rate during the whole time step DELT. Taking appropriate time steps, such that the rate of change can be regarded as effectively constant, will give good approximations of the value of the state variable.

Exercise 12
a. Simplify the program for the case that you are only interested in the total dry matter increase (do not consider biomass distribution into shoots and roots). Assume that the crop is completely covering the soil (GPHOT = GPHST). Run this program.

2.3.3 Program modifications with forcing functions

Until now we assumed that all external conditions, or driving variables, are constant. However, CO$_2$ assimilation rates are strongly
dependent on irradiation and irradiation itself can vary from day to day over a relatively wide range. If we want to make the model realistic, we should introduce the actual irradiation level instead of a fixed rate of gross CO₂ assimilation. Irradiation will drive CO₂ assimilation in the model and is not affected by the state of the system. Therefore we call it a driving or forcing function. More generally, forcing functions are defined as those variables that are not affected by processes within the system, but characterize the influence from outside. They are an input to the model. In very simplified models, forcing functions can be introduced in the program as parameters:

PARAM GRA = 400.

Very often forcing functions show a characteristic pattern over a certain time period (day or year). An equation describing such regular fluctuations in time may provide approximate values for the use in a general program. For example, the yearly course of daily incoming short-wave irradiation is reasonably well represented by a sinusoidal curve, just like daily gross photosynthesis. For the daily gross photosynthesis (GRA, expressed as glucose) the equation is

GRA = 300. + 200. * SIN (2 * PI * (DATE - (364./4.) + 10.) / 365.)
PARAM PI = 3.141592

DAY stands for the number of a day in the year; counting starts from 1 January. GRA reaches a minimum value of 100.0 (kg ha⁻¹ d⁻¹) on 21 December (DATE = 365) and a maximum value of 500.0 on 21 June (DATE = 172). DATE can be calculated by:

DATE = DATEI + TIME
PARAM DATEI = 60.

In this way simulation starts on 1 March (DATEI = 60.). TIME is a variable generated by CSMP which expresses the current time during simulation. At the start of simulation TIME = 0., and its value is augmented by DELT when the integration of all state variables is accomplished. (The symbolic name TIME is reserved by CSMP to keep track of time, and cannot be used for other purposes). A second way of keeping track of the number of the day is to give the variable TIME an initial value. This can be done in the TIMER statement:

TIMER TIME = 60., FINTIM = 210., DELT = 1., PRDEL = 5.

When the time course of a driving variable has been measured, direct use of these values is another option for formulating a forcing function. Measured values, with the corresponding dates can be introduced by a FUNCTION statement:

FUNCTION GRAT = (60., 300.), (100., 400.), (150., 450.), (210., 500.)

In this statement, an ordered set of pairs defines the content of a table, named GRAT. The first value in each pair of numbers between parentheses stands
for the independent variable (TIME, d), the second expresses the dependent variable (GRA, kg ha\(^{-1}\) d\(^{-1}\)). The distance between the coordinates of two pairs does not have to be equal in size; the value of the independent variable should always increase, but the dependent variable can vary in an arbitrary way. The current value of the dependent variable is calculated by means of an AFGEN function (Arbitrary Function GENERator), which performs a linear interpolation in the function table. Function name and independent variable should be specified as arguments of the AFGEN function:

\[
\text{GRA} = \text{AFGEN} (\text{GRAT}, \text{TIME})
\]

Another example of a forcing function that plays a critical role in growth models is temperature. The next exercise illustrates how maintenance respiration can be modelled more realistically by taking the effect of temperature into account.

Exercise 14
Extend the program of Exercise 12 so that maintenance respiration becomes dependent on temperature. Assume a linear temperature course for the simulation period between 10 °C on the first day and 20 °C on the last day. Use the following table:

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAINTENANCE COEFFICIENT</td>
<td>0.008</td>
<td>0.015</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Repeat the simulation for a more realistic course of the temperature.

AFGEN provides a simple linear interpolation between 2 points \((x_1, y_1)\) and \((x_2, y_2)\). The function value \(y\) for a certain \(x\) is expressed as:

\[
y = y_1 + \frac{(y_2 - y_1) \cdot (x - x_1)}{(x_2 - x_1)}
\]

In a sense, a broken line is generated by connecting subsequent points.

2.3.4 The structure of the CSMP language

CSMP is a problem-oriented language designed to facilitate the digital simulation of continuous processes on large-scale digital computers. The advantage of using such a language is that it simplifies the programming. The user is not concerned with the rather difficult programming of numerical integration and interpolation methods, and he need not to worry about the computational order of the statements. (We will return to this important point). A convenient output form is provided by the program itself. The programmer is only responsible for writing the statements that define the model and supplying it with a proper data set. An additional advantage specific for CSMP is that the full capability of the widely used FORTRAN language is available. In addition to FORTRAN facilities, CSMP includes a set of functions that are particularly suited to working with a continuous system (e.g. INTGRL and AFGEN functions).
Every simulation run essentially starts from a well defined initial condition. When needed, one can separate this part from the description of the structure of the model itself. The determination of the final situation of a simulation run and decision for a possible new run can be separated as well in a program. To do so, a CSMP model can be divided into three segments – INITIAL, DYNAMIC and TERMINAL – that describe the computations to be performed before, during and after each simulation run. The TERMINAL segment will not be discussed here.

The INITIAL segment is exclusively used for initialization of variables and computations of variables to be expressed in more basic parameters. Statements in the INITIAL segment are executed only once per simulation run. Assume for example the initial weights of shoot and root depend on the weight of the seed sown, then the simulation model can be modified as:

```
TITLE DRY MATTER PRODUCTION
INITIAL
INCON SEED = 150.
WSHI = SEED * 0.6 * 0.5
WRTI = SEED * 0.6 * 0.5
```

The factor 0.6 is a reasonable value for conversion of seed into plant material; a shoot:root ratio of 1 is used here.

The DYNAMIC segment contains the complete description of the system dynamics, together with any other computations and decisions to be performed for successful simulation. For most simple models, the DYNAMIC segment consists of one section:

```
DYNAMIC
TDW = WSH + WRT
WSH = INTGRL (WSHI, GSH)
    and so on, as in Figure 17 until:
    ...

END
```

In more complicated systems, the DYNAMIC segment can be divided in several sections, each section dealing with a separate submodel (Subsection 2.3.2).

Specification of an INITIAL segment is optional and is often omitted for small models. In that case the DYNAMIC segment has not to be declared explicitly by the DYNAMIC label.

One of the main advantages of CSMP is its sorting routine. It enables the user to write a simulation program with its statements in the same order as he thinks about the process or system and in which he considers it most lucid and readable. Such an order of statements, however, is often the reverse of what the computational order must be. The CSMP sorting routine finds the proper order from any sequence of statements presented. Sorting of statements is necessary
because computations have to be performed in a correct order: calculation of
rate variables must always precede the updating of state variables. This is a con-
sequence of the concept of dynamic simulation. Also all variables,
used to compute rate variables at time \( t \), must have the appropriate value, and
not one corresponding with one time interval \( \Delta t \) earlier or later. Sequencing
statements in an appropriate computational order is also required if one pro-
grams in FORTRAN, but with FORTRAN the sequencing must be done by the
programmer (and one is usually not warned when it is done incorrectly).
The FORTRAN program that results from the sorting and some other con-
versions by the CSMP compiler is called UPDATE. It is accessible like other
computer generated files.
The CSMP programming system sorts the statements in the INITIAL and
DYNAMIC segments automatically, independently of each other.

2.3.5 Some basic CSMP programming rules

To write a correct CSMP program, a minimum knowledge of the common expres-
sions of this language is necessary. The intention of this part is to provide
a summary of frequently used CSMP statements. Readers who want to know
more are referred to a CSMP manual (IBM, 1975).

Data statements

Data statements are used to assign numeric values to parameters, constants
and initial conditions. For instance:

\[
\text{PARAM P1} = \ldots, \ P2 = \ldots
\]
\[
\text{CONSTANT C1} = \ldots, \ C2 = \ldots
\]
\[
\text{INCON I1} = \ldots, \ I2 = \ldots
\]

Parameters specified in a PARAM statement are constant during the simulation
run. Variables can be introduced by means of a FUNCTION label (see Subsec-
tion 2.2.3).

Structure statements

Structure statements describe the functional relationships between the vari-
able of the model. FORTRAN statements can be used within a CSMP program,
and all FORTRAN functions are valid (Table 3). Some examples of structure
statements:

\[
Y = (A + B) \times C
\]
\[
\text{ROOT} = \sqrt{X \times 2 + Y \times 2}
\]
\[
A = \int \text{GRL} \ (2, \ X \times 2 + \frac{R}{D})
\]

For more information about available CSMP and FORTRAN functions see
Tables 2 and 3 and particularly the Program Reference Manual (IBM, 1975).
Expressions should be written at the right hand side of the equal sign and
their numeric value is assigned to the variable at the left. The calculation of an
expression is performed according to the standard hierarchy:
- evaluation of brackets (in combination with FORTRAN or CSMP func-
tions)
- exponentiation (\( \times \times \))
- multiplication and division (\( \times, \ / \))
- addition and subtraction (\( \ +, \ - \))

Operators of the same hierarchy are performed from left to right.
Output control statements

The TITLE statement allows the user to specify the program and it appears at the top of each page of the output listing. A PRINT statement is used to specify variables whose values will be printed at each PRDEL interval. For output of some variables in printed graph form the OUTPUT statement is used. For examples see Subsection 2.2.2,

Execution control statements

In a TIMER statement we specify the values of certain system variables.
FINTIM : finish time for terminating a simulation
OUTDEL : time interval for print-plot output
PRDEL : time interval for printing the values of requested variables
DELT  : integration interval
TIME  : initial value of time, to be specified only if not zero.

A condition to terminate the simulation, e.g. when TDW exceeds 20 000 kg ha\(^{-1}\), can be introduced by a FINISH label:

FINISH TDW = 20000.

Also the integration method is specified in an execution control statement, for instance:

METHOD RECT

If METHOD RECT is not specified, the RKS method is used by default (see Section 2.3).

The statement
END : completes the specifications of the model.
STOP  : terminates the simulation run(s)
ENDJOB: terminates the job.

Syntax

Some syntactic rules may be helpful when editing a program.
- maximum 6 characters for names of variables
- each statement on one line
- a statement followed by three dots (\ldots) means that statement will be continued on the next line:
- spaces between variable names and operators are allowed
- columns 1 to 72 can be used for the program, columns 73-80 are for identification
- statements can begin in any column, except for ENDJOB, which must begin in the first column
- * in the first column stands for comment.
2.4 A simple model of potential crop production

H. van Keulen

2.4.1 Introduction

In Section 2.1, potential crop production was defined as the total dry matter production of a green crop surface that, during its entire growth period, is optimally supplied with water and all essential nutrient elements, and grows without interference from weeds, pests and diseases. From this concept, a step may be made to the estimation of potential yield, i.e. the production of economically useful plant parts, by taking into account the phenological development of a particular crop species or cultivar, and the associated partitioning of dry matter over various organs of the plant, as outlined in Section 2.2. In this Section a scheme is presented to calculate both total dry matter production and economic yield for a number of crops, based on radiation and temperature regime, only.

The principle of the procedure is that repetitive calculations are performed, starting at some point in time at which the state of the crop can be described in quantitative terms, either determined from experimental data or estimated from other known relations. For most crops a suitable point in time is emergence, which is defined as the moment of transition from growth of the seedling from the reserves in the seeds to growth originating from carbohydrates formed in the process of assimilation. Transplanted rice is a special case, because the seedlings, growing on a nursery bed, are uprooted after some time and replanted on the site where they will eventually mature. The moment of transplanting is then a better starting point.

The state of the crop at the start of the calculations is characterized by measurable quantities, e.g. the weight of the aerial plant parts, the weight of the roots and the green leaf area, active in the assimilation process. From this state and the environmental conditions in the following period the rates of the relevant processes, such as assimilation and respiration, are calculated. These basic processes govern the rates of change of the various quantities that can thus be calculated. Realization of these rates over the relevant time interval and addition to the quantities present at the beginning of the period yield the magnitude of the quantities at the end of the period. Or, in mathematical notation:

\[ Q_{t+\Delta t} = Q_t + R \Delta t \]  

(7)

where
$Q_{i+1}$ is quantity at time $t + \Delta t$
$Q_i$ is quantity at time $t$
$R_q$ is the rate of change of quantity $Q$ during time interval $\Delta t$
$\Delta t$ is time interval between the beginning of the period and the end of the period.

Exercise 15
If the unit of $Q$ is kg ha$^{-1}$, and the unit of $\Delta t$ is days, what is the unit of $R_q$?
Suppose $Q_i = 200$, $R_q = 15$ and $\Delta t = 10$, what will $Q_{i+1}$ be?

The calculations are then repeated for the next time interval, and so on until the end of the growth period of the crop. In this way the growth curve i.e. the cumulative dry matter production (Section 2.1) is obtained. By partitioning the dry matter produced during each time interval according to the coefficients given in Section 2.2, the weight of the various organs can be calculated. The partitioning coefficients are a function of the development stage of the vegetation and that 'quantity' must therefore also be calculated. This may be done in the way suggested in Section 2.2, by adding the average air temperatures in the course of the growing period and dividing the accumulated temperature sum at any moment by the sum required for the completion of a certain phenological phase. The ratio obtained is the required quantity which is defined as the development stage.

The approach followed assumes that the rates of change calculated at the beginning of a time interval do not change during that interval. This assumption puts a restriction on the length of the time interval applied. In theory infinitely small time intervals would have to be applied, because realization of a rate of change over even a small interval results in different values for the quantities and this would thus lead to a different rate of change for the next small time interval. That would, however, hardly be possible from a practical point of view. Moreover, the deviations are often within reasonable limits even if the time interval has a finite size. In our approach we have chosen a period of ten days which, on the one hand, permits calculations for an entire growth period of some hundreds of days to be performed in a reasonable time. On a pocket calculator, and, on the other hand, yields acceptable results to the purpose pursued here.

The principles of the calculation procedure outlined so far are those underlying the state variable approach in systems analysis and modelling. This approach will not be further elaborated upon in this volume; for description of this approach see de Wit & Goudriaan (1978) and Penning de Vries & van Laar (1982).
Exercise 16
In the biological sciences, often the growth rate — i.e. the rate of increase of a quantity — is proportional to the quantity present, thus:

\[ R_n = a \cdot Q_n \]

Calculate the time course of the quantity \( Q \) for a thirty day period when \( Q_0 = 5 \, \text{kg ha}^{-1} \) (\( Q_0 \) is the quantity at time zero) and the value of the proportionality factor \( a = 0.1 \, \text{d}^{-1} \); use for \( \Delta t \) a value of 5 days. Repeat the calculation for a value of \( \Delta t = 3 \) days. Compare the results. What do you notice? Explain the difference.

2.6.2 An actual example

This example concerns an experiment with the rice variety IR8, one of the so-called high yielding varieties (HYV) developed at the International Rice Research Institute. The experiment was carried out in Paramaribo, Suriname, South America (5°49' N, 55°09' W). The rice was transplanted on 10 November 1972 (Van Slobbe, 1973). The air temperatures used in the calculations were obtained from reported ten-day averages for the experimental period. Radiation was calculated from monthly averages of sunshine duration reported (Section 3.1). These data were used to calculate potential gross CO₂ assimilation (Section 2.1), which is given in Table 9.

<table>
<thead>
<tr>
<th>Date (Month)</th>
<th>( F_p ) (kg ha(^{-1}) d(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 15</td>
<td>332</td>
</tr>
<tr>
<td>Feb. 15</td>
<td>344</td>
</tr>
<tr>
<td>March 15</td>
<td>368</td>
</tr>
<tr>
<td>April 15</td>
<td>364</td>
</tr>
<tr>
<td>May 15</td>
<td>354</td>
</tr>
<tr>
<td>June 15</td>
<td>378</td>
</tr>
<tr>
<td>July 15</td>
<td>417</td>
</tr>
<tr>
<td>Aug. 15</td>
<td>454</td>
</tr>
<tr>
<td>Sept. 15</td>
<td></td>
</tr>
<tr>
<td>Oct. 15</td>
<td></td>
</tr>
<tr>
<td>Nov. 15</td>
<td>336</td>
</tr>
<tr>
<td>Dec. 15</td>
<td>283</td>
</tr>
</tbody>
</table>
Table 10. Calculation scheme for potential production.

<table>
<thead>
<tr>
<th>Column no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>Tₘ</td>
<td>TSUM</td>
<td>DYS</td>
<td>GASS</td>
<td>MRES</td>
<td>ASAG</td>
<td>GTW</td>
<td>FR</td>
<td>GRT</td>
<td>WRT</td>
<td>FL</td>
<td>GLV</td>
</tr>
<tr>
<td>1 Nov. 2</td>
<td>27.2</td>
<td>272</td>
<td>0.18</td>
<td>60.5</td>
<td>2.1</td>
<td>58.4</td>
<td>40.9</td>
<td>0.35</td>
<td>14.3</td>
<td>183</td>
<td>0.395</td>
<td>16.2</td>
</tr>
<tr>
<td>2 Nov. 3</td>
<td>26.3</td>
<td>535</td>
<td>0.36</td>
<td>127.2</td>
<td>8.2</td>
<td>119.0</td>
<td>83.3</td>
<td>0.165</td>
<td>13.7</td>
<td>320</td>
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<tr>
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<td>793</td>
<td>0.53</td>
<td>216.0</td>
<td>20.7</td>
<td>195.3</td>
<td>136.7</td>
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</tr>
<tr>
<td>4 Dec. 2</td>
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<td>41.2</td>
<td>219.2</td>
<td>153.4</td>
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<tr>
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<td>1320</td>
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<td>64.2</td>
<td>230.8</td>
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<td>11.3</td>
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<td>6a Jan. 1-7</td>
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<td>1502</td>
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<td>4.0</td>
<td>671</td>
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<tr>
<td>6b Jan. 8-10</td>
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<td>1580</td>
<td>1.10</td>
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<td>71.2</td>
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<td>75.7</td>
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<td>1.75</td>
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<td>244.3</td>
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<td>0</td>
<td>671</td>
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Table 10. (continued)

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<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
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<td>WLV</td>
<td>FS</td>
<td>GST</td>
<td>WST</td>
<td>PG</td>
<td>GGR</td>
<td>WGR</td>
<td>LAI</td>
<td>TADW</td>
<td>TDW</td>
<td>TDWL</td>
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<td>0</td>
<td>0</td>
<td>0.25</td>
<td>126</td>
<td>879</td>
<td>6.0</td>
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<td>549</td>
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<td></td>
</tr>
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<td>3753</td>
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<td>3176</td>
<td>0.69</td>
<td>125.6</td>
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<td>6.0</td>
<td>6453</td>
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<td>7711</td>
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<td>1803</td>
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<td>3176</td>
<td>1.0</td>
<td>205.0</td>
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<td>169.6</td>
<td>6827</td>
<td>3.0</td>
<td>12402</td>
<td>13073</td>
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The calculation procedure is illustrated in Table 10; the letters in the following text refer to the lines in Table 10, which are indicated in the last column (No. 24) of the table.

Line a specifies the situation at time zero. Because it concerns transplanted rice, the day of transplanting is chosen. Root dry matter after transplanting equals 40 kg ha⁻¹ (Column 10); above ground 100 kg ha⁻¹ is present, which consists entirely of leaf blades (Column 13). The green area, intercepting solar energy for the assimilation process, is calculated from the weight of the leaf blades, assuming a constant ratio between the area and the weight of leaf blades. This ratio is called the specific leaf area, expressed in square meters of green area per kg of dry matter of leaf blades. For rice, its value is 25, thus the area is 2500 m² ha⁻¹. From this, the leaf area index (LAI), i.e. the ratio of leaf area to soil surface area, is calculated. Since one hectare is 10,000 m², the leaf area index at transplanting time equals 0.25 (Column 20).

Line b describes the first full ten days of the growing period. The average daily air temperature during that period is 27.2 °C (Column 1), which when integrated over the period yields a temperature sum of 272 d °C (Column 2). As explained in Section 2.2, the accumulated temperature sum is a measure of the phenological development stage of the crop. For the variety IR8 the required temperature sum for anthesis is 1500 d °C, assuming a base temperature of 0 °C. The development stage (Column 3) is calculated as the ratio of the temperature sum accumulated and the value of 1500 d °C, hence 272/1500 = 0.18.

In Table 9, potential daily gross assimilation, \( F_{a0} \), expressed in CH₁O is given for the middle of each month of the year in kg ha⁻¹ d⁻¹. The value for any ten-day period is obtained by interpolation between the values given in Table 9. For the second ten-day period of November that value is found directly from the table: 336 kg ha⁻¹ d⁻¹. This represents potential gross assimilation, i.e. that realized by a closed green canopy, which intercepts all incoming energy. For a leaf area index of 0.25, only part of the solar energy is

<table>
<thead>
<tr>
<th>LAI</th>
<th>Reduction factor</th>
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<tbody>
<tr>
<td>0.0</td>
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<tr>
<td>0.25</td>
<td>0.18</td>
</tr>
<tr>
<td>0.5</td>
<td>0.33</td>
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<td>0.55</td>
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<td>0.70</td>
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<td>2.0</td>
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<td>0.86</td>
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<td>3.0</td>
<td>0.91</td>
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<td>3.5</td>
<td>0.94</td>
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<td>4.0</td>
<td>0.96</td>
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</tr>
<tr>
<td>5.0</td>
<td>1.0</td>
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</table>
intercepted (Section 2.1), hence the potential as dictated by the environment is not realized. The reduction factor for various values of LAI is given in Table 11, calculated from Equation 5, in Section 2.1. For LAI = 0.25, the reduction factor equals 0.18. In Column 4, the rate of gross assimilation is introduced

\[ \text{GASS} = 336 \times 0.18 = 60.5 \text{ kg ha}^{-1} \text{ d}^{-1} \]

As explained in Section 2.1, part of the energy fixed in the assimilatory process is respired by the crop to maintain the existing structures. For the vegetative material of a rice plant, the relative maintenance respiration rate is assumed to be 0.015 kg CH\textsubscript{2}O per kg dry matter per day during the pre-anthesis phase when, especially in the potential production situation, the nitrogen content of the material is relatively high. Hence, the rate of maintenance respiration expressed in CH\textsubscript{2}O is obtained by multiplying the total live dry matter present (Column 23) by the relative maintenance respiration rate, R\textsubscript{m}:

\[ \text{MRES} = 140 \times 0.015 = 2.1 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 5)} \]

The amount of assimilation products available for increase in dry weight of the crop equals the difference between gross assimilation and maintenance respiration. Thus:

\[ \text{ASAG} = 60.5 - 2.1 = 58.4 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 6)} \]

The conversion of primary assimilation products into structural plant material again entails loss of energy. In the present approach, this growth respiration is represented by its complement, the conversion efficiency, E\textsubscript{c} (Section 2.1). This means that the dry weight increment is equal to the conversion efficiency times the available assimilation products. For vegetative material of average composition E\textsubscript{c} equals 0.7. Thus:

\[ \text{GTW} = 0.7 \times 58.4 = 40.9 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 7)} \]

The total increase in dry matter is utilized concurrently for the growth of various plant parts. In the early stages there is growth of roots, leaf blades and leaf sheaths and stems. The fraction of the increment partitioned to each of the organs is, under potential growth conditions, primarily determined by the phenological state of the crop (Section 2.2). In Table 12, the fractions allocated to each of the organs are given as a function of development stage.

