FAO-WMO ROVING SEMINAR

ON

CROP-YIELD WEATHER MODELLING

LECTURE NOTES AND EXERCISES

BY

RENÉ GOMMES

1. Chapter one : Introduction

Crop-yield weather modelling refers to the techniques which can be used operationally to determine the likely effect of weather on yields.

Although the incidence of weather conditions on yields is well established, its quantitative assessment is not always straightforward: time series analyses of agricultural statistics show that the inter-annual variability[1] of crop yields can be roughly subdivided into 3 components : (i) trend, (ii) direct weather factors and (iii) indirect weather effects, pests, diseases, weed competition, etc.

In developed countries, the trend - due to improved technology and management[2] - accounts for about 80% of the variability. The remaining 20 % is shared about equally between weather, and pests and diseases, of which many are also weather dependent. If the trend is removed from the time series, we can therefore assume that the largest fraction of the residual variability is due to weather.

In developing countries, often still at a subsistence farming level, the technology component is significantly less marked, and some countries among the poorest show no yield trend at all[3]. This is a situation where the impact of weather can have dramatic conditions and threaten the food security of millions of people. When the same farmers will be gradually forced by circumstances to adapt to more commercial farming, they will go through a transition phase where their vulnerability to weather vagaries will increase.

The quantitative assessment of climate effects on crops is thus no doubt the economically most important application of agrometeorology in developed and developing countries alike; the applications of crop weather modelling cover the spectrum of scales form the farmer’s field to entire countries, from individuals to governments.

The majority of current model uses involve some kind of forecast of yields based essentially on weather and management. In most cases, the purpose is a better utilisation of resources and hence a more environment-friendly and sustainable agriculture.

As is many other areas, crop modelling technology, tools and methods has undergone rapid developments in the recent years. An article by Sakamoto and LeDuc (1981) indicates stages in crop weather technology, starting with data-only until approximately 1940, when the first crop-weather *indices* were developed. This was followed around 1960 by statistical empirical models and, from about 1980 by process-oriented models, also known as deterministic or analytical models.

The approach describes an evolution mainly driven by computer technology, as it was perceived at the time. It is now clear that the four stages identified by

---

[1] Strictly: variance.

[2] Throughout this manual, the word *management* is used as a shortcut for *on-farm management decisions by farmers*.

[3] There is no trend either in some developed countries where yields are close to their potential values and where any yield increase, though technically feasible, would be uneconomical.

Sakamoto and his colleague, in particular indices (Walker, 1989), are still being used today, as they correspond as well to specific input data timeliness and user demand requirements. Some new methods have been developed since the early eighties, but it is difficult to say where the major methodological developments will lead.

The author's view is that we will witness an evolution along five axes:

- development of scale-specific models. Although almost all current models were originally developed for modelling a crop at the scale of a field, some of them are being used at the level of countries and even of the planet in global change impact studies. The inputs used are almost meaningless at the national and regional scales, even if - and sometimes precisely because - they have been gridded. Model use for a particular purpose depends on whether its complexity is appropriate to the question being asked and whether the model has been tested in diverse environments (Boote et al., 1996). It is suggested that there is an optimal model type with an adequate time step and number of input data at all geographic scales. It could even be argued that the most detailed models will be replaced at the farm level by direct sampling of assimilation rates and other parameters (Fredrick and Lemeur, 1997), and that models could in the future loose importance at that scale;
- development of non-parametric and rule based models, because of their simplicity of calibration and use, and low cost . On the scale of models outlined by Sakamoto and LeDuc, they come after deterministic models. A parallel progress will be process-oriented models with outputs as probability density functions. Both developments will be possible because of the availability of faster computers;
- integration of real-time inputs in the models, provided either by direct (and possibly automatic) measurements on crops and weather at ground stations, or through aircraft or satellite remote sensing. We currently witness this evolution for Leaf Area Index and evapotranspiration at the regional scale. This will replace some of the model components which currently estimate the same parameters;
- a greater inter-compatibility of models (Maracchi and Sivakumar, 1995). Users should be in a position to assemble their models by using building blocks (modules), for instance the root component of CERES, and the assimilation block of WOFOST. The first step should be the harmonisation of data files in the direction of a universal self-documented format;
- development of models which can take into account, at various scales, the effect of weather factors which physically harm plants (frost, sandy wind, very strong winds), and a better integration of crop, pathogens and competitors.

The current lecture notes are meant as a general introduction to the subject of agrometeorological crop modelling. As indicated in the title, the focus is on the effect of weather (as opposed to other factors) and on applications which fall traditionally in the province of agrometeorology (as opposed to many other fields like plant breeding).

After the present introduction (1), the volume is subdivided into 6 main chapters : (2) Fundamentals; (3) an overview of model types; (4) quality checking of models; (5) some method and tools for operational crop modelling; (6) agrometeorological applications of models; (7) exercises, followed by the bibliographic references.

Chapters are arranged following a logical sequence, but the author is well aware that several alternative options could have been chosen. For instance, chapter 3 (Overview of model types) could have been dealt with before chapter 2. Chapter 5, dealing with special inputs such as those provided by remote sensing could have been inserted in 3.5 (3.5.3. to 3.5.5), etc. This apparent redundancy, combined with frequent cross referencing was maintained to allow a more flexible use of the material presented. For instance, a less technical presentation of the subject could skip section 2.2.

Fundamentals are subdivided into (i) the basic ecophysiological aspects, such as water in plants, the conversion of radiant energy into biomass energy and the links between CO_2 assimilation and water use; (ii) the second part of the chapter deals with model components, i.e. essentially with the practical implementation of the basic ecophysiological aspects.