The instantaneous values of the partitioning factors for roots, leaf blades and stems plus leaf sheaths are read from this table through interpolation. The independent variable, i.e. the development stage, is taken as the value halfway between the beginning and the end of the ten-day period. For this period therefore, \((0 + 0.18)/2 = 0.09\).
Table 12. Partitioning factors for dry matter to various plant organs as a function of development stage

<table>
<thead>
<tr>
<th>Development stage</th>
<th>( f_0 )</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
<th>( f_3 )</th>
</tr>
</thead>
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<tr>
<td>0</td>
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<td>0.025</td>
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</tr>
<tr>
<td>0.1</td>
<td>0.325</td>
<td>0.40</td>
<td>0.275</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>0.225</td>
<td>0.425</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>0.3</td>
<td>0.14</td>
<td>0.46</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0.075</td>
<td>0.485</td>
<td>0.44</td>
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</tr>
<tr>
<td>0.5</td>
<td>0.075</td>
<td>0.475</td>
<td>0.45</td>
<td>0</td>
</tr>
<tr>
<td>0.6</td>
<td>0.07</td>
<td>0.42</td>
<td>0.51</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>0.075</td>
<td>0.32</td>
<td>0.61</td>
<td>0</td>
</tr>
<tr>
<td>0.8</td>
<td>0.055</td>
<td>0.21</td>
<td>0.735</td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>0.04</td>
<td>0.1</td>
<td>0.36</td>
<td>0.5</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
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<td>2.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

In Column 8, the fraction allocated to the root is introduced, which is equal to 0.35. Thus the rate of increase in root dry weight is:

\[
\text{GRT} = 0.35 \times 40.9 = 14.3 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 9)}
\]

The weight of the root system at the end of the period is obtained by adding the rate of increase from Column 9 multiplied by the length of the time interval to the weight at the end of the preceding ten – day period (Line a, Column 10). Thus:

\[
\text{WRT} = 40 + 14.3 \times 10 = 183 \text{ kg ha}^{-1} \text{ (Column 10)}
\]

The fraction of the dry weight increment allocated to the leaf blades is again obtained from Table 12 at development stage 0.09, which equals 0.395. The rate of increase in dry weight of the leaf blades is calculated as:

\[
\text{GLV} = 0.395 \times 40.9 = 16.2 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 12)}
\]

The weight of the leaf blades at the end of the ten – day period is obtained by adding the rate of increase times \( \Delta t \) to the value at the beginning of the ten – day period (Line a, Column 13). Hence,

\[
\text{WLV} = 100 + 16.2 \times 10 = 262 \text{ kg ha}^{-1} \text{ (Column 13)}
\]

The remainder of the above ground vegetative material is designated ‘stems’ in the present approach. It consists not only of the true stems, but contains also the leaf sheaths and the ear structures other than the seed. For the present
ten-day period the fraction of the increment allocated to the stem is obtained from Table 12 at development stage 0.09, which equals 0.255. The rate of increase in stem dry weight is equal to that fraction multiplied by the rate of total dry matter increase:

$$\text{GST} = 0.255 \times 40.9 = 10.4 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 15)}$$

The weight of the stem at the end of the ten-day period follows from the addition of the rate of increase times the length of the time interval to the weight at the end of the preceding ten-day period (Line a, Column 16):

$$\text{WST} = 0 + 10.4 \times 10 = 104 \text{ kg ha}^{-1} \text{ (Column 16)}$$

During this ten-day period, the crop is still in its vegetative phase, hence the fraction allocated to the grain is zero (Column 17). Therefore the values in Columns 18 and 19 also remain zero.

The leaf area index at the end of the ten-day period is obtained from the dry weight of the leaf blades (Column 13) by multiplying with the specific leaf area of 25 and taking into account the surface area:

$$\text{LAI} = 262 \times 25 \times 10^{-4} = 0.65 \text{ m}^2 \text{ m}^{-2} \text{ (Column 20)}$$

At the end of all calculations for the ten-day period, three auxiliary variables are calculated that are helpful for comparison with measured data. In Column 21, total above ground dry weight is introduced, which is the sum of the weight of leaf blades (Column 13), stems (Column 16) and grains (Column 19). Thus:

$$\text{TADW} = 262 + 104 + 0 = 366 \text{ kg ha}^{-1}$$

The total dry weight of the vegetation (Column 22) is equal to the above-ground dry weight, plus the weight of the root system (Column 10):

$$\text{TDW} = 262 + 104 + 0 + 183 = 549 \text{ kg ha}^{-1}$$

The total dry weight of live material (TDW/L, Column 23) that is subject to maintenance respiration is equal to the total dry weight, because no dead material is present as yet. With this calculation, the treatment of the first ten-day period is finalized and the calculations can be repeated for the next ten-day period.

The conditions are not basically different for that period (Line c) from those in the previous one, therefore the line will be described in less detail. Line c refers to the last ten-day period of November. The average air temperature then is 26.3°C (Column 1). The accumulated temperature sum for
the crop at the end of the period is obtained by adding the 263 d °C for this
ten-day period to the value accumulated up till the beginning of the period
(Column 2, Line b). Therefore the value in Column 2, Line c, equals:

\[ \text{TSUM} = 272 + 263 = 535 \text{ d °C} \]

The corresponding value of the development stage is found by dividing the
value in Column 2 by 1500 d °C, the required temperature sum for anthesis of
this variety:

\[ \text{DVS} = \frac{535}{1500} = 0.36 \text{ (Column 3)} \]

The value of potential gross assimilation for the last ten-day period of No
vember is obtained by interpolation in Table 9:

\[ \text{GRA} = 336 + \frac{1}{3} \times (283 - 336) = 318 \text{ kg ha}^{-1} \text{ d}^{-1} \]

The first and second value within the brackets are for the middle of December
and the middle of November, respectively. To account for the influence of
incomplete light interception, due to the low leaf area index, potential assimila-
tion must be multiplied by the reduction factor from Table 11 for an LAI = 0.65:

\[ 0.33 + (0.15/0.5) \times (0.55 - 0.33) = 0.40 \]

In Column 4, therefore, the rate of gross assimilation is introduced as:

\[ \text{GASS} = 318 \times 0.40 = 127.2 \text{ kg ha}^{-1} \text{ d}^{-1} \]

Maintenance respiration for the period is calculated from the total live plant
dry weight at the beginning (Column 23) and the relative maintenance respira-
tion rate, 0.015 kg CH_2O per kg dry weight per day:

\[ \text{MRES} = 549 \times 0.015 = 8.2 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 5)} \]

Carbohydrates available for increase in structural dry weight of the vegetati-
on are equal to:

\[ \text{ASAG} = 127.2 - 8.2 = 119.0 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 6)} \]

From this, the total rate of increase in dry weight is calculated, taking in
account the conversion efficiency:

\[ \text{GTW} = 119.0 \times 0.7 = 83.3 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 7)} \]
The partitioning factors for the various plant organs are obtained from Table 12, at the appropriate value of the development stage:

\[ DVS = 0.18 + 0.5 \times (0.36 - 0.18) = 0.27 \]

Thus:

- FR = 0.165 (Column 8)
- FL = 0.445 (Column 11)
- FS = 0.39 (Column 14)
- FG = 0. (Column 17)

The rate of increase in root dry weight is calculated by multiplying the increase in total dry weight by the partitioning factor:

\[ GRT = 0.165 \times 83.3 = 13.7 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 9)} \]

and the total root weight at the end of the ten-day period equals:

\[ \text{WRT} = 183 + 13.7 \times 10 = 320 \text{ kg ha}^{-1} \text{ (Column 10)} \]

The rate of increase in leaf dry weight is obtained by multiplying FL and DMI, hence:

\[ GLV = 0.445 \times 83.3 = 37.1 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 12)} \]

and the dry weight at the end of the period follows from addition of the increment to that present already:

\[ \text{WLV} = 262 + 37.1 \times 10 = 633 \text{ kg ha}^{-1} \text{ (Column 13)} \]

The rate of increase in stem dry weight is calculated from total increase in dry weight and the fraction partitioned to the stem:

\[ GST = 0.39 \times 83.3 = 32.5 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 15)} \]

Total stem weight at the end of the ten-day period equals:

\[ \text{WST} = 104 + 32.5 \times 10 = 429 \text{ kg ha}^{-1} \text{ (Column 16)} \]

The leaf area index at the end of the ten-day period follows from the dry weight of the leaf blades:

\[ \text{LAI} = 633 \times 25 \times 10^{-4} = 1.6 \text{ m}^2 \text{ m}^{-2} \text{ (Column 20)} \]
Total above – ground dry weight at the end of this ten – day period equals:

\[
TADW = 633 + 429 + 0 = 1062 \text{ kg ha}^{-1} \text{ (Column 21)}
\]

The total dry weight of the vegetation is:

\[
TDW = 633 + 429 + 0 + 320 = 1382 \text{ kg ha}^{-1} \text{ (Column 22)}
\]

which is all live material, hence:

\[
TDWL = 1382 \text{ kg ha}^{-1} \text{ (Column 23)}
\]

The calculations for the Lines d, e and f follow exactly the same pattern as the preceding ones; they are therefore not treated here. Line g refers to the first ten – day period of January.

---

Exercise 17

Calculate the following variables by hand for the third period of 10 days (1-10 December, line d of Table 10):
Tsum, DVS, MRES, ASAG, GTW, F1, GLV, WLV and LAI.

---

2.4.3 Comparison with measurements

In Figure 19, the calculated time course of dry matter production is compared to the measured data and a very satisfactory agreement between both is evident. The measured grain yield (at 12% moisture content) was 7.5 t ha\(^{-1}\), which again is close enough to the calculated value of 7.7 t ha\(^{-1}\) (6827 x 1.12).

The calculation procedure, outlined in the preceding Subsection was also applied to a set of data from IRRI, Los Baños. In a maximum annual production trial, rice was grown year – round, three different cultivars being used (Yoshida et al., 1972). The first one was IR8, for which parameters identical
Figure 19. Comparison of measured and calculated above-ground dry-matter accumulation for bunded rice grown in Paramaribo, Suriname.

Figure 20. Measured and calculated grain yields for bunded rice transplanted on different dates at IRRI, Los Banos, the Philippines.
to those of the preceding section were used. The other two were the early maturing cultivars, 1R-747-B2 and 1R-667-98, respectively. For these varieties, the required temperature sum from transplanting to anthesis was set at 1100 d °C, i.e. a development rate of 0.0182 d⁻¹ at a temperature of 20 °C.

The results of the calculations are presented in Figure 20, along with the measured data. The figure shows that the pattern of grain yield with time of transplanting is identical for the measured and the calculated data, but that the calculations are consistently of a higher level. It would seem, therefore, that in the experiments the potential, dictated by weather conditions was not fully reached. Reasons for the discrepancy can only be speculated upon, but nitrogen application of 125 — 150 kg N ha⁻¹, more than two — thirds of which applied as a basal dressing seems hardly sufficient for yields of over 6000 kg ha⁻¹ (Section 4.1). It would seem, therefore, that the conclusion reached by the authors that a maximum annual yield of over 28000 kg ha⁻¹ is possible, is valid. The more so, if it is considered that the year 1971 was unfavourable in terms of radiation as is shown in Figure 20 by the result calculated with long — term average radiation data.

In Figure 21, the measured and calculated growth curves are shown for a

![Figure 21: Measured and calculated above-ground dry-matter accumulation for spring wheat, grown in Israel.](image-url)
spring wheat crop grown in the Central Negev Desert in Israel under irrigation (Hochman, 1982). The variety Lachish used in this experiment requires a temperature sum of 1500 d °C from emergence to anthesis and 850 d °C from anthesis to maturity, both at a base temperature of 0 °C. The partitioning functions used in the model are given in Section 3.4, where the same experiment is used to illustrate the effect of water shortage on production.

These examples show that potential yield and production may be estimated with reasonable accuracy on the basis of crop characteristics and weather conditions.

Exercise 18
Calculate the grain yield for the rice variety IR8, transplanted in Los Baños on January 20. Use the basic data given in Table 13. Assume for each month three ten-day periods as in Table 10. The values for $F_p$ are averages for the month and are not, as in Table 9, applicable to the middle of the month.

<p>| Table 13. Basic data for Exercise 12. $F_a$ and $F_w$ expressed in CO₂, $F_p$ expressed in CH₄O, Los Baños, Philippines, 14° N. |
|---------------------------------|--------|--------|--------|--------|--------|--------|</p>
<table>
<thead>
<tr>
<th>Month</th>
<th>$H_a$ (MJ m⁻² d⁻¹)</th>
<th>$T_a$ (°C)</th>
<th>$H_w$ (MJ m⁻² d⁻¹)</th>
<th>$f_a$ (kg ha⁻¹ d⁻¹)</th>
<th>$F_a$ (kg ha⁻¹)</th>
<th>$F_w$ (kg ha⁻¹)</th>
<th>$F_p$ (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>14.07</td>
<td>23.4</td>
<td>22.60</td>
<td>0.47</td>
<td>616</td>
<td>252</td>
<td>303</td>
</tr>
<tr>
<td>F</td>
<td>18.31</td>
<td>24.5</td>
<td>25.11</td>
<td>0.34</td>
<td>674</td>
<td>281</td>
<td>368</td>
</tr>
<tr>
<td>M</td>
<td>20.03</td>
<td>24.8</td>
<td>28.55</td>
<td>0.37</td>
<td>734</td>
<td>311</td>
<td>393</td>
</tr>
<tr>
<td>A</td>
<td>23.81</td>
<td>25.3</td>
<td>30.82</td>
<td>0.28</td>
<td>781</td>
<td>334</td>
<td>447</td>
</tr>
<tr>
<td>M</td>
<td>21.00</td>
<td>27.0</td>
<td>31.55</td>
<td>0.42</td>
<td>800</td>
<td>342</td>
<td>414</td>
</tr>
<tr>
<td>J</td>
<td>18.48</td>
<td>26.0</td>
<td>31.58</td>
<td>0.52</td>
<td>804</td>
<td>342</td>
<td>385</td>
</tr>
<tr>
<td>J</td>
<td>16.80</td>
<td>26.0</td>
<td>31.60</td>
<td>0.59</td>
<td>803</td>
<td>343</td>
<td>363</td>
</tr>
<tr>
<td>A</td>
<td>15.70</td>
<td>25.5</td>
<td>31.28</td>
<td>0.62</td>
<td>791</td>
<td>339</td>
<td>348</td>
</tr>
<tr>
<td>S</td>
<td>15.96</td>
<td>25.9</td>
<td>29.69</td>
<td>0.58</td>
<td>757</td>
<td>323</td>
<td>344</td>
</tr>
<tr>
<td>O</td>
<td>15.16</td>
<td>25.9</td>
<td>26.73</td>
<td>0.54</td>
<td>698</td>
<td>293</td>
<td>327</td>
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<tr>
<td>N</td>
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<td>25.3</td>
<td>23.46</td>
<td>0.54</td>
<td>633</td>
<td>261</td>
<td>295</td>
</tr>
<tr>
<td>D</td>
<td>12.31</td>
<td>24.2</td>
<td>21.78</td>
<td>0.54</td>
<td>600</td>
<td>244</td>
<td>278</td>
</tr>
</tbody>
</table>
TITLE DRY MATTER PRODUCTION

*Calculations and data entirely based on:
*In: Modelling of agricultural production: weather, soils and crops.
*Keulena, H. van & J. Wolf (eds.), Simulation Monographs, Pudoc,
*Wageningen, the Netherlands, 479 pp.

*Each line is explained in the text (chapter 2.4) and in table 10, page 50.

INITIAL

* initial constants of table 10.
INCON DATEI = 314., TSUMI = 0.
INCON WRTI = 40., WLVI = 100., WSTI = 0., WGRI = 0.

DYNAMIC

* column 1, temperature as a function of the daynumber
   TEMP = AFGEN (TEMPT, DATE)
* column 2, temperature sum (C.d)
   TSUM = INTGRI (TUMI, TEMP)
* column 3, development stage of vegetative (V) and generative (G) phase
   DVS = DVSV + DVSQ
   DVSV = AMIN1 (TUMI/1500., 1.)
   DVSQ = AMAX1 (0., (TUMI-1500.)/800.)
* column 4, gross assimilation rate (kg CH2O.ha-1.d-1)
   GASS = GRA * FH
   GRA = AFGEN (GRAT, DATE)
   FH = AFGEN (FHT, LAI)
* column 5, maintenance respiration (kg CH2O.ha-1.d-1)
   MRES = TDWL * RM
   RM = AFGEN (RTM, DVS)
* column 6, available assimilates for growth (kg CH2O.ha-1.d-1)
   ASAG = AMAX1 (0., GASS-MRES)
* column 7, growth rate of total dry weight (kg dry matter.ha-1.d-1)
   GTW = ASAG * EG
   EG = AFGEN (EGT, DVS)
* column 8, partitioning factor for roots
   FR = AFGEN (FRT, DVS)
* column 9, growth rate of roots (kg dry matter.ha-1.d-1)
   GRT = FR * GTW
* column 10, weight of roots
   WRT = INTGRI (WRTI, GRT)
* column 11, partitioning factor for leaves
   FL = AFGEN (FLT, DVS)
* column 12, growth rate of leaves
   GLV = FL * GTW - RLD * WL
   RLD = AFGEN (RLD, DVS)
* column 13, weight of leaves
   WL = INTGRI (WLVI, GLV)
* column 14, partitioning factor for stem
   FS = AFGEN (FST, DVS)
* column 15, growth rate of stem
   GST = FS * GTW
* column 16, weight of stem
   WST = INTGRI (WSTI, GST)
* column 17, partitioning factor for grain
   FG = AFGEN (FGT, DVS)
* column 18, growth rate of grain
   GGR = FG * GTW
* column 19, weight of grain
   WGR = INTGRI (WGRI, GGR)
*column 20, leaf area index (ha leaf ha-1 ground)
LAI = WLV * SLA
PARAM SLA = 0.0025
*column 21, total above dry weight (kg dry matter ha-1)
TADW = WLV + WST + WGR
*column 23, total dry weight of live material
TDWL = WLV + WST + WGR + WRT

*functions derived from tables 9-12
*table 9
FUNCTION GRAT = 0, 310, 15, 332, 46, 344, 74, 368, ...
105, 364, 135, 354, 165, 378, 196, 417, ...
227, 454, 319, 336, 349, 283, 365, 308.
*table 10
FUNCTION TEMPT = 0, 26.0, 313, 26.0, 314, 27.2, 323, 27.2, ...
324, 26.3, 334, 26.3, 335, 25.8, 343, 25.8, ...
*table 11
FUNCTION FHT = 0.0, 0.00, 0.25, 0.18, 0.5, 0.33, 1.0, 0.55, 1.5, 0.70, ...
2.0, 0.80, 2.5, 0.86, 3.0, 0.91, 3.5, 0.94, 4.0, 0.96, ...
4.5, 0.98, 5.0, 1.00, 6.0, 1.00
*table 12
FUNCTION FRT = 0.0, 0.600, 0.1, 0.325, 0.2, 0.225, 0.3, 0.140, ...
0.4, 0.075, 0.5, 0.075, 0.6, 0.070, 0.7, 0.070, ...
0.8, 0.055, 0.9, 0.040, 1.0, 0.000, 2.0, 0.000
FUNCTION FLT = 0.0, 0.375, 0.1, 0.400, 0.2, 0.425, 0.3, 0.460, ...
0.4, 0.485, 0.5, 0.475, 0.6, 0.420, 0.7, 0.320, ...
0.8, 0.210, 0.9, 0.100, 1.0, 0.000, 2.0, 0.000
FUNCTION FST = 0.0, 0.025, 0.1, 0.275, 0.2, 0.350, 0.3, 0.400, ...
0.4, 0.440, 0.5, 0.450, 0.6, 0.510, 0.7, 0.610, ...
0.8, 0.735, 0.9, 0.360, 1.0, 0.000, 2.0, 0.000
FUNCTION FGT = 0.0, 0.000, 0.1, 0.000, 0.2, 0.000, 0.3, 0.000, ...
0.4, 0.000, 0.5, 0.000, 0.6, 0.000, 0.7, 0.000, ...
0.8, 0.000, 0.9, 0.500, 1.0, 1.000, 2.0, 1.000
*relative maintenance rate (table 4)
FUNCTION RMT = 0, 0.015, 0.99, 0.015, 1, 0.01, 2, 0.01
*conversion efficiency (table 4)
FUNCTION EGT = 0, 0.7, 0.99, 0.7, 1, 0.8, 2, 0.8
*relative leaf death rate
FUNCTION RLDT = 0, 0, 0.99, 0, 1, 0.02, 2, 0.02

DATE = AMOD (DATE + TIME + 364, 365.) + 1.
TIMER FINTIM = 100, DELT = 1, PRDEL = 10.
FINISH DVS = 2.
METHOD RECT
PRINT DATE, DVS, WGR, WLV

END
STOP
ENDJOB
LIST OF ABBREVIATIONS

ASAG = Assimilates available for growth. kg CH2O.ha-1.d-1
DATE(I) = Date in julian daynumber (Initial) -
GTW = Growth of total dry weight kg DM.ha-1.d-1
DVS = Development stage -
DVSG = Development stage of generative phase -
DVSV = Development stage of vegetative phase -
EG = Conversion (growth) efficiency kg DM.kg-1 CH2O
FH = Fraction light intercepted -
FG = Fraction of dry weight increment allocated to the grains -
FL = idem, to leaf blades -
FR = idem, to roots -
FS = idem, to stems -
GASS = Actual gross assimilation rate kg CH2O.ha-1.d-1
GRA(T) = Potential gross assimilation (Table) kg CH2O.ha-1.d-1
GGR = Growth rate of grain (dry matter) kg DM.ha-1.d-1
GLV = Growth rate of leaves (" ) kg DM.ha-1.d-1
GRT = Growth rate of roots (" ) kg DM.ha-1.d-1
GST = Growth rate of stem (" ) kg DM.ha-1.d-1
LAI = Leaf area index ha leaf.ha ground-1
MRES = Maintenance respiration rate kg CH2O.ha-1.d-1
RLD(T) = Relative leaf death (Table) kg DM.kg DM-1.d-1
RM(T) = Relative maintenance rate (Table) kg CH2O.kg DM-1.d-1
SLA = Specific leaf area ha leaf.kg DM leaf-1
TSUM(I) = Temperature sum (Initial) °C.d
TEMP(T) = Daily temperature (Table) °C
TADW = Total above dry weight kg DM.ha-1
TDW = Total dry weight kg DM.ha-1
TDWL = Total dry weight of living material kg DM.ha-1
WGR(I) = Weight of grain (Initial) kg DM.ha-1
MLV(I) = Weight of leaves (Initial) kg DM.ha-1
WRT(I) = Weight of roots (Initial) kg DM.ha-1
WST(I) = Weight of stems (Initial) kg DM.ha-1
3. CROP PRODUCTION AS DETERMINED BY WATER AVAILABILITY.

A closed crop evaporates almost as much water as a free water surface. This means an evaporation of 4 mm or 40,000 litres ha$^{-1}$ day$^{-1}$ for a nice day in summer-time in the Netherlands. The demand for water thus is very large.

If the water supply from the soil is too small to compensate the loss by evaporation this demand for water is not met. To limit the water use the plant then closes its stomata. This results, however, in a limited CO$_2$-absorption as a result of which the assimilation declines. That is why the growth rate at water shortage is smaller than the potential growth rate.

In this chapter we will discuss the factors, that determine the transpiration and with that also determine the water use and the growth. We will also derive to what extent the growth rate is reduced by water shortage.

![Diagram](image)

**Fig. 1.** Cross section of a leaf nearby a stoma.

3.1. **Relation between transpiration and assimilation**

**An equation for the transpiration rate**

Transpiration (evaporation) is a process of diffusion of vapour from the leaf through the stomata to the open air (fig. 1.). The rate of a diffusion process can be written, according to Ohm's law, as

$$\text{diffusion rate} = \frac{\text{difference in concentration}}{\text{resistance}}$$
The transpiration rate $T$ is then represented as

$$ T = \frac{H_2O_{\text{int}} - H_2O_{\text{ext}}}{r_s + r_b} $$

In this formula $H_2O_{\text{int}}$ is the concentration of vapour inside the leaf in the stomatal cavity. The air in the stomatal cavity is saturated with vapour, because the cells, that surround the stomatal cavity are covered with a small water-film. That is why the vapour concentration in the stomatal cavities is the maximum possible at the given leaf temperature.

$H_2O_{\text{ext}}$ is the vapour concentration in the open air. The open air generally is not saturated with vapour, so that a difference in concentration exists, that results in vapour diffusion from the leaf to the open air. The drier the open air, the larger the difference in concentration, so the quicker the diffusion takes place and the larger the transpiration is.

![Diagram](image)

**Fig. 2.** The amount of vapour per m$^3$ air in air, saturated with vapour, increases if the temperature rises. The ratio between the actual vapour concentration $H_2O_{\text{act}}$ and that in air saturated with vapour $H_2O_{\text{sat}}$ reflects the relative air humidity and changes with the temperature.

The air can contain more vapour at a higher temperature (fig. 2.). If the temperature rises at a certain vapour concentration in the air $H_2O_{\text{act}}$, the difference with the maximum possible vapour concentration $H_2O_{\text{sat}}$ is going to be
higher in saturated air (fig. 2). The relative air humidity $\frac{H_2O_{act}}{H_2O_{sat}}$ then falls. This happens, for instance, at the middle of the day, when the air temperature rises as a consequence of a higher radiation. Because the air in the stomatal cavities stays saturated with vapour, the difference in vapour concentration between stomatal cavity and the air outside increases, so that the transpiration rate also increases.

During its way to get out of the leaf the vapour has to pass two resistances (fig. 1.): the stomatal resistance ($r_{stomata}$) and a boundary layer resistance ("boundary layer"). The boundary layer consists of a small layer of stagnating air of about 1 mm thickness, that, so to speak, is stuck to the leaf area. Air of this thin layer of a relatively high vapour concentration, is more quickly replaced by drier air at a higher windspeed (compare this with the drying of laundry). The resistance $r_b$ of the boundary layer thus diminishes at a higher windspeed, so that the transpiration generally increases.

The further the stomata are open, the smaller their resistance against evaporation is, so the higher the transpiration rate is.

The transpiration rate is expressed in $g \, H_2O \, cm^{-2} \, leaf \, area \, s^{-1}$ and the vapour concentration in $g \, H_2O \, cm^{-3}$. From the transpiration rate formula we can deduce then that the resistances have the dimension $s \, cm^{-1}$.

![Graph showing moisture in soil and transpiration over time]

**Fig. 3.** The influence of drying of the soil on the transpiration and the assimilation of young trees of the walnut species Carya illinoinensis. Transpiration and assimilation of the plants, subjected to drying, are expressed as percentage of that of the control group, optimally supplied with water.
Influence of the opening of the stomata

The degree of opening of the stomata is adjustable. In case of water shortage the plant closes its stomata to limit the water use. In that case it is not possible that vapour molecules diffuse out, but it also is not possible that $\text{CO}_2$ enters. During water shortage not only the transpiration decreases, but also the assimilation and with that the growth.

This is illustrated in fig. 3 with young trees of an American walnut species. The trees were grown in pots. A part of the pots, the control group, was optimally supplied with water. The other pots did not get any water from September 7 till the wilting point of the trees was reached on September 23, after which water was supplied again. It is shown that the transpiration as well as the assimilation decrease to practically zero at the wilting point, as the soil in the pots dries out more and more. If the pots are supplied with water again the transpiration and the assimilation recover theirselves at the old level. The decrease of transpiration and assimilation during water shortage is caused by the further closing of the stomata till they are almost totally closed at the wilting point. After elimination of the water shortage the stomata open again.

A comparison to calculate the assimilation rate

It was shown that the assimilation rate decreases proportionally to transpiration rate, as the stomata close. This suggests that the assimilation rate $A$, analogue to the transpiration rate, can be written as

$$A = \frac{\text{CO}_2 \text{ ext} - \text{CO}_2 \text{ int}}{r_b^1 + r_s^1 + r_m^1 + r_x^1}$$

in which $\text{CO}_2 \text{ ext}$ is the $\text{CO}_2$-concentration in the open air and $\text{CO}_2 \text{ int}$ the $\text{CO}_2$-concentration of the chloroplasts in the plants. In the chloroplasts the $\text{CO}_2$ is combined and processed in the photosynthesis, so that the $\text{CO}_2$-concentration there is lower than the concentration (about 340 ppm) in the open air. The difference in concentration results in a $\text{CO}_2$-transport into the leaf.

The resistances, that have to be passed during this transportation, consists of: the boundary layer of the leaf ($r_b^1$), the stomata ($r_{\text{stomata}}^1$), the way from the stomatal cavity through the intercellular spaces to the cell area and from there, dissolved in the cellular moisture, to the chloroplasts ($r_{\text{mesophyll transportation}}^1$), and the carboxylation, this is $\text{CO}_2$ combined to enzymes ($r_{\text{carboxylation}}^1$). It appears from table 2.1. that the rate, with which $\text{CO}_2$ is combined enzymatically is the limiting factor when the stomata of $C_3$ species are open. The stomatal resistance is limiting, when the stomata close.
Table 1. The order of magnitude of the resistances $r$ and $r^{-1}$ for vapour transportation and $CO_2$-transportation respectively both in $s.cm^{-1}$. The diffusion resistances for $CO_2$ are about 1,5 x those for water vapoour.

<table>
<thead>
<tr>
<th></th>
<th>$r(H_2O)$</th>
<th>$r^{-1}(CO_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary layer</td>
<td>0,15</td>
<td>0,20</td>
</tr>
<tr>
<td>Stomata (open)</td>
<td>1,00</td>
<td>1,60</td>
</tr>
<tr>
<td>Stomata (closed)</td>
<td>40-200</td>
<td>60-300</td>
</tr>
<tr>
<td>Mesophyl transport</td>
<td>-</td>
<td>0-10</td>
</tr>
<tr>
<td>Carboxylation ($C_3$-spp)</td>
<td>-</td>
<td>3,20</td>
</tr>
<tr>
<td>Carboxylation ($C_4$-spp)</td>
<td>-</td>
<td>0,90</td>
</tr>
</tbody>
</table>

The above mentioned formula for the assimilation rate can be used when the photosynthesis is limited by the rate with which $CO_2$ is supplied. This is the case at high light intensities and if the stomata are (partly) closed. The factor light is limiting at low light intensities, particularly for $C_4$-species and that is why it is then not allowed to use this formula.

**Response of stomata to external conditions**

The opening situation of the stomata always implies a compromise between limiting the water use by keeping them closed as much as possible on the one hand and letting in $CO_2$ as much as possible by opening them as far as possible on the other. This compromise continually changes with the circumstances. Different species also have different strategies.

Almost all species close their stomata at night. Photosynthesis does not take place in the dark, so that no $CO_2$ is required. The stomata then are closed, which limits the water use.

The photosynthesis rate increases with the light intensity so that more $CO_2$ is needed at a higher light intensity. A number of species, like field bean and perennial rye-grass, regulate their stomatal opening in dependency of the light intensity: the higher the light intensity, the further the stomata are open (smaller $r_s$). The water use per kg dry matter produced of such species is smaller than the water use of species, that open their stomata very wide in day-time independently of the light intensity. A more direct regulation of the stomatal opening is obtained by a direct dependence of the degree of opening on the
CO₂-concentration in the stomatal cavity. If the photosynthesis decreases by, for instance, a lower light intensity or by N-shortage, less CO₂ has to be absorbed and the stomata can be closed more, which limits the water use. This stomatal behaviour is found at most C₄-species, but also for beans of the species Phaseolus.

Many species have built in an extra safety-valve against too high transpiration. If the relative air humidity gets below a certain minimum value, at which the transpiration would become very large, then they close their stomata.

**The relation between transpiration and assimilation rate**

Transpiration as well as assimilation is very dependent on all kinds of environmental conditions. Most environmental conditions influence both almost equally strong. Consequently it appears that their relation stays constant during a series of environmental circumstances.

The stomatal resistance is the limiting factor to both processes of water shortage. The corresponding influence of water shortage on transpiration and assimilation was found experimentally, but follows also from the analogy of the earlier given formulas.

![Graph](image)

**Fig. 4.** Influence of radiation intensity on the transpiration $Y_{pot}$, the growth rate $P_{pot}$ and on their ratio in a crop, well supplied with water and nutrients.

The transpiration of a crop, well supplied with water and nutrients is proportional to the radiation intensity. In the temperate climates of such crops is almost proportional to the light intensity, hence
also to the radiation intensity. The radiation intensity then does not influence the ratio between transpiration and assimilation. In tropical and subtropical zones, and particularly in arid zones, the radiation is high and light saturation of crop assimilation takes place. Because the potential transpiration stays proportional to the radiation intensity, the relation between transpiration and assimilation then increases at increasing radiation.

**Transpiration coefficient**

The growth rate is closely related to the assimilation rate. As a consequence the relation between transpiration rate and growth rate is about constant in the temperate zones (fig. 4.). A deviation takes place at low light intensities, because the growth rate becomes negative as a consequence of the relatively high maintenance respiration. The relation tends to increase proportionally with the transpiration at a high radiation like in arid and semi-arid zones.

The relation between transpiration rate and growth rate is called the transpiration coefficient. The transpiration coefficient reflects the number of kg $H_2O$ transpired per kg dry matter produced. The transpiration coefficient for a large set of environmental conditions stays constant with in a plant species. Between species, however, large differences come about related to the efficiency of their assimilation and with their stomatal reaction. The $C_4$-species, assimilating efficiently, have a lower transpiration coefficient than the $C_3$-species. They make a more efficient use of the available water. Also the species with stomata that react on light intensity or on the internal $CO_2$-concentration, deal more efficiently with the water, so that those species also have a lower transpiration coefficient.

3.2. **How strongly is growth reduced by water shortage?**

The assimilation rate of a green, closed crop, that is optimally supplied with water and nutrients is deduced from the available amount of light. We obtain the potential growth rate by taking into account the respiration. The growth rate will be smaller than the potential growth rate at water shortage. Now we will deduce how strong the reduction of the growth rate is as a function of the degree of water shortage.
Reduction factor

The ratio between transpiration rate $T$ and growth rate $P$, the transpiration coefficient, stays constant for a large range of light intensities in a crop that is well supplied with water and nutrients (fig. 4.). This ratio also hardly changes under water shortage, because transpiration and assimilation are reduced to about the same degree by the closure of the stomata. Consequently we are able to relate the actual situation with water shortage to the potential situation in an optimal environment through the formula

$$\frac{T_{pot}}{P_{pot}} = \frac{T_{act}}{P_{act}}$$

The ratio between the actual and potential growth rate is then reflected with the formula

$$P_{act} = \frac{T_{act}}{T_{pot}} \cdot P_{pot}$$

![Graph showing spectral distribution of global radiation, dispersed by a leaf, and terrestrial temperatures.](Image)

Fig. 5. Spectral distribution of the global radiation, the global radiation dispersed by a leaf (dispersal = reflection + transmission) and the thermal radiation, radiated from terrestrial surfaces.
The term $\frac{T_{act}}{T_{pot}}$ then is a reduction factor, that reflects to what extent the growth rate is reduced with respect to the growth rate of an optimum water supply.

First we will discuss the factors, that determine the potential transpiration. After that we will consider the influence of water availability on uptake and transpiration.

3.2.1. Potential transpiration

Available radiation energy

About 50% of the solar global radiation is in the visible area (wave-length 400–700 nm) and about 50% is in the near-infra-red area (wave-length 700–3000 nm; fig. 5.). Evaporation requires energy. The radiation energy in the visible— as well as that in the near-infra-red can be used for evaporation. Only the radiation in the visible area, the visible light, on the other hand can be used for the photosynthesis.

Of the visible radiation falling on a leaf, 10% is reflected (reflection), 10% is transmitted (transmission) and 80% is absorbed. From the radiation in the near-infra-red on the other hand 40% is reflected, 40% is transmitted and only 20% is absorbed (fig. 5.). The consequence is that 25% of the total global radiation, falling on a crop, is reflected. The remaining 75% is absorbed by a closed crop.

A crop radiates heat, just like all other surfaces. This is long-waved radiation in the far-infra-red (wave-length 3000 nm) (fig. 5.). As a result there is an upward flux of long-wave radiation during 24 hours a day. The sky provides also thermal radiation, but less. The net flux from the crop is larger in clear weather than in cloudy weather (table 2.). Under a clear sky, it cools down faster than under a clouded sky.
Table 2. Radiation data for a very clear and a cloudy day in the Netherlands in summer.

<table>
<thead>
<tr>
<th>Clear \x10^6 J m^-2 day^-1</th>
<th>Cloudy \x10^6 J m^-2 day^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total global radiation</td>
<td>30</td>
</tr>
<tr>
<td>Absorbed by the crop (75%)</td>
<td>22.5</td>
</tr>
<tr>
<td>Loss of heat by thermal radiation</td>
<td>8.6</td>
</tr>
<tr>
<td>Net radiation</td>
<td>13.9</td>
</tr>
</tbody>
</table>

The difference between the downward energy flux and the upward energy flux is called net radiation. This net radiation reflects the radiation energy, absorbed by a closed crop (table 1:2).

Where does this absorbed energy go to?

No energy gets lost, so the crop has to use the energy again one way or another.

The energy transfer, realized by evaporation, is called "latent" (hidden) loss of heat. This in contrast with the "sensible" loss of heat, that takes place because the leaf warms up by absorbing radiation. As a result of the difference in temperature, heat flows from the leaf to the surrounding air (sensible heat). This transfer of heat takes place by conduction (convection). Finally, some light energy is converted into chemical energy during photosynthesis.

This balance between absorption and transfer and use of energy can be represented by the equation

\[ R_n = E + C + F \]

in which \( R_n \) reflects the absorbed net radiation, \( E \) the latent loss of heat, \( C \) the convection term, that reflects the sensible heat loss and \( F \) the energy absorbed during photosynthesis.

A closed crop only uses about 5% of the net radiation for photosynthesis. Leaf temperature and air temperature differ little, so that the convection term also is negligible small. Particularly when the stomata are open almost all energy is used for evaporation of water.
Potential transpiration

To evaporate 1 kg water \(2.5 \times 10^6\) J is required. Suppose that all net radiation is used for evaporation. During a very clear day with a net radiation of \(13.9 \times 10^6\) J m\(^{-2}\), 5.6 kg H\(_2\)O m\(^{-2}\) evaporates. For H\(_2\)O, 1 kg = 1 litre = 1 dm\(^3\), so that 1 mm = 1 litre m\(^{-2}\). So the evaporation of such a clear day amounts to 5.6 mm. From table 5.2, we conclude in a similar way the evaporation of a cloudy day as 1.5 mm day\(^{-1}\). On an average the evaporation during summer in the Netherlands amounts to 3 mm day\(^{-1}\).

32.2. Actual transpiration

Drying of the soil

As the soil dries out further, the power with which water is held in the soil, increases. We say that the suction tension of the soil increases. Then it becomes harder for the plant to take water from the soil, so that water shortage appears in the plant and the stomata close partially. The actual transpiration of the crop then becomes smaller than the potential transpiration.

To be able to calculate the actual transpiration we have to know how much water is available to the plant and to what extent transpiration is reduced by the increase of the suction tension of soil.

Available soil moisture

The quantity of soil moisture that can be absorbed, consists of

a) the amount of moisture, available in the rooted area and

b) the amount of moisture, that becomes available to the crop through capillary supply from the layers beneath the rooted area.

If these bottom layers are in contact with ground water, then

c) moisture can be absorbed from the ground water.

The quantity that can be absorbed, is drawn upon by

a) evaporation by the crop (transpiration) and by the soil (evaporation) and

b) the drainage water under the influence of gravity to deeper layers, not in the reach of the plant roots.

Now we will start with a soil, where the available moisture is depleted by evaporation and is replenished only by precipitation. This is so called hanging water profile.
In the autumn and in the winter the precipitation in the Netherlands is much larger than the evaporation, so that the available amount of moisture is maximal in the spring. We say that the soil is at field capacity. The suction tension in the soil then is about 100 mbar, which corresponds with pF 2.0 (\(\log 100 = 2.0\)). Soil moisture, present in the profile at a suction tension, that is higher than 15,000 mbar (pF 4.2), cannot be absorbed by the plants. The difference in amount of moisture between pF 2.0 and 4.2 indicates how much water is available to the plants. The amount is dependent of the type of soil. Humous sand, that is found at old arable land, can contain 24 vol % water of available moisture (fig. 6.). So 24 mm water per 100 mm thickness of the soil layer is available to the plants if the soil is at field capacity.

The amount of water available to the crop is also determined by the root depth. With a root depth of 500 mm and at pF 2.0 on a humous, sandy soil 500 x 0.24 = 120 mm water is available to the crop.

Fig. 6. The relation between the percentage of moisture of the soil and its suction tension for some types of soil, expressed in pF-values.
Fig. 7. If the suction tension in the soil, expressed in PF, increases, the actual transpiration $T_{act}$ becomes smaller. The potential transpiration $T_{pot}$ is the transpiration at PF 2.0.

Fig. 8. a: Actual evapotranspiration of a potato crop on a sandy soil in a rather dry year. The potential transpiration and the rainfall are also presented.
b: The reduction of the corresponding growth rate.
Reduction of the transpiration

The available soil moisture declines in the course of the growing season, because the evaporation is higher than the rainfall during the summer. The water uptake is hampered by the smaller availability of moisture, through which the stomata partly close to reduce the water use. The resulting reduction in transpiration is presented in fig. 7, as a function of the suction tension of the soil. An average curve is presented. The curve is dependent of the plant species and of the drying power of the air. The stomata are closed earlier in drier air to maintain the transpiration at an acceptable level.

Course of available soil moisture and transpiration in the growing season

We get an impression of the course of the percentage of moisture in the growing season by keeping a balance of the water supply in the rooted area, as this is the result of depletion by evaporation on the one hand and supply by rainfall on the other. The soil moisture can be converted to a pf-value with the aid of fig. 1.6. With this pf we read from fig. 7, for each point in time whether the transpiration is reduced and, if so, to what extent. The result of such a calculation for a potato crop on a sandy soil is shown in fig. 8.a. In a rather dry year. Particularly later in the growing season drought effects develop.

3.2.3. Reduction of growth

A disadvantage of limitation of the evaporation by closing the stomata is that the plant can absorb less CO\textsubscript{2}. Growth is reduced by the lowered CO\textsubscript{2}-assimilation.

As was already deduced earlier, the growth rate \( P \) decreases proportionally with the transpiration rate \( T \). In a formula:

\[
\frac{P_{\text{act}}}{P_{\text{pot}}} = \frac{T_{\text{act}}}{T_{\text{pot}}} \quad \text{or} \quad P_{\text{act}} = \frac{T_{\text{act}}}{T_{\text{pot}}} P_{\text{pot}}
\]

The course of the potential growth rate of a potato crop is shown in fig. 8.b. At first this rate is low, because the crop is not closed. The reduction factor \( \frac{T_{\text{act}}}{T_{\text{pot}}} \) is read from fig. 8.a., which gives the actual growth rate \( P_{\text{act}} \).
4 CROP PRODUCTION AS DETERMINED BY NUTRIENT AVAILABILITY

4.1 Crop yield and nutrient requirements

H. van Keulen

A1.1 Introduction

In the previous chapters it has been shown that plants need energy (supplied by the sun), carbon dioxide and water to produce organic material. However, plant tissue contains not only oxygen, hydrogen and carbon, but also other elements like nitrogen, phosphorus and sulphur in proteins, and potassium accompanying organic anions. Many other elements are found in small quantities as constituents of enzymes.

These elements must be taken up by the root system from the soil. In many cases the soil in its natural situation does not supply sufficient plant nutrients to satisfy the demand of the crop. The yield level obtained is then determined by the amount of the limiting element that can be absorbed by the vegetation.

In the foregoing chapters a quantitative treatment has been given of the influence of energy and water on the agricultural production process. In this chapter the influence of plant nutrients will be treated, with this difference, however, that the dynamic aspect, i.e. the change with time, is not considered.

4.1.2 Nutrient supply and crop response

Since the discovery, during the middle of last century, that inorganic ions are needed by growing crops, an enormous number of fertilizer experiments have been carried out at different locations, with various elements and with many crops. In general these trials yield information of the type presented in Figure 39, i.e. the measured yield is presented as a function of the amount of an element supplied. This graph, referring to experiments carried out at IRR1, in the Philippines (Tanaka et al., 1964), shows clearly one of the difficulties encountered in interpreting these experiments: the results are extremely variable.

It should be realized, therefore, that to obtain a yield response to fertilizer application two conditions must be fulfilled:

- the fertilizer that is applied to the soil (or in the case of bunded rice to the water) must be taken up by the crop.
- after uptake by the crop it must be utilized to produce the required plant material, i.e. grains in the case of rice and maize, roots in the case of cassava.

Both processes may be hampered by external or internal conditions. A presen-
Figure 39. Relation between nitrogen application and grain yield for bunded rice grown at IRRI, Los Banos, the Philippines in the dry season and the wet season (Tanaka et al., 1964).

tation such as that in Figure 39 gives no clue to the relative importance of both in the final response. For useful interpretation of fertilizer experiments, yield determinations must be accompanied by chemical analysis of the harvested material, so that the uptake of the element by the vegetation can be calculated and its distribution in the plant.

When in fertilizer experiments both yield and chemical composition have been determined, graphical presentation of the results as suggested by de Wit (1953) facilitates interpretation. The method is illustrated in Figure 40, using the same data as in Figure 39.

Figure 40 consists of three graphs: in the first quadrant, Quadrant a, the relation is given between the economic yield (grain) and the total uptake of the element in the above ground parts of the vegetation, that is both in grain and in straw. This value is calculated by multiplying the amounts of grain and straw harvested by their respective nitrogen concentrations.

Exercise 48

Calculate the total uptake of nitrogen for the following experiment:

<table>
<thead>
<tr>
<th>N application (kg ha⁻¹)</th>
<th>Yield (kg ha⁻¹)</th>
<th>Nitrogen concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>grain</td>
<td>straw</td>
</tr>
<tr>
<td>0</td>
<td>4400</td>
<td>4500</td>
</tr>
<tr>
<td>50</td>
<td>5450</td>
<td>5200</td>
</tr>
<tr>
<td>100</td>
<td>6200</td>
<td>6250</td>
</tr>
<tr>
<td>150</td>
<td>6350</td>
<td>6400</td>
</tr>
</tbody>
</table>
Quadrant b shares the uptake axis with Quadrant a, while on the vertical axis the amount of fertilizer applied is given in downward direction. Quadrant c shows the relation between fertilizer application and yield, i.e. that given in Figure 39. The three graphs are not independent, as one can always be constructed from the other two through elimination of one variable.

The lower end of the curve in Quadrant a passes through the origin, i.e. at zero uptake no yield is to be expected. Because uptake refers to total uptake in both grain and straw, theoretically a situation could exist where only vegetative material is produced, which contains some nitrogen, so that zero yield is associated with a small nitrogen uptake. For all practical purposes, however, that phenomenon may be neglected and the easily obtained origin may be considered part of the curve. At low levels of nitrogen uptake, a proportional relation exists between total uptake and grain yield. This proportionality reflects the existence of a minimum nitrogen concentration, both in grain and in straw. In the grain, no further accumulation of dry matter can take place beyond the point where nitrogen has been diluted to its minimum concentra-
tion. In the straw, which in the reproductive phase loses nitrogen to the developing grains, a residual non-ruminal level of nitrogen remains. The fact that each unit of nitrogen taken up, yields a constant amount of grain also indicates that the ratio between grain yield and total dry matter yield (the harvest index) is not strongly influenced in that range.

A different situation may arise under arid and semi-arid conditions. Moisture limitation during the post-anthesis phase may hamper crop assimilation due to stomatal closure and accelerated leaf senescence, and thus interfere with the growth of the storage organs. The consequence of such behaviour is a very unfavourable harvest index. An additional effect is that not all the nitrogen in the vegetative plant parts can be remobilized and translocated, but material dies with a high residual nitrogen content. Moreover, the nitrogen content of the storage organs is high, because nitrogen is incorporated preferentially in the storage organs and is subsequently not diluted (van Keulen, 1977; van Keulen & van Heemst, 1982). The art of nitrogen fertilizer application in such situations is to apply the fertilizer judiciously so that the moisture is just depleted when the seed ripens. In semi-arid regions, too liberal an application at the early growth stages must be avoided, because that leads to abundant vegetative growth with the associated high water use and the risk of moisture shortage during the reproductive stage. These intricate interrelations are treated and simulated in detail elsewhere (van Keulen & Seligman, 1986).

The combination of a poor harvest index and a high protein content in the harvested plant material, decreases the efficiency of nitrogen utilization considerably, even under limited nitrogen supply. In such situations it is, therefore, much more difficult to predict the effect of nitrogen uptake on economic yield quantitatively.

A similar situation may arise when a high proportion of the total nitrogen uptake takes place after anthesis. Such a process hardly influences the harvest index, but it leads to high protein contents in the storage organs and incomplete remobilization of the proteins from the vegetative material. However, such a situation rarely occurs under conditions of limited nitrogen supply, except if temporary water shortage during the pre-anthesis phase is followed by abundant water supply during the post-anthesis phase. In the situations described here, the yield—uptake curve must thus be applied cautiously.

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**Exercise 49**

Calculate the harvest index for the treatments of the experiment presented in Exercise 48.

What is the mathematical relation between the harvest index and the grain/straw ratio?
With increasing uptake of nitrogen the yield - uptake curve deviates from the straight line, reflecting an increase in nitrogen concentration in the harvested products. The efficiency of nitrogen utilization, expressed as grain yield per unit nitrogen taken up, thus decreases. However, the quality of the harvested material, in terms of its protein content increases.

Finally, the yield curve reaches a plateau level, where further uptake of nitrogen is not reflected in higher yields. At that point, nitrogen availability is no longer the determinant factor for growth and production. The level of the plateau in any actual situation is determined by the growth factor that is constraining. If there is a sufficient supply of the other major inorganic elements, such as phosphorus and potassium, and the other chemical properties of the soil are also favourable (pH, salinity), the yield plateau is equal to that calculated for Production Situation 2, i.e. for situations where either radiation or water may be at times limiting. If by means of proper drainage and irrigation facilities also the moisture status of the soil can be maintained around its optimum value, the yield plateau is that of Production Situation 1, i.e. potential production determined by radiation and temperature only. The influence of other limiting factors on the level of the plateau will be treated in more detail in Subsection 4.1.2. The yield - uptake curve will extend to a point where the vegetation has taken up so much nitrogen that the maximum concentration in the tissue is maintained throughout the plant's life cycle.

Various analyses of yield - uptake curves have shown that the relationship is independent of the type of fertilizer applied, provided the fertilizer is only effective through its main acting element (van Keulen & van Ittersum, 1982; van Keulen, 1982; van Keulen, 1977; de Wit, 1953).

The relation in Quadrant b appears to be linear over the complete range of applications presented, which is characteristic for the majority of fertilizer experiments for nitrogen. Of course, when very high amounts of fertilizer are applied, a situation may be created where the vegetation is continuously 'saturated' with nitrogen, i.e. it is always at its maximum concentration, so that uptake does not increase any more at the highest application levels. For most practical situations, however, the relation in Quadrant b may be characterized by two parameters: the intercept with the uptake axis, representing the uptake from the unfertilized soil, and the slope with respect to the vertical, representing the proportion of the applied fertilizer taken up by the above-ground plant material. This is referred to as the recovery fraction.

The nitrogen uptake at zero fertilizer application shows wide fluctuations, partly because of soil characteristics, partly because of variations in environmental conditions like temperature and rainfall. Furthermore, management influences are of importance such as crop rotation and water management.

The fertilizer recovery fraction may vary between 0.1 and 0.8: the efficiency of uptake is influenced by such factors as fertilizer type, method and timing of application, environmental conditions, etc.
Exercise 50
In a certain situation, the uptake of nitrogen at zero N application is 20 kg ha⁻¹ and at a fertilizer rate of 100 kg ha⁻¹ the nitrogen uptake is 60 kg ha⁻¹. What is the recovery fraction of the applied nitrogen?

The recovery fraction is smaller than one, because many processes are competing for the applied nitrogen: uptake by plants, immobilization by bacteria, volatilization, leaching and denitrification. The linearity of the application rate - uptake relation suggests strongly that all these processes proceed at a rate which is proportional to the concentration of mineral nitrogen (NO₃⁻, NH₄⁺) in the soil solution, so that they can be described as first - order reactions.

It is obvious from this presentation that the curves in Quadrant c may vary widely under different conditions, because both uptake without fertilizer application and recovery of applied fertilizer show wide variability. In order to suggest methods for improvement in a given situation it is, however, necessary to know all three relations depicted in Figure 40.

Exercise 51
Construct the three quadrant diagram for the experiment given in Exercise 48.

4.1.3 Yield - uptake relations

Initial slope

Rice

In Figure 41, a number of representative examples are given for yield - uptake curves of nitrogen on rice, representing a range of cultivars, environmental conditions, fertilizer treatments and management practices. The plateau level in the various examples presented is not necessarily the yield level of Production Situation 2, because at the higher rates of N application other elements could have been in short supply. However, information about this is, in general, lacking. For our purpose that is immaterial because only the initial slope of the yield - uptake curve is considered here, and points on this slope materialize only if elements other than nitrogen are not limiting. Examination of the various curves shows that the initial slope, expressed in kg grain (at a moisture content of 0.15 kg kg⁻¹) per kg nitrogen taken up varies in the examples between 51 (Figure 41a) and 80 (Figure 41b). These variations reflect differences in grain/straw ratios in the various experiments, resulting from
Figure 41. The relation between total nitrogen uptake (u, in kg ha\(^{-1}\)) and grain yield, y (t ha\(^{-1}\)), at a moisture content of 0.15 kg kg\(^{-1}\) and the relation between nitrogen application, A (kg ha\(^{-1}\)), and nitrogen uptake of bunded rice. Numbers in lower half of the graphs denote recovery fractions of applied fertilizer. a. India (Majumdar, 1973). b. Peru (Sanchez et al., 1973). c. USA (Reddy & Patrick, 1978). d. Philippines (Khind & Ponnampuruma, 1981). e. Thailand (Koyama et al., 1973). f. Indonesia (Ismundji & Sisimiyati, 1976).

differences in growing conditions or cultivar characteristics. The experiment of Figure 41a was carried out in India with a local tall indica cultivar, Raghuraj, producing a relatively abundant vegetative apparatus, hence the average grain/straw ratio of 0.53. On the other hand, the improved short straw culi-
var IR8 growing under the conditions of the coastal plain in Peru, ended up with a grain/straw ratio of 1.3 (Figure 41b).

Exercise 52
Calculate the harvest index for the examples of Figures 41a and 41b.

In both situations, however, and in the other examples in Figure 41, the minimum nitrogen concentration in the grains was around 0.01 kg kg\(^{-1}\), whereas in the straw the residual N concentration was around 0.004 kg kg\(^{-1}\). On the basis of these parameters the initial efficiency, \(E_m\), can be calculated as:

\[ E_m = \frac{1}{(0.01 + s/g \times 0.004)} \tag{78} \]

where

\( s \) is weight of straw (kg ha\(^{-1}\))
\( g \) is weight of grain (kg ha\(^{-1}\))

Exercise 53
Calculate the ‘theoretical’ efficiencies for the two examples of Figures 41a and 41b.

In an extensive analysis of yield—uptake curves for nitrogen on rice (van Keulen, 1977), it was shown that the initial efficiencies are always within the range set by the two extremes in Figure 41. Also in pot trials similar values are obtained.

In Figure 42, a similar analysis is presented for the effect of phosphorus on rice. Because less sufficiently detailed field data are available where phosphorus is the limiting factor for rice production, some results of pot trials have also been included. The minimum phosphorus concentrations in grain and straw found in various experiments are 0.0011 and 0.0005 kg kg\(^{-1}\), respectively. Applying the same reasoning as in the case of nitrogen and, assuming a value of one for the grain/straw ratio, leads to an initial efficiency of 625 kg grain per kg phosphorus taken up. The slopes in Figure 42 vary between 410 and 625 kg kg\(^{-1}\), the variability being again mainly the result of variations in the grain/straw ratio.
Figure 42. The relation between total phosphorus uptake, $u$ (kg ha$^{-1}$), and grain yield, $y$ (t ha$^{-1}$), at a moisture content of 0.15 kg kg$^{-1}$ and the relation between phosphorus application, $A$ (kg ha$^{-1}$), and phosphorus uptake for bunded rice. Numbers in lower half of the graphs denote recovery fractions of applied fertilizer (in a and d, $u$, $y$ and $A$ in g pot$^{-1}$). a. pot experiment, India (Dash et al., 1982). b. Mali (Traoré, 1974). c. Nigeria (Fredere, 1966). d. pot experiment, India (Sudanandan et al., 1980). e. India (Agarwal, 1980). f. India (Motsara & Datta, 1971).
Exercise 54
Calculate the grain/straw ratio of the experiment presented in Figure 42b, where the initial efficiency is 410 kg grain per kg P taken up.

In Figure 43 yield—uptake curves for potassium on rice are presented for situations where a clear effect of increased potassium uptake on yield was observed. The number of sufficiently detailed experimental reports found in the literature is still smaller than for phosphorus. The variation in initial slope for this element is larger than for either nitrogen or phosphorus. One reason is that at maturity the larger part of the potassium is found in the straw. Therefore, variations in the grain/straw ratio have a more pronounced effect on the slope of these curves, whereas also losses of potassium due to inevitable leaf loss at the end of the growing period will have greater effect. Another reason for the variability may be the fact that the element has a double function in the plant. For one part it is an essential element for certain physiological functions, for another part it serves as a positive charge, accompanying organic and inorganic anions during transport through the plant. In the latter function it may be almost completely replaced by other positive ions, if present in sufficient amounts.

However, the minimum concentrations in the vegetative material at maturity seem to be around 0.008 kg kg\textsuperscript{–1} and in the grains between 0.0025 and 0.005 kg kg\textsuperscript{–1}. The combination of these two values with a grain/straw ratio of one, yields an initial slope of 55 – 80 kg grain per kg potassium absorbed. The examples presented in Figure 43 all fall within this range.
Weather data

Section 5.1 discusses the nature and precision of weather variables required for crop growth modelling. These variables are:

- at production level 1: daily values of solar radiation, maximum and minimum temperature, and air humidity;
- at production level 2: in addition to those at level 1: daily precipitation values, air humidity, and windspeed.

Some hints are given about pitfalls in data collection.
5.1 Historic weather data

5.1.1 Introduction

Solar radiation is by far the most important weather variable for crop growth simulation at production level 1, but air temperature can also be crucial. Air humidity is important in very dry weather for some crops. For simulation at production level 2, precipitation is an essential input. Solar radiation, temperature, and air humidity are also important, but windspeed has a small effect on transpiration.

Weather data can be obtained from national meteorological services and from the Consultative Group on International Agricultural Research (CGIAR) institutes (e.g. Oldeman et al., 1987). Inspect all data carefully for definitions and units of variables. For data obtained locally or from small stations, inspect also the measuring conditions. Much information about interpreting weather data and environmental physics can be found in Rose (1966), Monteith (1973), Campbell (1977), Doorenbos and Kassam (1979), and Oldeman and Frere (1982). The World Meteorological Organization recently produced a hardware-software-training package for a data base management system for climatological data (CLICOM). There are still few weather data for modelling available, particularly if sets of 5 to 25 years of historical data for all six variables without missing values are required.
The one day time interval of crop growth simulation corresponds well with the periodicity with which weather data are often reported. Average values can be used if the basic data available are only weekly or monthly means. Obviously, the impact of short deviations from the mean can then not be evaluated. The use of averages for radiation, temperature, windspeed, and humidity is appropriate for many purposes. Values of precipitation per day, either observed or generated, are essential for simulating water-limited production (Van Keulen and Wolf, 1986). Daily values of radiation are required if sensitive phases (tillering, panicle initiation in cereals) fall in periods of variable cloudiness.

When the simulation time interval is about six hours, intermediate values of the weather parameters are estimated from the daily values in the module LIQ. These may be replaced by actual data when available.

Weather data are given in the form of CSMP-Tables: a set of 365 values per variable. It is practical to always supply a full year data rather than only a growing season, so that crop growth or derived weather variables can easily be obtained outside the main season.

Two other input parameters characterize a site: latitude and elevation above sea level. The first affects the maximum amount of solar radiation and daylength, the second the CO2 concentration of the air.

5.1.2 Solar radiation

Solar radiation is a key meteorological variable and its values should be obtained as accurately as possible. Daily values of the
'total global radiation' should be obtained, if possible, from a properly calibrated Kipp solarimeter or a RIMCO pyranometer or similar instruments. 'Total' refers to the sum of visible and near infrared radiation (400-1300 nm), 'global' refers to radiation coming from all directions. Readings given in sunshine hours (method Campbell-Stokes) have to be converted into J m\(^{-2}\) J\(^{-1}\) (Van Keulen and Wolf, 1986, pg 64, indicate how to do this). Radiation on fully overcast days is 20% of the value on fully clear days by convention, though in reality, days with even less radiation occur. The radiation unit conversion factor in the program maintains proper calculating units.

Solar radiation can be partitioned in two ways: photosynthetically active radiation (PAR, 400-700 nm wavelength) and near infrared (700-1300 nm), and from direct (from a point source) and diffuse radiation. PAR is always about 50% of the total solar radiation and this fraction varies little with radiation intensity (Monteith, 1973). But the fraction diffuse of the total radiation depends strongly on the daily total. The relation between the fraction diffuse and the daily total radiation relative to the extraterrestrial radiation at that location and date appears to be universal (Spitters et al., 1986). It is built into the subroutine SUASTC. The difference between direct and diffuse radiation is important for photosynthesis, but it is accounted for automatically because SUASTC is called in the FUPHOT function or in the SUPHOL subroutine, whichever is used to compute photosynthesis.
For the six hour time interval module, radiation is supposed to be partitioned equally over morning and afternoon, and is zero at night.

5.1.3 Minimum and maximum temperature

Temperature affects the rate of most physiological processes. The maximum and minimum temperatures are not used as such, but an effective temperature is calculated from them. How this is done depends on the process and the time interval. The effective temperature for processes that continue during the complete time interval is the average of maximum and minimum temperature. The effective temperature for photosynthesis is assumed to be the average daytime temperature, calculated as the mean of the 24 hour average and the maximum temperature.

Maximum and minimum temperature (or values at 14.00 h and sunrise, respectively) can easily be accurately measured. Values used here are based on observations at the standard screen height of 1.5 m above the soil surface.
The temperature near the soil surface can be different from the air temperature at screen height. Small plants may have a higher temperature using the day and a lower one at night. This is not accounted for here, but it may be worthwhile to explicitly consider near surface temperatures when studying crop emergence. The leaf temperature and that of the growing point can also deviate several degrees from the air temperature, the higher the transpiration rate the lower the leaf temperature relative to air temperature. Such deviations mean that using standard meteorological temperatures is not always totally satisfactory. However, they are as yet the best available.

5.1.4 Precipitation

Rain is a particularly important driving variable in the semi-arid and subhumid tropics, but is also important in dry periods in temperate zones. Its values can change more from day to day than any other meteorological variable. On wet days its value is often 2-20 mm, but can reach 100 mm or more in intensive tropical storms. Determining its value deserves proper attention and this is more difficult than it seems. Measurements can underestimate the real value (TNO, 1977). An accuracy of more than 5-10% for absolute values of precipitation is difficult to attain. The wind profile around the raingauge is very important: the height of the raingauge above the surface and its exposure have repercussions of 10-20% and more on the amount of rain caught in the gauge. The standard raingauge at a meteorological station in the Netherlands has an orifice of 200 cm², with its rim at 40 cm from the soil surface; it underestimates reality by a few percent (TNO, 1977). The
imprecision in precipitation measurements is significant for simulation.

The spatial variability of precipitation is also quite large. Its value must be determined at the field for which the study is undertaken whenever precipitation is a key variable for simulation. Though the quality of data of the nearest official meteorological station may be better, less accurate data from the field for which the simulation is performed can be more relevant.

Rainfall occurs generally over periods much shorter than 24 hours, the time interval of simulation. Observations of rainfall intensity with recording raingauges, are rarely made routinely. This is a serious handicap for runoff calculations. In the module for partially saturated soils, it is assumed that all precipitation from a single day is received in the first soil water balance time interval.

Interception of precipitation by leaves, stems, and fruits is 10-20% of the fresh weight of leaves, or almost equivalent to their dry weight. These amounts are equivalent to a layer of water of less than 1 mm per occasion, which is neglected here. In environments with a large number of small rain showers interception should be taken into account.

Dew rarely amounts to more than 0.1 mm d-1 and is difficult to measure. Dew is partly condensed soil evaporation. Though the amounts of dew are small and negligible for water balance studies, wetness of the surface can be crucial for other processes. The leaf-wet-period is important in simulating crop damage by pathogens, because diseases develop quicker on wet than on dry surfaces.
5.1.5 Humidity

The air humidity affects transpiration and evaporation, and reduces photosynthesis in some crops when its value is very low. Good measurements of air humidity are not easy to come by, but are not of overriding importance in crop simulation.

Air humidity can be measured in several ways and expressed in different units. The absolute concentration, expressed as the water vapour pressure in kPa (1 kPa = 10 mbar), is preferred (its value generally changes little during the day, so that the time at which the reading is taken is less important). Humidity expressed in other units can be converted to kPa by equations. Relative humidity changes a lot during the day, and should be avoided as a basic measurement of humidity.

If reliable values for air humidity are unavailable, they may be approximated by assuming that the air is saturated with vapour at dawn when the daily minimum temperature is reached. The vapour pressure can then be obtained by calling the FUVP function for this temperature. This approximation will provide values which are too high in the dry season of arid and semi-arid environments.

5.1.6 Windspeed

Canopy transpiration is only sensitive to windspeeds up to 1-2 m s⁻¹. Plant lodging due to high wind speeds and gusts is not considered here.

Windspeed is measured directly as a rate and averaged over 24 hours, or obtained as daily windrun and expressed in m s⁻¹. It is often measured at 2 m over a low grass sward at a standard meteorological station. This reference height is input to the FURSC
function. Observations made at other heights must be converted (cf Van Keulen and Wolf, 1986 pg 210). Windspeed during the day is generally higher than at night, and that the effective windspeed is taken as 1.33 times the average value; this factor is somewhat arbitrarily chosen and may need adjustment in specific situations. Thermal air instability inside the canopy occurs spontaneously during the day when there is almost no wind and enhances gas exchange. This is accounted for by limiting the windspeed to a lower value of 0.2 m s⁻¹.

5.1.7 Carbon dioxide

The CO₂ concentration was about 340 vppm (cm³ m⁻³) at sea level in 1986, and its value rises steadily (Goudriaan, 1987). The CO₂ concentration fluctuates very little during the year, and usually does not change significantly inside the canopy. Its value at sea level is specified with a parameter. The volumetric CO₂ concentration decreases by 12% per 1000 m elevation.
6. SIMULATION MODELS PRODUCTION LEVEL 1 (L1.CSM) and 2 (L2.CSM).
Figure  A relational diagram of the essence of a system at production level 1 when light is the limiting factor and temperature often exerts also an important influence. The diagram is drawn according to Forrester (1961): rectangles represent quantities, valve symbols represent flows, circles auxiliary variables and underlined variables external variables; drawn lines represent flows of material, broken lines flows of information.
INITIAL

*For parameters and functions needed to run the model, see checklist on page 55 of this manual
*Crop data ORYZA SATIVA, rice, CV IR36

**Photosynthesis and respiration
PARAM PLMP=47.0, PLEI=0.50
FUNCTION PLMTT=-11.0,0.00, 0.0,0.0, 10.,0.0, 25.,1.00,...
35.,1.00, 42.,0.0, 45.,0.0
FUNCTION PLMH= 0.0,1.00, 1.0,1.0, 2.0,0.99, 3.0,0.86,...
4.0,0.71
FUNCTION PLETT=-11.0, 1.00, 0.0,1.0, 15.,1.0, 25.,0.90,...
35.,0.60, 45.,0.2, 50.,0.01

PARAM CRGLV=1.326, CRGST=1.326, CRGSO=1.462, CRGRT=1.326
PARAM CPGLV=0.408, CPGST=0.365, CPGSO=0.357, CPGRT=0.365
PARAM FCLV =0.419, FCST =0.431, FCST =0.487, FCRT =0.431
PARAM RMCLV=0.02, TPR =25., Q10=2.

**Biomass partitioning and aging
FUNCTION CALVT = 0.0,0.51, 0.5,0.51, 0.6,0.47, 0.7,0.32,...
0.8,0.25, 1.0,0.00, 1.1,0.00, 2.5,0.00
FUNCTION CASTT = 0.0,0.49, 0.5,0.49, 0.6,0.53, 0.7,0.68,...
0.8,0.74, 1.0,1.00, 1.1,0.27, 1.2,0.00,...
2.1,0.0
FUNCTION CASST = 0.0,0.86, 0.5,0.86, 0.6,0.86, 0.7,0.95,...
0.8,0.94, 1.0,0.89, 1.1,1.00, 2.5,1.00

PARAM FSTR=0.25, FEPSO=0.8, GSORM=0.50
FUNCTION LLVT =0.0,0.0, 1.0,0.0, 1.3,0.007, 1.8,0.012,...
2.5,0.012
FUNCTION LRTT =0.0,0.0, 1.0,0.0, 1.3,0.011, 1.8,0.010,...
2.5,0.010

**Phenological development
PARAM DRCV=0.013, DRCR=0.028
FUNCTION DRVTT=-11.,0.10, 10.,0.10, 19.,0.80, 25.,1.00,...
27.,1.10, 32.,1.20, 40.,1.00, 45.,1.0
FUNCTION DDRT=-11.,0.45, 10.,0.45, 19.,0.75, 25.,0.90,...
28.,1.00, 30.,1.10, 40.,1.10, 45.,1.1
FUNCTION DRT =0.0,1.0, 24.,1.
FUNCTION DRT =0.0,1.0, 1.1,1.

PARAM SLC=370., SSC=1000., WDLV=0.015
FUNCTION SLT =0.0,0.82, 0.6,1.00, 2.1,1.00
FUNCTION PLHT=0.0,0.00, 1.0,1.00, 2.1,1.
**Initialization**
PARAM DATEB=197.
PARAM WLVI=6.8, WSTI=6.8, WSOI=0.
PARAM DSI=0.18

*---------------------
WRTI =WLVI
ALVI =WLVI/(SLC*AFGEN(SLT,DSI))
CPW =1.
DRW =1.
PCW =1.

**DYNAMIC**

**Weights of Crop Components**
* for explanation see page 36, table 10 (column 10,13,16,19)
* on page 50 and page 53-54 of this manual.

WLV =INTGR(WLVI,GLV-LLV)
WST =INTGR(WSTI,GST*(1.-FSTR))
WIR =INTGR(0.,GST*(FSTR*(FCST/0.444))-LSTR)
WSO =INTGR(WSOI,GSO)
WEPSO =WSO*FEPSO
WRT =INTGR(WRTI,GRT-LRT)
WSS =WLV+WST+WSO+WIR
WCR =WSS+WRT
WLVD =INTGR(0.,LLV)
WRTD =INTGR(0.,LRT)

**Growth Rates and Loss Rates**
* for explanation see page 23 (growth resp.), table 4 on page 23
* and eq. 6 on page 24 of this manual
* CRG.. is 1/conversion efficiency.

GLV =CAGLV/CRGLV
GST =CAGST/CRGST
GRT =CAGRT/CRGRT
GSO =CAGSO/CRGSO

LLV =WLV*AFGEN(LLVT,DS)
LRT =WRT*AFGEN(LRTT,DS)
LSTR =INSW(AFGEN(CASTT,DS)-0.01,WIR*0.1,0.)

**Carbohydrate Available for Growth, Export**
* for explanation see table 10 (column 6) on page 50
* and page 52 of this manual (ASAG).
CAGCR =PCGW*0.682-RMCR*0.682+LSTR*0.111*0.947
* for explanation see table 12 on page 53 (CA..T are part. factors)
CAGSS =CAGCR*AFGEN(CASTT,DS)*CPW
CAGRT =CAGCR-CAGSS
CAGLV =CAGSS*AFGEN(CALVT,DS)
CAGST =CAGSS*AFGEN(CASTT,DS)
CAGSO =CAGSS-CAGLV-CAGST

CELV =PCGW-(RMLV+RMST+0.5*RMA)
CELVN =INTGR(0.,INSW(CELV,1.,-CELVN/DELT))
**PHOTOSYNTHESIS, GROSS AND NET**

PCGW = PCGC*PCEW

* for explanation on crop photosynthesis see exercise 1, 2 on page
* 21, and page 17-20 of this manual.

PCGC = FUPHOT(PLMX,PLFA,ALV,RDTM,DATF,LAT)

* for explanation on leaf photosynthesis see page 15-16
* of this manual.

PLMX = PLMX*AFGEN(PLMTT,TPAD)*LIMIT(200.,600.,SLA)/SLC
PLEA = PLEI*AFGEN(PLETT,TPAD)
PCGT = INTGR(0.,PCGW)
RCRT = INTGR(0.,RMCR+RGCR)
PCNT = INTGR(0.,PCGW-(RMCR+RGCR))

**RESPIRATION**

RMCT = INTGR(0.,RMCR)
RMCR = RMLV+RMST+RMSO+RMRT+RMMA

* for explanation on maintenance resp. see table 4 on page 23
* and page 23 of this manual.

RMLV = WLV*RMGLV*TPEM*0.75
RMST = WST*0.010*TPEM+WIR*0.0
RMRT = WRT*0.015*TPEM
RMSO = AMINI(1000.,WSO)*0.015*TPEM
TPEM = Q10**((TFAV-TFR)/10.)

RMMA = 0.20*PCGW*0.5

* for explanation on growth resp. see page 23-24 of this manual.

RGCR = RGIV+RGST+RGSO+RGRT+RLSR
RGIV = GLV*CGLV
RGST = GST*CGST
RGSO = GSO*CGSO
RGRT = CRT*CPCRT
RLSR = LSR*1.111*0.053*1.467

**CARBON BALANCE CHECK**

CKCRD = FUCCKH(CKCI,CKCFL,TIME)

CKCIN = (WLV-WLVI)*FCLV+(WST-WSTI)*FCST+...
(WSO-WSOI)*FCSO+(WRT-WRTI)*FCRT+WIR*0.444

CKCFL = PCNT*0.2727-(WLVD+FCLV+WRTD*FCRT)

**LEAF AREA**

* for explanation see page 54 of the manual (LAI).

ALV = INTGR(ALVI,GLA-LLA+GSA)
GLV = GLV/SLN
LIA = LLV/SLA
GSA = 0.5*GST/SSC
SLN = SLV*AFGEN(SLT,DS)
SLA = (WLV+0.5*WST*(SLC/SSC))/ALV
**PHENOLOGICAL DEVELOPMENT OF THE CROP**
* for explanation see page 29, exercise 5 on page 31, exercise 6
* on page 32, exercise 7 on page 33, page 51 and table 10 (column 3)
* (DVS) on page 50 of this manual.
  DS = INGRW(DSI,INSW(DS-1,DRV,DRR))
  DRV = DRCV*DRED*AFGEN(DRVT,TPAV)
  DRED = (TPH(TIDATE)+TPH(TIDATE))/2.
  (IDATE) = DATE
  IDATE = DATE

**WEATHER DATA AND TIME**
* for explanation see chapter 5 on page 88-96 of the manual.
  RLTM = RDTM(TIDATE)*RDUCF
  RDTM, DLA, DLF = SUASTR(DATE, LAT)
  TPAV = (TPHT(TIDATE)+TPHT(TIDATE))/2.
  (TPHT) = (TPHT(TIDATE)+TPAV)/2.
  DATE = AMOD(DATEB+TIME+364.,365.)+1.
  IDATE = DATE

**RUN CONTROL AND OUTPUT**

**METHOD RECT**
  TIMER DELT = .1., TIME = 0., FINTIM = 1000., PRDEL = 10., OUTDEL = 10.
  FINISH DS = 2., TPAV = 3.

PRINT DATE, WLV, WST, WIR, WSO, WRT, GLV, GST, GSO, GRT, ...
  SLA, PLMX, ALV, DS, TPAV, RDTM, PCGT, RCRT, RMCT

**PAGE GROUP**
  WLV = WLV+WLV
  WLVST = WLVST+WST+WIR
  WLVSO = WLVST+WSO
  HI = WSO/WSS
  RSH = RMLV+RMST+RMSO+RMMA+RGLV+RGST+RGSO+RLSR
  WSTR = WST+WIR

*weatherdata Los Banos (IRRI) 1984*

PARAM RDUCF = 1.6E6
PARAM ELV = 21.0
PARAM LAT = 14.17
PARAM ZREF = 2.0

* Daily minimum temperature in degrees Celsius
TABLE TPLT(1-365) = ...
   22.0, 21.4, 22.1, 21.4, 22.0, 22.0, 23.3, 21.4, 21.0, 21.5, ...
   etc.
* Daily maximum temperature in degrees Celsius
TABLE TPHT(1-365) = ...
   26.4, 27.9, 26.9, 24.5, 27.7, 28.5, 27.5, 28.7, 27.8, 28.6, ...
   etc.
* Daily total global irradiation in MJ/m**2/day
TABLE RDTMT(1-365) = ...
   9.85, 12.98, 8.88, 4.57, 10.52, 13.59, 9.63, 14.80, 12.52, 11.66, ...
   etc.

END
STOP

FUNCTION FUPHOT(PLMX, PLEA, ALV, RDTM, DATE, LAT)
C to compute daily canopy photosynthesis
IMPLICIT REAL(A-Z)
INTEGER IT, I
DATA KDIF/0.7155/, PI/3.1415926/, SCV/0.200/
CALL SUERRM(1.1, ALV, 0., -99., 6.)
CALL SUERRM(1.2, PLMX, 0., -99., 6.)
CALL SUERRM(1.3, PLEA, 0., -99., 6.)
IF ((PLMX LT 1.E-3).OR.(ALV LT 1.E-3).OR.(PLEA LT 1.E-3)) GOTO 10
CALL SUASTC(DATE, LAT, RDTM, RDT, FRDIF, COSLD, SINLD, DSINBE, SOLC, DAYL)
GAUSR = SQRT(0.15)
GDFG = 0.
REFH = (1. - SQRT(1.0 - SCV))/(1. + SQRT(1. - SCV))
DO 1 IT=1,3
   HOUR = 12.0 + DAYL*0.5*(0.5 + (IT-2)*GAUSR)
   SINB = AMAX1(0., SINLD + COSLD*COS(2.*PI*(HOUR+12.)/24.))
   REFS = REFH*2/((1.+1.6*SINB)
   PAR = 0.5*RDTM*SINB*(1.0+0.4*SINB)/DSINBE
   PARDIF = AMIN1(PAR, SINB*FRDIF*(RDTM/RDT)+0.5*SOLC)
   PARDIR = PAR - PARDIF
   KDIRBL = 0.5/SINB*KDIF/(0.8*SQRT(1. - SCV))
   KDRT = KDIRBL*SQRT(1. - SCV)
   FGROS = 0.
   DO 2 I=1,3
      ALVC = 0.5*ALV + GAUSR*(I-2)*ALV
      VISDF = (1. - REFS)*PARDIF*KDIF*EXP(-KDIF*ALVC)
      VIST = (1. - REFS)*PARDIR*KDIRT*EXP(-KDIRT*ALVC)
      VISD = (1. - SCV)*PARDIR*KDIRBL*EXP(-KDIRBL*ALVC)
      VISSHD = VISDF + VIST - VISD
      FGRSH = PLMX*(1. - EXP(-VISSHD*PLEA/PLMX))
      VISPP = (1. - SCV)*PARDIR/SINB
      IF (VISPP .LE. 0.) GO TO 3
      FGRSUN = PLMX*(1. - (PLMX - FGRSH)*(1. - EXP(-VISPP*PLEA/PLMX)))/
      (PLEA*VISPP)
   2   CONTINUE
   FGRA = EXP(-KDIRBL*ALVC)
   FGL = FGRA*FGRSUN + (1. - FGRA)*FGRSH
   IF(I.EQ.2) FGL = FGL*1.6
   FGROS = FGROS + FGL
   CONTINUE
   FGROS = FGROS*ALV/3.6
   IF(IT.EQ.2) FGROS = FGROS*1.6
   GDFG = GDFG + FGROS
1 CONTINUE
FUPHOT = GDFG*DAYL/3.6
GOTO 11
10 CONTINUE
FUPHOT = 0.
11 CONTINUE
RETURN
END
FUNCTION FUCCHK(CKCIN,CKCFL,TIME)
C check on crop carbon balance
C version 19-05-1987
FUCCHK=(CKCIN-CKCFL)/(CKCIN+CKCFL+1.E-10)
IF(ABS(CKCIN-CKCFL).LE.0.00001) RETURN
IF(ABS(FUCCHK).GT.0.01) WRITE (6,1) FUCCHK,CKCIN,CKCFL,TIME
1 FORMAT(//** error in carbon balance, please check ***/,
$'CKCRD=',F6.3,'CKCIN=',F6.2,'CKCFL=',F6.2,'AT TIME=',F6.1)
RETURN
END

SUBROUTINE SUASTR(DATE,LAT,RDTC,DAYL,DAYLP)
C to calculate daylengths, daily total irradiation at top of
C atmosphere
IMPLICIT REAL (A-Z)
DATA INSPI/-4.0/,PI/3.1415926/
CALL SUASTG(DATE,LAT,RDTC,RDTC,FRDIF,COSLD,SNLDA,DSINBE,SOAD,DAYL)
RAD =PI/180.
DAYLP =12.*(PI+2.*ASIN((-SIN(INSPI*RAD)+SNLDA)/COSLD))/PI
RETURN
END

SUBROUTINE SUERRM(MNR,X,XMIN,XMAX,NUNIT)
C to check if variable X is between its minimal and maximal value
C (XMIN and XMAX resp.). If not, an error message is written to a
C file with unit number NUNIT, (6 for F020.DAT when running CSMP)
C and the program is stopped. If XMIN or XMAX is -99., no minimum
C or maximum is set.
C version: 28-08-1987
C
IMPLICIT REAL(A-Z)
INTEGER IUNIT
IF((X.LT.XMIN+0.999).AND.(XMIN.NE.-99.)) GOTO 1
IF((X.GT.XMAX+1.001).AND.(XMAX.NE.-99.)) GOTO 1
RETURN
1 IUNIT=IFIX(NUNIT)
WRITE(IUNIT,1000)
WRITE(IUNIT,*) MNR,X,XMIN,XMAX
STOP
1000 FORMAT(//'**** error in variable or parameter value ****',
$/', 'message number, value, minimum and maximum: ')
END
SUBROUTINE SUASTC(DATE,LAT,RDTM,RDTC,FRDIFF,COSLD,SINLD,$
SDSINBE,SOLC,DAYL)
C to perform standard astronomical computations
IMPLICIT REAL (A-Z)
DATA PI/3.1415926/
RAD =PI/180.
CALL SUERRM(2.1,DATE,0.,365.,6.)
DEC =-ASIN(SIN(23.45*EAD)*COS(2.*PI*(DATE+10.)/365.))
COSLD =COS(DEC)*COS(LAT*RAD)
SINLD =SIN(DEC)*SIN(LAT*RAD)
AOB =SINLD*COSLD
CALL SUERRM(2.2,AOB,-1.0,1.0,6.)
DAYL =12.*((1.42+2.0*ASIN(AOB))/PI)
DSINBE=3600.*((DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
$ 12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT(1.-AOB*AOB)/PI)
DSINB =3600.*(SINLD*DAYL+24./*PI*COSLD*SQRT(1.-AOB**2))
SOLC =1370.(*(1.0+0.033*COS(2.*PI*DATE/365.))
RDTC =SOLC*DSINB
CALL SUERRM(2.3,RDTM,0.,RDTC,6.)
ATMTR =RDTM/RDTC
IF(ATMTR.GT.0.75) FRDIFF =0.23
IF(ATMTR.LE.0.75.AND.ATMTR.GT.0.35) FRDIFF =1.33-1.46*ATMTR
IF(ATMTR.LE.0.35.AND.ATMTR.GT.0.07) FRDIFF =1.-2.3*(ATMTR-0.07)**2
IF(ATMTR.LE.0.07) FRDIFF =1.00
RETURN
END
Figure A relational diagram of the essence of a system at production level 2 where water shortage is the main limiting factor. Potential rates of photosynthesis and transpiration yield the water use efficiency. The extent to which these rates are realized depends on the amount of water absorbed from the soil.
**Photosynthesis and respiration**
PARAM PLMXF=47., PLET=0.50
FUNCTION PLMTT=-11., 0.00, 0.0, 0.0, 10., 0.0, 25., 1.00,...
            35., 1.00, 42., 0.00, 45., 0.0
FUNCTION PLMHT= 0.0, 1.00, 1.0, 1.0, 2.0, 0.99, 3.0, 0.86,...
            4.0, 0.71
FUNCTION PLETT=-11., 1.00, 0.0, 1.0, 15., 1.0, 25., 0.90,...
            35., 0.60, 45., 0.0, 50., 0.01
PARAM CRGLV=1.326, CRGST=1.326, CRGSO=1.462, CRGRT=1.326
PARAM CPGLV=0.408, CPGST=0.365, CPGSO=0.357, CPGRT=0.365
PARAM FCLV =0.419, FCST =0.431, FCSS =0.487, FCRT =0.431
PARAM RMCLV=0.02, TPR =25., Q10=2.

**Biomass partitioning and aging**
FUNCTION CALVT = 0.0, 0.51, 0.5, 0.51, 0.6, 0.47, 0.7, 0.32,...
            0.8, 0.26, 1.0, 0.00, 1.1, 0.00, 2.5, 0.00
FUNCTION CASTT = 0.0, 0.49, 0.5, 0.49, 0.6, 0.53, 0.7, 0.68,...
            0.8, 0.74, 1.0, 1.00, 1.1, 0.27, 1.2, 0.00,...
            2.1, 0.0
FUNCTION CASST = 0.0, 0.86, 0.5, 0.86, 0.6, 0.86, 0.7, 0.95,...
            0.8, 0.94, 1.0, 0.89, 1.1, 1.00, 2.5, 1.00
PARAM FSTR=0.25, FEPSO=0.8, GSORM=0.50
FUNCTION LLVT =0.0, 0.0, 1.0, 0.0, 1.3, 0.007, 1.8, 0.012,...
            2.5, 0.012
FUNCTION LRTT =0.0, 0.0, 1.0, 0.0, 1.3, 0.011, 1.8, 0.010,...
            2.5, 0.010

**Phenological development**
PARAM DRCV=0.013, DRCR=0.028
FUNCTION DRVT=-11., 0.10, 10., 0.10, 19., 0.80, 25., 1.00,...
            27., 1.10, 32., 1.20, 40., 1.00, 45., 1.0
FUNCTION DRRTT=-11., 0.45, 10., 0.45, 19., 0.75, 25., 0.90,...
            28., 1.00, 30., 1.10, 40., 1.10, 45., 1.1
FUNCTION DRDT =0.0, 1.0, 24., 1.1
FUNCTION DRWT =0.0, 1.0, 1.1
PARAM SLG=370., SSC=1000., WDLV=0.015
FUNCTION SLT =-0.0, 0.82, 0.6, 1.00, 2.1, 1.00
FUNCTION PLHTT=0.0, 0.00, 1.0, 1.00, 2.1, 1.1

**Water relations and root growth**
PARAM WSSC =0.5, WFSC =1., FIEC=0.65
PARAM ZRTMC =-0.70, GZRTC =0.03
soil data, standard loamy soil, deep water table. 9/87

PARAM TKL1 =0.2, TKL2 =0.3, TKL3 =0.5
PARAM WCFC1 =0.36, WCWP1 =0.11, WCAD1 =0.01, WGST1 =0.50
PARAM WCFC2 =0.36, WCWP2 =0.11, WCAD2 =0.01, WGST2 =0.50
PARAM WCFG3 =0.36, WCWP3 =0.11, WCAD3 =0.01, WGST3 =0.50
INCON WCLI1 =0.36, WCLI2 =0.36, WCLI3 =0.36

**Surface and other soil characteristics
PARAM FRNOF =0.0, RFSD =0.2, WDCL =0.05, ZRTMS =0.9
PARAM EES =-20., CSG2 = 0.1, CSA = 0.15, CSB = 10.

**Initialization
PARAM DATEB =197.
PARAM WLVI =5.8, WSTI =6.8, WS0I =0.
PARAM DSI =0.18, ZRTI =0.2

WRTI =WLVI
ALVI =WLVI/(SLC*AFGEN(SLT,DSI))
CPEW =1.
DREW =1.
FCEW =1.
TPSI =(TPLT(IDATE)+TPHT(IDATE))/2.
IDATE =DATEB
WL1I =WCLI1+TKL1*1.E4
WL2I =WCLI2+TKL2*1.E4
WL3I =WCLI3+TKL3*1.E4
TKLT =TKL1+TKL2+TKL3

DYNAMIC
**WEIGHTS OF CROP COMPONENTS
WL =INTGLR(WLVI, GLV-LLV)
WST =INTGLR(WSTI, GST*(1.-FSTR))
Wir =INTGLR(0., GST*(FSTR*(PCST/0.444))-LSTR)
WSO =INTGLR(WSOI, GSO)
WEPSO =WSO*PEPSO
WRT =INTGLR(WRTI, GRT-LRT)
WSS =WLV+WST+WS0+WIR
WCR =WSS+WRT
WLVD =INTGLR(0., LLV)
WRTD =INTGLR(0., LRT)

**GROWTH RATES AND LOSS RATES
GLV =CAGLV/CRGLV
GST =CAGST/CRGST
GRT =CAGRT/CRGRT
GSO =CAGSO/CRGSO

LLV =WLV*AFGEN(LLVT, DS)
LRT =WRT*AFGEN(LRTT, DS)
LSTR =INSW(AFGEN(CASTT, DS)-0.01, WIR*0.1,0.)
**CARBOHYDRATE AVAILABLE FOR GROWTH, EXPORT**
\[
\text{CAGCR} = \text{PCGW} \times 0.682 - \text{RMCR} \times 0.662 + \text{LSTR} \times 1.111 \times 0.947
\]
\[
\text{CAGSS} = \text{CAGCR} \times \text{AFGEN(CASST,DS)} \times \text{CPEW}
\]
\[
\text{CAGRT} = \text{CAGCR} \times \text{CAGSS}
\]
\[
\text{CAGLV} = \text{CAGSS} \times \text{AFGEN(CALVT,DS)}
\]
\[
\text{CAGST} = \text{CAGSS} \times \text{AFGEN(CASTT,DS)}
\]
\[
\text{CAGSO} = \text{CAGSS} \times \text{CAGLV} \times \text{CAGST}
\]
\[
\text{CELV} = \text{PCGW} - (\text{RMLV} + \text{RMST} + 0.5 \times \text{RMMA})
\]
\[
\text{CELVN} = \text{INTGRL}(0, \text{INSW(CELV,1.,-CELVN/DELT)})
\]

**PHOTOSYNTHESIS, GROSS AND NET**
\[
\text{PCGW} = \text{PCGC} \times \text{PCFW}
\]
\[
\text{PCGC} = \text{FUPHOT(PLMX,PLEA,ALV,RDTM,DATE,LAT)}
\]
\[
\text{PLMX} = \text{PLMXF} \times \text{AFGEN(PLMIT,TPAD)} \times \text{LIMIT}(200, 600, \text{SLA}/\text{SLC})
\]
\[
\text{PLEA} = \text{PLEI} \times \text{AFGEN(PLETT,TPAD)}
\]
\[
\text{PCGT} = \text{INTGRL}(0, \text{PCGW})
\]
\[
\text{RCRT} = \text{INTGRL}(0, \text{RMCR} + \text{RGCR})
\]
\[
\text{PCCT} = \text{INTGRL}(0, \text{PCGW} - (\text{RMCR} + \text{RGCR}))
\]

**RESPIRATION**
\[
\text{RMCT} = \text{INTGRL}(0, \text{RMCR})
\]
\[
\text{RMCR} = \text{RMLV} + \text{RMST} + \text{RMSO} + \text{RMRT} + \text{RMMA}
\]
\[
\text{RMLV} = \text{WLV} \times \text{RMCLV} \times \text{TPM} \times 0.75
\]
\[
\text{RMST} = \text{WST} \times 0.010 \times \text{TPM} \times \text{WIR} \times 0.9
\]
\[
\text{RMRT} = \text{WRT} \times 0.015 \times \text{TPM}
\]
\[
\text{RMSO} = \text{AMIN1}(1000, \text{WSO}) \times 0.015 \times \text{TPM}
\]
\[
\text{TPM} = Q10^*(\text{TPAV-TPR}/10.)
\]
\[
\text{RMMA} = 0.20 \times \text{PCGW} \times 0.5
\]
\[
\text{RGCR} = \text{RGLV} \times \text{RGST} + \text{RGSO} \times \text{RGRT} + \text{RLSR}
\]
\[
\text{RGLV} = \text{GLV} \times \text{CPLGLV}
\]
\[
\text{RGST} = \text{GST} \times \text{CPSGST}
\]
\[
\text{RGSO} = \text{GSO} \times \text{CPSGSO}
\]
\[
\text{RGRT} = \text{GRT} \times \text{CPSGRT}
\]
\[
\text{RLSR} = \text{LSTR} \times 1.111 \times 0.053 \times 1.467
\]

**CARBON BALANCE CHECK**
\[
\text{CKCRI} = \text{FUCCHCK(CKCN,CKCFL,TIMC)}
\]
\[
\text{CKCII} = \text{(WLVD} - \text{WLVI} \times \text{FCLV} + (\text{WSI} - \text{WSIT}) \times \text{FCST} + \ldots
\]
\[
\text{=(WST} - \text{WSTI}) \times \text{FCSO} + (\text{WRT} - \text{WRTI}) \times \text{FCRT} + \text{WIR} \times 0.444
\]
\[
\text{CKCFL} = \text{PCNT} \times 0.2727 - (\text{WLVD} \times \text{FCLV} \times \text{WRTD} \times \text{FCRT})
\]

**LEAF AREA**
\[
\text{ALV} = \text{INTGRL(AlVI,GLA-LLA+GSA)}
\]
\[
\text{GLA} = \text{GLV/SLN}
\]
\[
\text{LLA} = \text{LLV/SLA}
\]
\[
\text{GSA} = 0.5 \times \text{GST/SSC}
\]
\[
\text{SLN} = \text{SLA} \times \text{AFGEN(SL,DS)}
\]
\[
\text{SLA} = (\text{WLV} + 0.5 \times \text{WST} \times (\text{SLA}/\text{SSC})) \times \text{ALV}
\]

**PHENOCLOGICAL DEVELOPMENT OF THE CROP**
\[
\text{DS} = \text{INTGRL} (\text{DSI,INSW(DS-.1.1.,DEV,DRAM)})
\]
\[
\text{DRV} = \text{DRCV} \times \text{DRED} \times \text{DREW} \times \text{AFGEN(DRVT,TPAV)}
\]
DRED = AFGEN(DRDT, DLP)
DRR = DRCR*AFGEN(DRRTT, TPAV)

WLVT = WLVT+WLV
WLVT = WLVT+WS+WIR
WLSO = WLVT+WLS
HI = WSO/WSS
RSH = RMLV+RMT+RMSO+RMMA+RGLV+RGST+RGSO+RLSR
WSTR = WST+WIR

**EFFECTS OF WATER SHORTAGE**

CPW = AMIN(1., 0.5+TRW/(TRC+1.0-10))
DREW = AFGEN(DRW+TRW/(TRC+1.0-10))
PCW = TRW/(TRC+1.0-10)
PLEH = AFGEN(PLHTT, VPDC)

**ROOTED DEPTH AND CROP HEIGHT**

ZRT = INTGRL(ZRTI, GZRT+AND(ZRTM-ZRT, 1.0-DS))
ZRTM = AMIN1(ZRTMC, ZRTMS, TKLT)
GZRT = GZRTC*WSERT*TERT
PLHT = AFGEN(PLHTT, DS)

**GROWTH ROOTED DEPTH**

WSERT = INSW(ZRT-TK1, WSE1, INSW(ZRT-TKL1-TKL2, WSE2, WSE3))
TERT = AFGEN(PLHTT, TPS)

**POTENTIAL TRANSPERSION AND DIFFUSION RESISTANCES CANOPY**

TRC = TRCPF*ACPF(-0.5*ALV) + TRCPD*AMIN1(2.5, ALV)
TRCPF = SUEVTR(RDTC, RDTM, 0.25, DLA/24., TPAD, VPA, ...
RSLL, RSBL, RSTL)

RSLI = LIMIT(RSLL, 2000., (C02E-C02I)/(PLNA+1.0-10)*...
(68.4*24.0/1.6)-RSBL-RSTL)
C02I = C02E*FICE
RSLL = (C02E-C02I)/(PLM+0.4+1.0-10)*(68.4/1.6)-10.
PLNA = (PGCC/(DLA/2.1)-RMV/0.33)/(AMIN1(2.5, ALV+1.0-10))
RSBL = 0.5*172.*SQRT(WDLV/(WDSAD*0.6))
RSTL = FURSC(WDSAD, AMIN1(2.5, ALV), PLHT, 2.)

TRRM = TRC/(ZRT+1.0-10)

**ACTUAL TRANSPERSION (WATER UPTAKE)**

TRW = TRW1+TRW2+TRW3
TRWL1 = TRRM*WSE1*ZRT1
TRWL2 = TRRM*WSE2*ZRT2
TRWL3 = TRRM*WSE3*ZRT3
TRWT = INTGRL(0., TRW)

WSE1 = FWS(TRC, ALV, WCL1, WSSC, WFSC, WCWP1, WCFC1, WCST1)
WSE2 = FWS(TRC, ALV, WCL2, WSSC, WFSC, WCWP2, WCFC2, WCST2)
WSE3 = FWS(TRC, ALV, WCL3, WSSC, WFSC, WCWP3, WCFC3, WCST3)
ZRT1 = LIMIT(0., TKL1, ZRT)
ZRT2 = LIMIT(0., TKL2, ZRT-TKL1)
ZRT3 = LIMIT(0., TKL3, ZRT-TKL1-TKL2)

**POTENTIAL EVAPORATION SOIL
EVSC = EVSPR*EXP(-0.5*ALV)+EVSPD
EVSPR, EVSPD=SUEVTR(RDTC, RDTM, RFS, 1.00, TFAV, VPA, ...
  0.00, RSBS, RSTS)
RFS = RFS*(1.0-0.5*WCL1/WCST1)
RSBS = 172.*SQR(T(WDCL/WDSS)
WDSS = F Mech(WDLV, ALV, PLHT, WDSAV)
RSTS = F Mech(WDSAV, 1.0, PLHT, 0.63*PLHT)

** EVAPORATION
EVSW = INSW(DSLR-1.1, EVSH, EVSD)
EVSH = AMIN1(EVSC, ...
  (WL1*0.0001-WCAD1*TKL1)*1000./DELT+WLFL1)
EVSD = AMIN1(EVSC, ...
  0.6*EVSC*(SQR(T(DSLR)-SQR(T(DSLR-1.))+WLFL1)
EVSW1 = EVSW*(FEVL1/FEVLT)
EVSW2 = EVSW*(FEVL2/FEVLT)
EVSW3 = EVSW*(FEVL3/FEVLT)
FEVL1 = AMAX1(WL1-WCAD1*TKL1*1.4, 0.)*...
  EXP(-EES*(0.25*TKL1))
FEVL2 = AMAX1(WL2-WCAD2*TKL2*1.4, 0.)*...
  EXP(-EES*(TKL1+(0.25*TKL2))
FEVL3 = AMAX1(WL3-WCAD3*TKL3*1.4, 0.)*...
  EXP(-EES*(TKL1+TKL2+(0.25*TKL3))
FEVLT = FEVL1+FEVL2+FEVL3

** AVAILABLE AND TOTAL SOIL WATER
WCL1 = WL1/(TKL1*1.4)
WCL2 = WL2/(TKL2*1.4)
WCL3 = WL3/(TKL3*1.4)
WL1 = INTRGL(WL1, (WLFL1-WLFL2-EVSW1-TRWL1)*10.0)
WL2 = INTRGL(WL2, (WLFL2-WLFL3-EVSW2-TRWL2)*10.0)
WL3 = INTRGL(WL3, (WLFL3-WLFL4-EVSW3-TRWL3)*10.0)
WSLMM = (WL1+WL2+WL3)/10.0
WLFL1 = RAIN*1.0-FRNOF
WLFL2 = AMAX1(0., WLFL1-(WCFC1*TKL1*1000.-WL1*0.10)/DELT)
WLFL3 = AMAX1(0., WLFL2-(WCFC2*TKL2*1000.-WL2*0.10)/DELT)
WLFL4 = AMAX1(0., WLFL3-(WCFC3*TKL3*1000.-WL3*0.10)/DELT)

** WATER BALANCE CHECK
** Explanation in section 5.4
CKWFL = F Mech(CKWF, CKWIN, TIME)
CKWF = INTRGL(0., (WLFL1-EVSW-TRW-WLFL4)*10.)
CKWIN = WL1-WLII+WL2-WLII+W13-WLII

** Weather data and time
RDTM = RDTMT(IDATE)*RDUCF
RDTC, DLA, DLP = SUA STR(DATE, LAT)
TPAV = (TPLT(IDATE)+TPHT(IDATE))/2.
TPAD = (TPHT(IDATE)+TPAV)/2.
DATE = AMOD(DATER+TIME+364., 365.)+1.
IDATE = DATE

**Extra weather data
WDSAV = AMAX1(0.2, WDST(IDATE))
WDSAD = 1.33*WDSAV
VPA = AMIN1(FUVP(TPAD), HUAAT(IDATE))
RAIN = RAIN1(IDATE)

VFDC = (FUVP(TPAD)-VPA)*AMIN1(1., 30./RSTL)
DSLR = INTGRL(1.,...
INSW = RAIN1(IDATE+1)-0.51*(1.00001-DSLR)/DELT

CO2E = 340.*0.88**(ELV/1000.)
TPS = INTGRL(TPST,(TPAV-TPS)/5.)

WUPC = TRC * 1.E4/(PCGC+1.E-10)
WUPT = TRWT*1.E4/(PCGT+1.E-10)

**RUN CONTROL AND OUTPUT
METHOD RECT
TIMER DELT = 1., TIME = 0., FINTIM = 1000., PRDEL = 10., OUTDEL = 10.
FINISH DS = 2., CELVN = 3., TPAV = 3.

PAGE GROUP
PRINT DATE, DLV, WST, WRT, WSO, WRT, SLA, PLM, ALV, DS, ZRT, ...
RAIN, RDTM, VPA, TPAV, TRC, TRW, EVSC, EVSW, WUPC, WUPT, ...
WSE1, WSE2, WSE3, DSLR

*Weather data Los Banos (IRRI) 1984

PARAM RDCF = 1.E6
PARAM ELV = 21.0
PARAM LAT = 14.17
PARAM ZREF = 2.0

* Daily total precipitation in mm
TABLE RAIN1(1-365) = ...
   0.4, 0.0, 0.0, 1.4, 0.0, 1.1, 1.4, 0.0, 0.0, 0.0, ...
e tc.
* Daily minimum temperature in degrees Celsius
TABLE TPLT(1-365) = ...
   22.0, 21.4, 22.1, 21.4, 22.0, 22.0, 23.3, 21.4, 21.0, 21.5, ...
e tc.
* Daily maximum temperature in degrees Celsius
TABLE TPHT(1-365) = ...
   26.4, 27.9, 26.9, 24.5, 27.7, 28.5, 27.5, 26.7, 27.8, 28.6, ...
e tc.
* Daily representative vapour pressure in kPa
TABLE HUAAT(1-365) = ...
   2.08, 2.02, 2.20, 2.37, 2.01, 2.04, 2.53, 1.94, 1.96, 2.09, ...
e tc.
* Daily mean windspeed in m/s
TABLE WDST(1-365) = ...
1.6, 1.4, 1.1, 0.9, 1.6, 1.2, 1.0, 1.3, 1.3, 1.1, ...
   etc.
* Daily total global irradiation in MJ/m**2/day
TABLE RDTM(1-365) = ...
   9.85,12.98, 8.88, 4.57,10.52,13.59, 9.63,14.80,12.52,11.66, ...
   etc.
END
STOP

FUNCTION FUPHOT(PLMx,PLEA,ALV,RDTM,DATE,LAT)
C to compute daily canopy photosynthesis
   etc.

FUNCTION FUCCHK(CKCIN,CKCFL,TIME)
C check on crop carbon balance
   etc.

SUBROUTINE SUASTR(DATE,LAT,RDT,C.DAYL,DAYLP)
C to calculate daylengths, daily total irradiation at top of
C atmosphere
   etc.

SUBROUTINE SUERRR(MNR,X,XMIN,XMAX,NUNIT)
C to check if variable X is between its minimal and maximal value
C (XMIN and XMAX resp.). If not, an error message is written to a
C file with unit number NUNIT, (6 for FOR06.DAT when running CSMP).
C and the program is stopped. If MIN or MAX is -99., no minimum
C or maximum is set.
C version: 28-08-1987
   etc.

SUBROUTINE SUASTC(DATE,LAT,RDTM,RDT,RFRFC,FAND,FOSLD,SINL,D,$DSINBE,SOCL,DAYL)
C to perform standard astronomical computations
   etc.

SUBROUTINE SUEVTR(RDTM,RDTM,RC,FRD,TPAD,VPA,RSN,RSB,RST,EVP,F,EVPF)
C potential evapotranspiration rates for crop, soil or free water
   CALL SUERRR(3.1,FRD,0.,1.,6.)
   VPS=FUPV(3.1)
   VPA=AMIN1(VPA,VPS)
   CALL SUERRR(3.2,VPS,VPA,-99.,6.)
   SLOPE =415.6*10.*VPS/(TPAD+239.)**2
   APSCH =0.67*(RSB+RST+RSN)/(RSB/0.93+RST)
   RLWI =4.8972E-3*(TPAD+273.)**4*(0.618+0.0365*SQR1(10.*VPA))
   RLWO =4.8972E-3*1.00*(TPAD+273.)**4
   RLF =RLWO-RLWI*(RDTM/RDT)*FRD
   RDTM =RDTM*(1.-RC)-RLW
EVPR = 0.001*RDTH*SLOPE/((SLOPE+APSCH)*2390.)
DRYP = (VPS-VPA)*10.*1200./(RSB+RST)*FRD
EVPD = 86400.*0.001*DRYP/((SLOPE+APSCH)*2390.)
RETURN END

FUNCTION FURSC(WDS,ALV,HT,ZREF)
C calculation of turbulent resistance to water vapour exchange
IMPLICIT REAL (A-Z)
ZR = AMAXI(ZREF,HT+1.)
D = AMAXI(0.1,0.63*HT)
ZNOT = AMAXI(0.05,0.1*HT)
WDSX = AMAXI(0.2,WDS)
ALVX = AMAXI(1.,ALV)
FURSC = 0.74*(ALOG((ZR-D)/ZNOT))**2/(0.16*WDSX)*ALVX
RETURN END

FUNCTION FUWRED(WDLV,ALV,PLHT,WDS)
C calculation of windspeed at the soil surface
C version 26-03-1987
IMPLICIT REAL (A-Z)
IF(ALV.GT.0.0) THEN
PLHTX = AMAXI(0.05,PLHT)
WDSX = AMAXI(0.1,WDS)
MIXL = SQRT(1.2732*WDLV/(ALV/PLHTX))
A = SQRT(0.2*ALV*PLHTX/(2.*MIXL*0.5))
FUWRED = WDSX*EXP(-A*(1.0-0.05/PLHTX))
ELSE
FUWRED = WDS
ENDIF
RETURN
END

FUNCTION FUVP(TP)
C vapour pressure (kPa) as a function of temperature (oC)
FUVP = 0.100*6.11*EXP(17.47*TP/(TP+239.))
RETURN
END

FUNCTION FUWS(TRC,ALV,WCL,WSSC,WFS,T,WFC1,WCST)
C reduction to water uptake, depending on volumetric soil water
C content, transpiration requirements, and crop characteristics
C
C version: 13-05-1987
C
IMPLICIT REAL (A-Z)
DATA A,B,ALVMAX/0.76,0.15,2./
IF(WCL.LE. WCFC) THEN
C calculation for soil below field capacity
SDPF=1./(A*B+ALVMAX*TRC/(ALV+1.E-10))-(1.-WSSC)*0.4
IF(WSSC.LT.0.6) THEN
C correction for curves of groups with WSSC less than 0.6
SDPF=SDPF+0.025*AMIN1(0.,ALVMAX*TRC/(ALV+1.E-10)-6.)/
     (1.+5.*WSSC+4.*WSSC*WSSC)
ENDIF
SOILP=AMIN1(1.,AMAX1(0.,SDPF))
WCP=WCP+(1.00-SOILP)*(WCFC-WCP)
FUWS=(WCL-WCP)/(WCX-WCP+1.E-10)
ELSE
C calculation for soil above field capacity
FUWS=1.-(1.-WFSC)*(WCL-WCFC)/(WCST-WCFC+1.E-10)
ENDIF
IF(FUWS.GT.1.0) FUWS =1.0
IF(FUWS.LT.0.0) FUWS =0.0
RETURN
END
FUNCTION FUWCHK(CKWIN,CKWFL,TIME)
C check on soil water balance
C version 26-03-1987
FUWCHK=(CKWIN-CKWFL)/(CKWIN+CKWFL+1.E-10)
IF(ABS(CKWIN-CKWFL).LT.0.001) RETURN
IF(ABS(FUWCHK).GT.0.01) WRITE (6,1) FUWCHK,CKWIN,CKWFL,TIME
1 FORMAT(//,'*** ERROR IN WATER BALANCE, PLEASE CHECK ***',//,
  'CKWRD=',F6.3,'CKWIN=',F8.2,'CKWFL=',F8.2,'AT TIME=',F6.1)
RETURN
END
Checklist for Crop data
1 Checklist for Potential Production

INCON
MLVI : Weight of Leaves, Initial
WSII : Weight of Stem, Initial
DSI : Development Stage, Initial
WSOI : Weight of Storage Organ, Initial

PARAM
FCLV : Fraction Carbon in Leaf
FCRT : Fraction Carbon in Root
FCSO : Fraction Carbon in Storage Organ
CPQLV : CO₂ Production during Glucose transformation into Leaf Biomass
CPGST : Idem, into Stem Biomass
CPGRT : Idem, into Root Biomass
CPGSO : Idem, into Storage Organ Biomass
CRGLV : Rel. Carbohydrate Requirement for Leaf Growth
CRGST : Idem, for Stem Growth
CRGRT : Idem, for Root Growth
CRGSO : Idem, for Storage Organ Growth
PLMXP : Max. Rate of Photosynthesis of Single Leaves
PLEI : Initial Efficiency of Absorbed Light by leaves

LEAF PHOT.

\[ \log \alpha = \text{PLEI} \]

\[ \text{PLEI} \]

LIGHT INTENSITY

PARAM
SLC : Specific Leaf Weight
SSC : Specific Stem Weight
FSR : Fraction Stem Weight which is Remobilizable
RMCLV : Maintenance Respiration Coefficient Leaves at TPR °C
DRCV : Development Rate in Vegetative Period (= 1/vegetative period) at ___°C

\[ \text{kg leaf ha}^{-1} \text{ leaf} \]
\[ \text{kg stem ha}^{-1} \text{ stem} \]
\[ \text{kg } \text{ CO}_2 \text{ kg}^{-1} \text{ biomass} \]
\[ \text{kg } \text{ CO}_2 \text{ ha}^{-1} \text{ h}^{-1} \]
\[ \text{kg } \text{ CO}_2 \text{ ha}^{-1} \text{ h}^{-1} \]
\[ \text{(J m}^{-2} \text{ s}^{-1})^{-1} \]
DRCR : Development Rate in Generative Period (\(= 1/\text{generative period}\)) at \(\text{ degree}\) \(\text{C}\) \(\text{d}^{-1}\)

TPR : Reference Temperature for Maintenance Respiration \(\text{C}\)

\(Q_{10}\) : Maintenance Respiration is \(Q_{10}\) times Higher at a Temperature Increase of 10\(\text{C}\)

\[ Q_{10} = \frac{a+b}{b} \]

FEPSO : Fraction Economic Product in Storage Organ (Dry Weight) \(\text{kg kg}^{-1}\)

DATEB : Number of Day at Beginning of Simulation

FUNCTION \(\text{LLVI}\) : Relative Leaf Death Rate as Function of Development Stage = Fraction of Leaves Dying Each Day as Function of Development Rate.

\[ \text{FRACTION LEAF DAY}^{-1} \]

LRTT : Idem, for Roots

SLT : Multiplication Factor for Specific Leaf Weight as Function of Development Stage

\[ \text{MULTIPLICATION FACTOR} \]
PLMTT : Multiplication Factor for Maximum Photosynthesis at Light Saturation as Function of Temperature

PLETT : Multiplication Factor for Light Use Efficiency as Function of Temperature

DRVTT : Multiplication Factor of Development Rate in Vegetative Period as Function of Temperature

DRRTT : Idem, for Generative Period

DRDT : Multiplication Factor of Development Rate in Vegetative Period as function of Daylength.

(graph see next page)
MULTIPLICATION FACTOR

CASST : Fraction of Available Carbohydrates going to Shoot + Storage Organ as a Function of the Development Stage.

FRACTION

CALVT : Fraction of Available Carbohydrates for Shoot + Storage Organ going to the Leaves as Function of Development Stage.

FRACTION

CASIT : Idem, going to the Stems.

FRACTION
2. Checklist for Actual Production

**INCON**
- **ZRTI** : Root Length, Initial

**PARAM**
- **FIEC** : Fraction of External CO$_2$ Concentration in the Leaf ([CO$_2$])
- **WDLV** : Leaf Width
- **ZRTMC** : Maximum Root Zone, Crop Characteristic
- **GZRTC** : Growth of Root Length at Certain Soil Temperature and Without Water Stress (m.d$^{-1}$)
- **WSSC** : Water Stress Sensitivity Coefficient (1 - 5: very sensitive - hardy)
- **WFSC** : Water Flooding Sensitivity Coefficient (1 - 3: insensitive - sensitive)

**FUNCTION**
- **DRWT** : Multiplication Factor of Development Rate in the Vegetative Phase as a function of Actual Transpiration/Potential Transpiration.

**PLHT**
- **PLHIT** : Plant Height as a function of Development Stage

- **MULTIPLICATION FACTOR**

- **PLANT HEIGHT**
Checklist for Soil data

1 Checklist for Potential Production

No Soil Data needed.

2 Checklist for Actual Production

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCON</td>
<td>Relative Water Content (Volumetric)</td>
<td></td>
</tr>
<tr>
<td>WCLI1</td>
<td>Initial, Soil Layer 1</td>
<td>( m^3 \cdot m^{-3} )</td>
</tr>
<tr>
<td>WCLI2</td>
<td>Idem, Soil Layer 2</td>
<td>( m^3 \cdot m^{-3} )</td>
</tr>
<tr>
<td>WCLI3</td>
<td>Idem, Soil Layer 3</td>
<td>( m^3 \cdot m^{-3} )</td>
</tr>
<tr>
<td>PARAM</td>
<td>Thickness Soil Layer 1</td>
<td>( m )</td>
</tr>
<tr>
<td>TKL1</td>
<td>Idem, Soil Layer 2</td>
<td>( m )</td>
</tr>
<tr>
<td>TKL2</td>
<td>Idem, Soil Layer 3</td>
<td>( m )</td>
</tr>
<tr>
<td>TKL3</td>
<td>Idem, Soil Layer 3</td>
<td>( m )</td>
</tr>
<tr>
<td>ZRTHS</td>
<td>Maximum Root Zone, Soil Characteristic</td>
<td>( m )</td>
</tr>
<tr>
<td>WCFC1</td>
<td>Water Content of Soil Layer 1 at Field Capacity</td>
<td>( m^3 \cdot m^{-3} )</td>
</tr>
<tr>
<td>WCFC2</td>
<td>Idem, of Soil Layer 2</td>
<td></td>
</tr>
<tr>
<td>WCFC3</td>
<td>Idem, of Soil Layer 3</td>
<td></td>
</tr>
<tr>
<td>WCWP1</td>
<td>Water Content of Soil Layer 1 at Wilting Point</td>
<td>( m^3 \cdot m^{-3} )</td>
</tr>
<tr>
<td>WCWP2</td>
<td>Idem, of Soil Layer 2</td>
<td></td>
</tr>
<tr>
<td>WCWP3</td>
<td>Idem, of Soil Layer 3</td>
<td></td>
</tr>
<tr>
<td>WCS11</td>
<td>Water Content of Soil Layer 1 at Saturation</td>
<td>( m^3 \cdot m^{-3} )</td>
</tr>
<tr>
<td>WCS12</td>
<td>Idem, of Soil Layer 2</td>
<td></td>
</tr>
<tr>
<td>WCS13</td>
<td>Idem, of Soil Layer 3</td>
<td></td>
</tr>
<tr>
<td>WCAD1</td>
<td>Water Content of Soil Layer 1 when Air Dry</td>
<td>( m^3 \cdot m^{-3} )</td>
</tr>
<tr>
<td>WCAD2</td>
<td>Idem, of Soil Layer 2</td>
<td></td>
</tr>
<tr>
<td>WCAD3</td>
<td>Idem, of Soil Layer 3</td>
<td></td>
</tr>
<tr>
<td>ERSOF</td>
<td>Fraction Run Off</td>
<td></td>
</tr>
<tr>
<td>CESL</td>
<td>Extinction Coefficient of Evaporation in Soil</td>
<td></td>
</tr>
</tbody>
</table>

(graph see next page)
\[ \text{EVAP}_{1CK} = \text{EVAP}_0 \cdot e^{-(\text{EESL} \cdot 1CK)} \]

SOIL DEPTH

\[ \text{EVSLE} : \text{Maximum Evaporation of Soil when 1 Day of } mm.d^{-1} \]
no Rainfall (to calculate evaporation of soil after at least 2 days no rainfall).

RCSE : Reflection Coefficient of Soil

FUNCTION:

No Functions Needed.
### Abbreviations in Main Programs

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALV(I)</td>
<td>Area leaves (initial)</td>
</tr>
<tr>
<td>CAG(CR, LV, RT, SO, SS, ST)</td>
<td>Carbohydrates (glucose) available for growth of total crop (CR), leaves (LV), roots (RT), storage organs (SO), shoot plus storage organs (SS) and stems (ST)</td>
</tr>
<tr>
<td>CALVT</td>
<td>Relation of relative fraction of CAGLV to DS</td>
</tr>
<tr>
<td>CASST</td>
<td>Relation of relative fraction of CAGSS to DS</td>
</tr>
<tr>
<td>CASTT</td>
<td>Relation of relative fraction of CAGST to DS</td>
</tr>
<tr>
<td>CELV</td>
<td>Carbohydrate export (glucose, 24 h total) from leaves plus stems, excluding remobilization</td>
</tr>
<tr>
<td>CELVN</td>
<td>Number of days that CELV is negative</td>
</tr>
<tr>
<td>CKCFL</td>
<td>Sum of carbon fluxes into and out of the crop</td>
</tr>
<tr>
<td>CKCIN</td>
<td>Carbon in the crop accumulated since simulation started</td>
</tr>
<tr>
<td>CKCHR</td>
<td>Difference between carbon added to the crop since initialization and the net total of carbon fluxes, relative to their sum</td>
</tr>
<tr>
<td>CKWFL</td>
<td>Sum of water fluxes into and out of soil compartments</td>
</tr>
<tr>
<td>CKWIN</td>
<td>Change in total soil water content since initialization</td>
</tr>
<tr>
<td>CKWRF</td>
<td>Relative difference between two water balance computations</td>
</tr>
<tr>
<td>CO2E</td>
<td>CO2 concentration ambient air</td>
</tr>
<tr>
<td>CO2I</td>
<td>CO2 concentration in stomatal cavity</td>
</tr>
<tr>
<td>CPEW</td>
<td>Effect of water stress on carbohydrate partitioning</td>
</tr>
<tr>
<td>CPG(LV, RT, SO, ST)</td>
<td>Weight of CO2 produced during formation (=growth) of 1 kg of dry matter of leaves (LV), roots (RT), storage organs (SO) and stem (ST)</td>
</tr>
<tr>
<td>CRG(LV, RT, SO, ST)</td>
<td>Weight of carbohydrates required for growth of 1 kg of leaves (LV), roots (RT), storage organs (SO), stems (ST)</td>
</tr>
<tr>
<td>CSA</td>
<td>Soil evaporation constant A (Subsection 5.3.6)</td>
</tr>
<tr>
<td>CSB</td>
<td>Soil evaporation constant B</td>
</tr>
<tr>
<td>CSC2</td>
<td>Soil evaporation constant C2</td>
</tr>
<tr>
<td>CUG(CR, LV, RT, SO, SR, ST)</td>
<td>Weight of carbohydrates used for growth of the whole crop (CR), leaves (LV) roots (RT), storage organs (SO), shielded reserves (SR) and stems (ST)</td>
</tr>
<tr>
<td>DATE(B)</td>
<td>Julian date (at beginning of simulation)</td>
</tr>
<tr>
<td>DLA</td>
<td>Daylength, astronomical</td>
</tr>
<tr>
<td>DLF</td>
<td>Daylength effective for photoperiodism</td>
</tr>
<tr>
<td>DR(R, V)</td>
<td>Development rate crop in the vegetative (V) and reproductive (R) phase</td>
</tr>
<tr>
<td>DRC(R, V)</td>
<td>Development rate constant in the vegetative (V) and reproductive (R) phase</td>
</tr>
<tr>
<td>DRDT</td>
<td>Relation of DRED to daylength</td>
</tr>
<tr>
<td>DRED</td>
<td>Effect of daylength in DRV</td>
</tr>
<tr>
<td>DREW</td>
<td>Effect of water stress in DRV</td>
</tr>
<tr>
<td>DRRTT</td>
<td>Relation of DRR to temperature</td>
</tr>
<tr>
<td>DRSL</td>
<td>Water drained from deepest soil layer (equals WLFL4)</td>
</tr>
<tr>
<td>DRVTT</td>
<td>Relation of DRV to temperature</td>
</tr>
<tr>
<td>DWRT</td>
<td>Relation of DREW to level of water stress</td>
</tr>
<tr>
<td>DS(I)</td>
<td>Phenological development stage crop (initial)</td>
</tr>
<tr>
<td>DSLR</td>
<td>Number of days since last rain</td>
</tr>
<tr>
<td>kg ha⁻¹ d⁻¹</td>
<td>Kilogram per hectare per day</td>
</tr>
<tr>
<td>m³ ha⁻¹</td>
<td>Cubic meter per hectare</td>
</tr>
<tr>
<td>m³ ha⁻¹</td>
<td>Cubic meter per hectare</td>
</tr>
<tr>
<td>vppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>d⁻¹</td>
<td>Day to the power of -1</td>
</tr>
<tr>
<td>mm d⁻¹</td>
<td>Millimeter per day</td>
</tr>
</tbody>
</table>
| d             | Day
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTIME</td>
<td>time in current day</td>
<td>d</td>
</tr>
<tr>
<td>DTMIN</td>
<td>minimum timestep for SAWAH</td>
<td>d</td>
</tr>
<tr>
<td>DTMX1</td>
<td>maximum timestep for SAWAH</td>
<td>d</td>
</tr>
<tr>
<td>DTFX</td>
<td>fixed timestep for SAWAH</td>
<td>d</td>
</tr>
<tr>
<td>EES</td>
<td>extinction coefficient for evaporation in soil</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>ELV</td>
<td>elevation of growth site above sea level</td>
<td>m</td>
</tr>
<tr>
<td>EVSC</td>
<td>potential soil evaporation rate for current weather conditions and crop</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>EVSD</td>
<td>evaporation rate soil on dry days (i.e. almost no rain)</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>EVSH</td>
<td>evaporation rate soil on humid days</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>EVSPD</td>
<td>potential evaporation soil due to drying power air</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>EVSPR</td>
<td>potential evaporation soil due to radiation</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>EVSW</td>
<td>evaporation rate from the soil (actual value)</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>EVSW1-3</td>
<td>EVSW for individual soil compartments</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>FADL</td>
<td>fraction to adapt time interval to account for daylength</td>
<td>-</td>
</tr>
<tr>
<td>FC(LV,RT,SO,ST)</td>
<td>fraction weight of carbon of total dry weight in leaves (LV), roots (RT), storage organs (SO) and stems (ST)</td>
<td>kg kg⁻¹</td>
</tr>
<tr>
<td>FEPSO</td>
<td>fraction economic product in storage organs (dry weights)</td>
<td>kg kg⁻¹</td>
</tr>
<tr>
<td>FEVL1-3/FEVLT</td>
<td>fraction of EVSW from soil compartments 1-3</td>
<td>fraction</td>
</tr>
<tr>
<td>FIEC</td>
<td>ratio of CO₂ vs CO₂</td>
<td>fraction</td>
</tr>
<tr>
<td>FRNOF</td>
<td>fraction of precipitation that runs off</td>
<td>-</td>
</tr>
<tr>
<td>FSTR</td>
<td>fraction stem weight at flowering that is remobilizable</td>
<td>kg kg⁻¹</td>
</tr>
<tr>
<td>GAR</td>
<td>growth rate of available reserves (glucose)</td>
<td>kg ha⁻¹d⁻¹</td>
</tr>
<tr>
<td>G(CR,LV,RT,SO,SR,ST)</td>
<td>growth rate (dry matter) of the whole crop (CR), leaves (LV), roots (RT), storage organs (SO), shielded reserves (SR, starch) and stems (ST)</td>
<td>kg ha⁻¹d⁻¹</td>
</tr>
<tr>
<td>GLA</td>
<td>growth rate leaf area</td>
<td>kg ha⁻¹d⁻¹</td>
</tr>
<tr>
<td>GSA</td>
<td>growth rate photosynthetically active stem area</td>
<td>ha ha⁻¹d⁻¹</td>
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<tr>
<td>GSOAV</td>
<td>running average of GSO</td>
<td>ha ha⁻¹d⁻¹</td>
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<tr>
<td>GSOAVH</td>
<td>maximum value of GSOAV</td>
<td>ha ha⁻¹d⁻¹</td>
</tr>
<tr>
<td>GSGM</td>
<td>maximum growth rate storage organs</td>
<td>kg ha⁻¹d⁻¹</td>
</tr>
<tr>
<td>GSRM</td>
<td>maximum relative growth rate storage organs</td>
<td>kg ha⁻¹d⁻¹</td>
</tr>
<tr>
<td>GSRC</td>
<td>potential rate of GSR</td>
<td>kg ha⁻¹d⁻¹</td>
</tr>
<tr>
<td>GZRT</td>
<td>growth rate rooting depth</td>
<td>m d⁻¹</td>
</tr>
<tr>
<td>GZRTC</td>
<td>maximum value of GZRT</td>
<td>m d⁻¹</td>
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<tr>
<td>HI</td>
<td>harvest index (based on above ground dry matter)</td>
<td>kg kg⁻¹</td>
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<tr>
<td>HUAAT</td>
<td>table of values of VPA during year</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>runner in DO-loops</td>
<td>-</td>
</tr>
<tr>
<td>IDATE</td>
<td>integer value of DATE</td>
<td>d</td>
</tr>
<tr>
<td>ITYL</td>
<td>integer value soil type number</td>
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<tr>
<td>KEEP</td>
<td>CSMP variable, 0.0 during trial run DYNAMIC, otherwise 1.</td>
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<tr>
<td>KMSA1</td>
<td>soil characteristic</td>
<td>-</td>
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<tr>
<td>KMSA1X</td>
<td>table of characteristics of soil types</td>
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<tr>
<td>KMSA2</td>
<td>soil characteristic</td>
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<tr>
<td>KMSA2X</td>
<td>table of characteristics of soil types</td>
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<tr>
<td>KMXX</td>
<td>table of characteristics of soil types</td>
<td>-</td>
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<tr>
<td>KMSX</td>
<td>soil characteristic</td>
<td>-</td>
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<tr>
<td>KST</td>
<td>soil characteristic</td>
<td>-</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>KSTX</td>
<td>table of characteristics of soil types</td>
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<tr>
<td>LAT</td>
<td>latitude (south of equator negative values)</td>
<td>degree</td>
</tr>
<tr>
<td>LLA</td>
<td>rate of loss of leaf area</td>
<td>ha ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>LLV</td>
<td>rate of loss of leaf weight (dry matter)</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>LLVT</td>
<td>relation of relative loss of leaves to DS</td>
<td></td>
</tr>
<tr>
<td>LRT</td>
<td>relative rate of loss of root dry matter</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>LRTT</td>
<td>relation of relative loss rate due to aging to DS</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>LSR</td>
<td>rate of loss of shielded reserves to WAR</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>LSTR</td>
<td>loss rate of stem reserves (glucose)</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>MCLV</td>
<td>trigger for mobilization of carbohydrates from leaves</td>
<td></td>
</tr>
<tr>
<td>MCSR</td>
<td>trigger for mobilization of carbohydrates from shielded reserves</td>
<td></td>
</tr>
<tr>
<td>MCRT</td>
<td>trigger for mobilization of carbohydrates from roots</td>
<td></td>
</tr>
<tr>
<td>MSWCA</td>
<td>soil characteristic</td>
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</tr>
<tr>
<td>MSWCAx</td>
<td>table of characteristics of soil types</td>
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<tr>
<td>NIGH</td>
<td>variable to indicate day part: night (1) or day (0)</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td>number of soil compartments simulated in SAWAH</td>
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</tr>
<tr>
<td>PCEW</td>
<td>effect of water stress on PCGC</td>
<td></td>
</tr>
<tr>
<td>PCGC</td>
<td>photosynthesis canopy, gross, in current weather and physiological state (level 1), as CO(_2) per daytime period</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>PCGD</td>
<td>PCGC expressed per 24 h (equal to PCGC for 1 d time steps)</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>PCGDV</td>
<td>running average of PCGD</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>PGST</td>
<td>PCGC totaled since start of simulation</td>
<td>kg ha(^{-1})</td>
</tr>
<tr>
<td>PCCW</td>
<td>photosynthesis canopy, gross, reduced by water shortage (level 2), as CO(_2)</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>PCNSH</td>
<td>net photosynthesis above ground part crop</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>PCNTH</td>
<td>net canopy photosynthesis totaled since start of simulation</td>
<td>kg ha(^{-1})</td>
</tr>
<tr>
<td>PLEA</td>
<td>PLEI at actual temperature</td>
<td>kg CO(_2) ha(^{-1}) h(^{-1})(J m(^{-2}) s(^{-1}))</td>
</tr>
<tr>
<td>PLEH</td>
<td>direct effect air humidity on PLMX</td>
<td></td>
</tr>
<tr>
<td>PLEI</td>
<td>initial efficiency use absorbed light by individual leaves as PLEA</td>
<td></td>
</tr>
<tr>
<td>PLETT</td>
<td>relation of PLEI to temperature</td>
<td></td>
</tr>
<tr>
<td>PLHT</td>
<td>plant height</td>
<td>m</td>
</tr>
<tr>
<td>PLHHT</td>
<td>relation of PLHT to DS</td>
<td></td>
</tr>
<tr>
<td>PLMDT</td>
<td>relation of PLMX to DS</td>
<td></td>
</tr>
<tr>
<td>PLMHT</td>
<td>relation of PLMX to air humidity</td>
<td></td>
</tr>
<tr>
<td>PLMXT</td>
<td>relation of PLMX to temperature</td>
<td></td>
</tr>
<tr>
<td>PLMX</td>
<td>maximum rate of photosynthesis of single leaves (CO(_2)) in current conditions</td>
<td>kg ha(^{-1})h(^{-1})</td>
</tr>
<tr>
<td>PLMXP</td>
<td>PLMX for standard SLC and optimal conditions</td>
<td>kg ha(^{-1})h(^{-1})</td>
</tr>
<tr>
<td>PLMXT</td>
<td>PLMX adjusted for leaf thickness</td>
<td>kg ha(^{-1})h(^{-1})</td>
</tr>
<tr>
<td>PLNA</td>
<td>daytime average of leaf net photosynthesis per unit area</td>
<td>kg ha(^{-1})d(^{-1})</td>
</tr>
<tr>
<td>Q10</td>
<td>Q10 of maintenance respiration sensitivity to temperature</td>
<td></td>
</tr>
<tr>
<td>RAIN</td>
<td>precipitation</td>
<td>mm d(^{-1})</td>
</tr>
<tr>
<td>RAINNE</td>
<td>amount of rain that infiltrates the soil</td>
<td>mm d(^{-1})</td>
</tr>
<tr>
<td>RAINTE</td>
<td>table of daily precipitation values during a year</td>
<td></td>
</tr>
<tr>
<td>RCRT</td>
<td>respiration crop, totaled (for CO(_2))</td>
<td>kg ha(^{-1})</td>
</tr>
<tr>
<td>RTDC</td>
<td>radiation, daily total global above atmosphere (400-1400 nm) J m(^{-2}) d(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>
RDTM  radiation, daily total global, measured (400-1400 nm)  J m⁻² d⁻¹
RDTMT table of measured daily total global radiation during year
RDUCF radiation units conversion factor variable
RFS reflection coefficient soil for RDTM fraction
RFSD RFS for dry soil fraction
RG(CR,LV,RT,SO,SR,ST) respiration (in CO₂) due to growth of the kg ha⁻¹ d⁻¹
whole crop (CR), leaves (LV), roots (RT), storage organs (SO) shielded reserves (SR) and stems (ST)
RLLV respiration caused by remobilization from dying leaves kg ha⁻¹ d⁻¹
RLSR respiration caused by remobilization (loss) of shielded kg ha⁻¹ d⁻¹
reserves
RMC(LV,RT,SO,ST) standard coefficient for maintenance respiration (CO₂) kg kg⁻¹ d⁻¹
of leaves (LV), roots (RT), storage organs (SO), stems (ST)
RM(CR,LV,RT,SO,ST) maintenance respiration (CO₂) of whole crop (CR), kg ha⁻¹ d⁻¹
leaves (LV), roots (RT), storage organs (SO), stems (ST)
RMCT RMCR, totaled since initialization kg ha⁻¹
RMLVD,W RMLV in daytime (D) and nighttime (N) kg ha⁻¹ d⁻¹
RMMA maintenance respiration due to metabolic activity kg ha⁻¹ d⁻¹
RSB(L,S) boundary layer resistance for water vapour diffusion from s m⁻¹
average leaf (L) or soil (S)
RSH respiration rate of the shoot (growth plus maintenance resp) kg ha⁻¹ d⁻¹
RSLLL leaf resistance for water vapour diffusion in average leaf s m⁻¹
RSLLM minimum value of RSLLL s m⁻¹
RST(L,S) resistance to diffusion for water vapour, CO₂ and heat due s m⁻¹
to turbulence in canopy from average leaf (L) or soil (S)
RUNOF water flowing from surface to other fields mm d⁻¹
SLA specific leaf weight, actual value (eventually corrected kg ha⁻¹
for contribution stem area)
SLC specific leaf weight constant kg ha⁻¹
SLN SLA for new leaves kg ha⁻¹
SLT relation of SLA to DS kg ha⁻¹
SST specific stem weight constant (SLC analogy)

TERT effect of temperature on root water uptake
TKL(I)1-3 thickness soil compartment I, 1-3 m
TKLT thickness of combined soil compartments m
TYL(1-NL) number indicating soil type of compartment

TPA(A,D,V) actual air temperature at each DTIME (A), in day time °C
(T) and 24h average (V)
TPEM temperature effect on maintenance respiration
TPHT table of maximum day temperatures during a year
TPLT table of minimum night temperatures during a year
TPR reference temperature for maintenance respiration °C
TPS(I) temperature of the soil (initial) °C

TRC transpiration rate canopy, potential value for current mm d⁻¹
weather and crop (level 1)
TRCP(D,R) potential transpiration canopy due to drying power air mm d⁻¹
(D) and absorbed radiation (R)
TRRM potential transpiration rate per unit W CO₂ leaf (mm d⁻¹)
TRW transpiration rate canopy, actual value with water mm d⁻¹
stress (level 2)
TRWLI-J,1-NL TRW from individual compartments 1-3 or 1-NL mm d⁻¹
TRWT TRW totaled since start of simulation mm
VPA humidity of the air, early morning value kPa
VPD vapour pressure difference kPa
VPDC vapour pressure deficit in canopy, daytime average kPa

WAR(I) weight available carbohydrate (glucose) in leaves (initial) kg ha\(^{-1}\)
WARR WAR relative to WLV
WC(AD,FC,ST,WP) volumetric water content of soil when air dry (AD), at wilting point (WP), field capacity (FC) and saturation (ST, equals relative total pore space); all variables are indexed 1-NL in SAWAH m\(^{3}\) m\(^{-3}\)
WCL(I)1-3 volumetric soil water content per compartment (initial) m\(^{3}\) m\(^{-3}\)
WCL(I)(1-NL) same as WCL(I)1-3 in module with soil water table m\(^{3}\) m\(^{-3}\)
WCR weight crop, including roots kg ha\(^{-1}\)
WCTX table of water content at saturation for soil types - m
WDCL width of soil clod (WDLV analogue) m
WDLV width of leaves

WDST table of daily values of observed wind speeds during a year m \(\text{s}^{-1}\)
WEPSO weight economic part of storage organs kg ha\(^{-1}\)
WFLEX water flow into the soil compartments due to changing soil water table

WFSC flooding stress sensitivity coefficient
WIR weight increment reserves (starch) since start simulation kg ha\(^{-1}\)
WLA water available to the crop in a layer m \(\text{ha}^{-1}\)

WLFL1-4 fluxes of water into layers 1-3 and out of layer 3 mm d\(^{-1}\) layer\(^{-1}\)
WL0(I) water standing above soil surface m
WL0X maximum level of water on the surface m
WLV(I) weight leaves (initial) kg ha\(^{-1}\)
WLVD weight dead leaves kg ha\(^{-1}\)
WLVD0 total above ground dry weight kg ha\(^{-1}\)
WLVT sum of WLV, WLVD and WST kg ha\(^{-1}\)
WLVT sum of WLV and WLVD kg ha\(^{-1}\)

WL1-3(I) volumetric soil water content per compartment (initial) kg ha\(^{-1}\)
WRT(I) weight roots (initial) kg ha\(^{-1}\)

WRTD weight dead roots kg ha\(^{-1}\)

WSF(1-3) effect of water stress on water uptake in layers 1-3 -
WSERT effect of water stress on root growth -
WSLAH total water in soil profile mm

WSO(I) weight storage organs (initial) kg ha\(^{-1}\)
WSR(I) weight of shielded reserves (starch) in stem (initial) kg ha\(^{-1}\)
WSS weight shoot plus storage organs kg ha\(^{-1}\)

WSC water stress sensitivity coefficient -

WSW(I) weight stems (initial) minus WSR or WIR contained in it kg ha\(^{-1}\)
WSR stem weight (WSW+WSR or WST+WIR, depending upon module) kg ha\(^{-1}\)

WTL(I) total water in the soil profile kg ha\(^{-1}\)

WUPC water use efficiency, current, relative to net photosynthesis leaves (water transpired per kg CO\(_2\) fixed, net, daytime) kg kg\(^{-1}\)

WUPT WUPC of total net photosynthesis and transpiration kg kg\(^{-1}\)

ZL(1-NL) depth of upper boundary of each soil compartment m

ZLH depth upper boundary compartment (SAWAH) m

ZREF reference height windspeed observations m

ZRT(I) rooting depth (initial) m

ZRTL rooting depth in individual layers (SAWAH) m

ZRTM maximum for ZRT m

ZRTM(C,S) maximum rooting depth, crop (C), soil (S) characteristic m

ZRT1-3 ZRT differentiated per soil compartment m

ZW(I) water table depth (initial) m

ZWTA table with observed ZW versus time
REFERENCES


Goudriaan, J. & H.H. van Laar, 1978b. Relations between leaf resistance, CO2-concentration and CO2-assimilation in maize, beans, Lalang grass and sunflower. Photo-


APPENDIX I

NUMERICAL EXAMPLES OF EQUATIONS USED IN THE MANUAL

Equation 3, page 19

Location: Lusaka, Zambia, latitude: 15° southern hemisphere
Date : 15 December
Crop : C3 crop (cereals)

\[ f_o = 0.59 \text{ (wet season)} \]
\[ F_{ov} = 333 + (356-333) \times (15-10)/(20-10) = 344.5 \]
\[ F_{oc1} = 784 + (834-784) \times (15-10)/(20-10) = 809.0 \]

\[ F_{oc} = 0.59 \times 344.5 + (1-0.59) \times 809 = 534.9 \text{ kg CO}_2 \cdot \text{ha}^{-1} \cdot \text{d}^{-1} \]

Equation 4, page 20

Location: Lusaka, Zambia, latitude: 15° southern hemisphere
Date : 15 December
Crop : C3 crop (cereals)

\[ H_a = 31.80 \times 10^6 \text{ J.m}^{-2} \cdot \text{d}^{-1} \text{ (table 3, page 22)} \]
\[ H_a = 16.72 \times 10^6 \text{ J.m}^{-2} \cdot \text{d}^{-1} \text{ (Agrometeorological report no. 9, Met.Dept. Lusaka, 1985)} \]

\[ f_o = \frac{(31.80 \times 10^6 - 16.72 \times 10^6)}{(31.80 \times 10^6 - 0.2 \times 31.80 \times 10^6)} = 0.59 \]

Equation 5, page 21

For a crop, \( k_a \) usually is 0.7 or 0.8
When \( \text{LAI}=1 \):
\[ f_n = 1 - e^{-0.7 \times 1} = 1 - 0.45 = 0.55 \text{; 55 \% is intercepted} \]
When \( \text{LAI}=5 \):
\[ f_n = 1 - e^{-0.7 \times 5} = 1 - 0.018 = 0.982 \text{; 98.2 \% is intercepted} \]

Equation 6, page 24

Location: Lusaka, Zambia, latitude: 15° southern hemisphere
Date : 15 December
Crop : C3 crop (cereals)

Suppose a crop dry weight of 150 kg DM.ha\(^{-1}\) (30 days after sowing) and a LAI of 0.2.
\[ F_{\text{net}} = F_{\text{net}}^* f_{\text{a}} * \frac{30}{44} = 534.9 \times (1 - e^{-0.8 \cdot 0.2}) \times \frac{30}{44} = 59.4 \text{ kg CH}_2\text{O ha}^{-1} \text{ d}^{-1} \]

\[ F_{\text{net}} = 0.70 \]

\[ R_{\text{es}} = 0.015 \]

\[ W = 150 \]

\[ W = 0.70 \times (59.4 - 0.015 \times 150) = 40.0 \text{ kg DM ha}^{-1} \text{ d}^{-1} \]

**Equation on page 65**

Suppose a C3 crop with open stomata at 30°C.

\[ r_e = 1.00 \text{ s cm}^{-1} \]

\[ r_b = 0.15 \text{ s cm}^{-1} \]

\[ \text{H}_2\text{O_{int}} = 30.10^{-6} \text{ g H}_2\text{O cm}^{-2} \text{ air} \]

\[ \text{H}_2\text{O_{ext}} = 13.10^{-6} \text{ g H}_2\text{O cm}^{-2} \text{ air (RH=43%) } \]

\[ T = \frac{30.10^{-6} - 13.10^{-6}}{1.15} = 14.78 \times 10^{-6} \text{ g H}_2\text{O cm}^{-2} \text{ s}^{-1} \]

\[ = 0.53 \text{ kg H}_2\text{O m}^{-2} \text{ leaf h}^{-1} \]

**Equation on page 67**

Suppose a C3 crop with open stomata.

\[ r_e = 1.60 \text{ s cm}^{-1} \]

\[ r_b = 0.20 \text{ s cm}^{-2} \]

\[ \text{CO}_2_{ext} = 6.222 \times 10^{-3} \text{ kg CO}_2 \text{ cm}^{-2} \text{ air (=340 ppm) } \]

\[ \text{CO}_2_{int} \text{ (stomatal cavity)} = 0.70 \times \text{CO}_2_{ext} = 4.355 \times 10^{-3} \]

\[ A = \frac{6.222 \times 10^{-3} - 4.355 \times 10^{-3}}{0.20 + 1.60} = 1.037 \times 10^{-3} \text{ kg CO}_2 \text{ cm}^{-2} \text{ leaf s}^{-1} \]

\[ = 37.3 \text{ kg CO}_2 \text{ ha}^{-1} \text{ leaf h}^{-1} \]

**Equation on page 77**

Location: Lusaka, Zambia, latitude: 15° southern hemisphere

Date: 15 December

Crop: C3 crop (cereals)

\[ P_{\text{net}} = 534.9 \text{ kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1} \]

Humous sand, 20 vol% \( \text{H}_2\text{O} \): \( pF = 3 \) (Figure 6, page 75)

\[ T_{\text{act}}/T_{\text{pot}} = 1 \] (Figure 7, page 76)

\[ F_{\text{act}} = 534.9 \text{ kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1} \]

Heavy clay, 20 vol% \( \text{H}_2\text{O} \): \( pF = 4.5 \) (Figure 6, page 75)

\[ T_{\text{act}}/T_{\text{pot}} = 0 \] (Figure 7, page 76)

\[ F_{\text{act}} = 0 \text{ kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1} \]
APPENDIX 11

ANSWERS TO EXERCISES

Exercise 1
The results are obtained from Table 1 (for C1 species) and Table 2 (for C2 species) through interpolation.

A general formulation to obtain a value y (gross assimilation in this case) corresponding to a value v (latitude in this case) by interpolation between two points \((x_1, y_1)\) and \((x_2, y_2)\) is:

\[
y = y_1 + (y_2 - y_1) \cdot \frac{(x - x_1)}{(x_2 - x_1)}
\]

Exercise 2
For \(\text{LAI} = 1.5\), Equation 5 yields:

\[
f_k = 1 - e^{-0.8 \times 1.5} = 0.7
\]

Multiplying gross assimilation obtained in Exercise 1 with this reduction factor results in the values for an LAI = 1.5.

Exercise 3
Follow the calculation scheme as given in Table 6, substituting your own latitude in the interpolation procedure.

Exercise 4
Development rate (d') for specified temperatures

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>10</th>
<th>17.5</th>
<th>25</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>o</td>
<td>0.0091</td>
<td>0.0143</td>
<td>0.0192</td>
<td>0.0213</td>
</tr>
<tr>
<td>*</td>
<td>0.0098</td>
<td>0.0147</td>
<td>0.0192</td>
<td>0.0222</td>
</tr>
<tr>
<td>x</td>
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<td>0.0192</td>
<td>0.0228</td>
<td>0.0233</td>
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<tr>
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<td>0.0250</td>
<td>0.0303</td>
<td>0.0333</td>
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<td>[]</td>
<td>0.0141</td>
<td>0.0192</td>
<td>0.0250</td>
<td></td>
</tr>
</tbody>
</table>

Notice that the relation between temperature and development rate is linear over a wide range of temperatures.

Exercise 5

\[
\text{TU}_{\text{pre-anthesis}} = 760 \text{ d °C}
\]

\[
\text{TU}_{\text{post-anthesis}} = 660 \text{ d °C}
\]

\[
T_{\text{threshold}} = 10 \text{ °C}
\]

Development stage in pre-silking period (ending when DVS = 1.0) follows from:

\[
\text{DVS} = \sum (T_1 - 10)/\text{TU}_{\text{pre-anthesis}}
\]

Development stage in post-silking period follows from:

\[
\text{DVS} = 1 + \sum (T_i - 10)/\text{TU}_{\text{post-anthesis}}
\]

where

- \(T_i\) is average air temperature on day \(i\)
- \(t_0\) is day of emergence
- \(t_1\) is day of silking
- \(t_2\) is day of maturity.
<table>
<thead>
<tr>
<th>Date</th>
<th>(T_{1-10})</th>
<th>(\Sigma(T_{1-10})) DVS</th>
<th>Date</th>
<th>(T_{1-10})</th>
<th>(\Sigma(T_{1-10})) DVS</th>
</tr>
</thead>
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<td>July</td>
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<td>5</td>
<td>8</td>
<td>29</td>
<td>Aug.</td>
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</tr>
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<td>36</td>
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<td>286</td>
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<td>31</td>
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<td>505</td>
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<td>518</td>
<td></td>
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<td>25</td>
<td>14</td>
<td>532</td>
<td></td>
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<td></td>
<td>26</td>
<td>16</td>
<td>548</td>
<td></td>
<td></td>
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<td></td>
<td>27</td>
<td>15</td>
<td>563</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For emergence on 15 June, the calculated temperature sum has to be diminished by 76 d °C, which is the temperature sum on 14 June.

<table>
<thead>
<tr>
<th>Development stage</th>
<th>1 June</th>
<th>15 June</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1 June</td>
<td>15 June</td>
</tr>
<tr>
<td>0.2</td>
<td>22 June</td>
<td>29 June</td>
</tr>
<tr>
<td>0.4</td>
<td>7 July</td>
<td>13 July</td>
</tr>
<tr>
<td>0.6</td>
<td>19 July</td>
<td>25 July</td>
</tr>
<tr>
<td>0.8</td>
<td>30 July</td>
<td>4 Aug.</td>
</tr>
<tr>
<td>1.0</td>
<td>9 Aug.</td>
<td>13 Aug.</td>
</tr>
<tr>
<td>1.5</td>
<td>26 Aug.</td>
<td>30 Aug.</td>
</tr>
<tr>
<td>2.0</td>
<td>12 Sept.</td>
<td>17 Sept.</td>
</tr>
</tbody>
</table>

**Days between emergence and silking:**
- 69 d
- 59 d

**Average development rate:**
- 0.01449 d⁻¹
- 0.01695 d⁻¹

**Days between silking and maturity:**
- 34 d
- 35 d

**Average development rate:**
- 0.02941 d⁻¹
- 0.02857 d⁻¹

---

**Exercise 6**

<table>
<thead>
<tr>
<th>DVS</th>
<th>Days after germination</th>
<th>Increase in leaf weight</th>
<th>Total leaf weight</th>
<th>Increase in stem weight</th>
<th>Total stem weight</th>
<th>Increase in total weight</th>
<th>Total dry weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.154</td>
<td>10</td>
<td>1200</td>
<td>200</td>
<td>300</td>
<td>1500</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>0.308</td>
<td>20</td>
<td>1400</td>
<td>1400</td>
<td>500</td>
<td>1900</td>
<td>3600</td>
<td>-</td>
</tr>
<tr>
<td>0.462</td>
<td>30</td>
<td>1700</td>
<td>2800</td>
<td>800</td>
<td>2900</td>
<td>6500</td>
<td>-</td>
</tr>
<tr>
<td>0.615</td>
<td>40</td>
<td>1200</td>
<td>4500</td>
<td>1200</td>
<td>2000</td>
<td>6500</td>
<td>-</td>
</tr>
<tr>
<td>0.769</td>
<td>50</td>
<td>5700</td>
<td>3800</td>
<td>3000</td>
<td>9500</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

DVS is calculated taking into account a 65 day period between emergence and silking at a constant temperature.

The fraction of the total weight increment allocated to the leaves in relation to the average development stage of the crop is given in the following table (Figure 76).

<table>
<thead>
<tr>
<th>DVS</th>
<th>Fraction to leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.077</td>
<td>1.0</td>
</tr>
<tr>
<td>0.231</td>
<td>0.8</td>
</tr>
<tr>
<td>0.385</td>
<td>0.737</td>
</tr>
<tr>
<td>0.539</td>
<td>0.586</td>
</tr>
<tr>
<td>0.692</td>
<td>0.400</td>
</tr>
</tbody>
</table>

---

![Figure 76](image_url)

Figure 76. The fraction of assimilates allocated to the leaf blades as a function of development stage for maize.
Exercise 11
A few specific job control commands are required to let your computer execute the job.
Ask your computer centre. CSMP has to be implemented on the computer system.

Exercise 12
\[ \begin{align*}
&\text{a. } T\overline{W} = \text{INTGRL} (T\overline{W}, \text{G\overline{T}W}) \\
&\text{GTW} = (\text{GPHIST} - \text{MAINT}) \cdot \text{CVF} \\
&\text{MAINT} = \text{TWT} \cdot 0.015 \\
&\text{PARAM CFV} = 0.7, \text{GPHIST} = 400. \\
&\text{INCONFW} = 100 \\
&\end{align*} \]

Exercise 14
\[ \begin{align*}
&\text{MAINT} = (\text{WSH} \cdot \text{WR}) \cdot \text{MC} \\
&\text{MC} = \text{AFGEN(MCTB, TEMP)} \\
&\text{FUNCTION MCTB} = (10, 0.008), (20, 0.015), (30, 0.030) \\
&\text{TEMP} = \text{AFGEN(TEMP\$TB, TIME)} \\
&\text{FUNCTION FEmer} = (60, 10), (210, 20) \\
\end{align*} \]

Adding these equations to the program of Exercise 12 results in a simulated dry matter production of 20.87 kg ha\(^{-1}\).

Exercise 15
\[ Q_i \text{ in } \text{kg ha}^{-1}, \Delta t \text{ in days. Then dimension of } R_i \text{ is kg ha}^{-1} \text{ d}^{-1}. \]
\[ Q_i, \Delta t = Q_i + R_i \cdot \Delta t = 200 + 15 \times 10 = 350 \text{ kg ha}^{-1} \]

Exercise 16
\[ Q_i, \Delta t = Q_i + R_i \cdot \Delta t = Q_i + a \cdot Q_i \cdot \Delta t = Q_i \cdot (1 + a \cdot \Delta t) \]

Numerical values: \( Q_0 = 5 \text{ kg ha}^{-1}, a = 0.1 \text{ d}^{-1} \)

<table>
<thead>
<tr>
<th>( \Delta t = 5 )</th>
<th>( \Delta t = 3 )</th>
<th>( \Delta t = 1 )</th>
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<tr>
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\( R_i \cdot \Delta t \)
The different values for $Q_n$ that result from the use of different time steps point to the fact that the smaller the time step, the more accurate the result will be. If the time step is five days, the assumption that $Q_i$ is constant over that period is more inaccurate than if the time step is 3 days. In general, the solution improves as the time step decreases.

The phenomenon described here, where the growth rate is proportional to the quantity present, is called exponential growth. A general expression for the quantity after $n$ time intervals can be found as follows:

\[
\begin{align*}
Q_1 &= Q_0 \times (1 + \Delta t \times a) \\
Q_2 &= Q_1 \times (1 + \Delta t \times a) \\
Q_n &= Q_{n-1} \times (1 + \Delta t \times a)
\end{align*}
\]

The expression for $Q_n$ can be transformed into:

\[
Q_n = Q_0(1 + \Delta t \times a)^n
\]

$Q_n$ is the value after $n$ steps of $\Delta t$, hence $n$ can be substituted by $\text{TIME}/\Delta t$:

\[
Q_n = Q_0(1 + \Delta t \times a)^{\text{TIME}/\Delta t}
\]

or

\[
Q_n = Q_0 \times ((1 + 1/N)^a)^{\text{TIME}}
\]

with $N = 1/(\Delta t \times a)$

These manipulations are helpful to arrive at a so-called analytical solution for the equation describing exponential growth. When $\Delta t$ approaches zero, $X$ approaches to infinity and the expression for $Q_n$ approaches:

\[
Q = Q_0 \times e^{\text{TIME}}
\]

The number $e$, the base of the natural logarithm stands for:

\[
e = \lim_{n \to \infty} (1 + 1/n)^n = 2.7182
\]

The equation with $e$ allows calculation on a pocket-calculator of the exact solution for $Q$ at 30 days:

\[
Q_n = Q_0 \times e^{(1.5 \times 30)}
\]

\[
e^{150} - e^1 = 20.09
\]

$Q_{30} = 100.43$

This result shows that time steps of 1 day still lead to underestimation of $Q$ at day 30.
### Exercise 18

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<th>GASS</th>
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<th>ASAG</th>
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<th>IWR</th>
<th>WRT</th>
<th>FL</th>
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### Exercise 17

\[
\text{STSM} = 55.5 + 25.8 \times 10 = 793
\]

\[
\text{DSM} = 793 - 1500 = 0.53
\]

\[
\text{Reduction factor (LAI=1.6)} = 0.72
\]

\[
\text{DNI} = 195.3 - 0.015 = 195.3
\]

\[
\text{GASS} = 0.77 \times 0.015 = 0.0115
\]

\[
\text{ASAG} = 195.3 - 0.77 = 195.3
\]

\[
\text{TADW} = 195.3 - 0.0115 = 195.3
\]

\[
\text{TDW} = 195.3 - 0.72 = 195.3
\]

\[
\text{TDWL} = 195.3 - 0.0025 = 195.3
\]

\[
\text{LAI} = 195.3 - 3.2 = 195.3
\]
Exercise 48

<table>
<thead>
<tr>
<th>$N_p$ (kg ha$^{-1}$)</th>
<th>$N_r$ (kg ha$^{-1}$)</th>
<th>$N_a$ (kg ha$^{-1}$)</th>
<th>$N_{in}$ (kg ha$^{-1}$)</th>
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Exercise 49

<table>
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<td>0.512</td>
<td>0.498</td>
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Denote grain weight by $g$ and straw weight by $s$. The grain/straw ratio equals $g/s$, and the harvest index equals $g/(g+s)$. Hence $g/(g+s) = (g/s)/(g/s + 1/s) = (g/s)/(g/s + 1)$.

Thus $HI = (g/s)/(g/s + 1)$

Exercise 50

Recovery fraction of the applied nitrogen equals $(60 - 20)/100 = 0.4$.

Exercise 51

See Figure 79

Exercise 52

From Exercise 49: $HI = (g/s)/(1 + g/s)$

For Figure 39a: $g/s = 0.53$, so $HI = 0.53/1.53 = 0.346$

For Figure 39b: $g/s = 1.3$, so $HI = 1.3/2.3 = 0.565$

Exercise 53

Theoretical efficiencies, in kg grain per kg nitrogen, for

Figure 41a: $E_m = 1/(0.01 + 1.89 \times 0.004) = 0.570$

Figure 41b: $E_m = 1/(0.01 + 0.77 \times 0.004) = 0.765$

Exercise 54

The grain/straw ratio is calculated from the initial efficiency according to:

$$E_m = 410 \div (1/(0.0011 + 0.0005 \times s/g))$$

$$g/s = 0.0005/(1/E_m - 0.0011) = 0.37$$
### APPENDIX III

**Day numbers in the Julian calendar**

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<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
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<th>Jun</th>
<th>Jul</th>
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