The overview of model types is subdivided into several somewhat arbitrary and overlapping categories. Global biomass models, including the issue of potential biomass determination, are followed by a short note on vegetation models and statistical models. Next comes a note on the semi-empirical models used by FAO for regional crop assessments. Simulation models proper, the process-oriented models, receive the most detailed treatment : some of the best known models are described, together with a short historical note and main features (CERES, WOFOST, EPIC), starting with CropSyst, on which particular emphasis will be put in the exercises.

Quality checking of models describes the procedures and caveats that a potential model user must be aware of before a model can be implemented in a decision-making process. This includes the general aspects of model evaluation, verification, etc.

Under some methods and tools for operational crop yield modelling we insist on more specific aspects like the growing number of uses of remote-sensing in operational applications, area averaging and a short introduction to random weather generators.

Agrometeorological applications of models elaborate on the potential uses of crop models in agrometeorological practice, of which crop forecasting appears to be one of the most important from a economic point of view. Two sections deal with farm-level applications and institutional customers, like crop insurance.

The exercises provide hands-on experience with models. They include an annex which provides a reminder about some of the physical units which are omnipresent in crop modelling. The exercises focus on some specific aspects covered in the lecture notes proper, and, conversely, some of the aspects presented in chapter 2 (fundamentals) were chosen because they easily lend themselves to a practical implementation in exercises. The students will be provided with a diskette having the relevant software and data.

Almost all exercises will be implemented in a spreadsheet. It is therefore essential that the students be familiar with basic spreadsheet use, graphing, the use of named cells, and regression.

The first exercises present some what-if experiments with basic equations taken from the manual in order to show the influence of the parameters.

For the practical work with a model we use CropSyst, developed by C. Stöckle at Washington State University (Stöckle et al., 1994 and other papers co-authored by Stöckle; see references). CropSyst was selected for several reasons: CropSyst is an up-to-standard model provided with a random weather generator; it is very user-friendly and exists for DOS and Windows 95[4]; it is multilingual; its is completely free and can be downloaded from the WWW site of the Biological Systems Engineering Department of Washington State University.

The current notes owe a lot to the participation of the author for several years in SuGrAm, the Support Group for Agrometeorology of the Joint Research Center of the European Union (JRC, Ispra, Italy), a think tank established to provide expertise to the EU MARS programme (Monitoring Agriculture by Remote Sensing); see Vossen and Rijks, 1995; Dallemand and Vossen, 1995; Rijks, Terres and Vossen, 1998). MARS constitutes arguably the most advanced regional crop forecasting system currently in **operation**, and the source of significant methodological progress.

The author is indebted to several colleagues who have kindly accepted to provided critical comments or specific inputs to this document : Michele Bernardi, FAO Agrometeorology Group; Cédric Gommes, ANAST-HémoLiège, University of Liège, Belgium; Graham Russell, Institute of Ecology & Resource Management University of Edinburgh, United Kingdom; Jin Chul Shin, National Crop Experiment Station, R.D.A, Suwon, Korea; Claudio Stöckle, Biological Systems Engineering Department of Washington State University, USA; Iwan Supit, MARS project, Institute of Space Applications, EU Joint Research Centre, Ispra, Italy; Bernard Tychon, Fondation Universitaire Luxembourgeoise, Arlon, Belgium. Their suggestions and contributions have allowed to improve the document and to remove some inconsistencies and errors. Needless to say, the author accepts full responsibility for remaining problems.

---

[4] Contrary to other models, the DOS and Windows versions are functionally equivalent. It has been the practice of many model developers to stop upgrading the DOS versions!

2. Chapter two : Fundamentals of crop modelling

2.1 Introduction

We start this introduction by borrowing the definition of a system from an old volume of *Schaum's Outline Series*: a system is an arrangement of physical components connected in such a manner as to form and/or act as an entire unit (Distefano et al., 1967)[5]. Crop models assume that plants are systems: they behave as an entire unit. Roots feed the leaves mineral substances and water; leaves assimilate CO_2, and the stems provide the link and transport of substances between the two, so that when leaves grow, roots can grow as well, and when water is absorbed by the roots, it is made available to the whole plant and transpired through the above-ground parts. The definition of a plant as a system thus makes sense.

The structure of a system is the set of links and connections between its components. Depending on the distance from which a system is looked at, the level of details can vary tremendously. Models attempt to describe the structure and the functioning of a system. Again, the word "description" can go from a simple verbal description to a mathematical description (rarely going beyond difference equations). When the mathematical description is coded into a computer programme that will compute the evolution of the numerical values attached to the model components, we talk of *computer simulation* : the machine mimics the behaviour of reality at a given resolution and with a given time step.

The resolution encompasses not only a spatial scale, but also the correlative level of detail of plant organs or cell components, biochemical and physiological processes, etc. There is also a link between the time step and the spatial scale.

Before we proceed, we must observe that so-called crop-weather models are more than just a description of the plant system. All of them include at least a soil component where the behaviour of water and possibly nutrients and organic matter is described. The system is thus larger than just a plant.

Models are characterised by state variables, rates, derived variables, parameters, inputs and outputs.

State variables, a concept borrowed from physics, are variables which completely describe the state of a system. This may be biomass (W_d, biomass of day d in g m^{-2}) , for instance. Rates express the speed at which the state variables change, for instance ΔW is the rate of change of biomass in g m^{-2} d^{-1}.

$$W_{d+1} = W_d + \Delta W \qquad (1a)$$

Derived variables are computed from state variables, but they do not have the same fundamental nature. For instance, if the density of leaves (expressed by the

[5] In a broader sense, a system can also be a structured organisation of people, theory, methods and equipment to carry out an assigned set of tasks, as in crop forecasting system when considering all the logistics and institutional arrangements involved in crop forecasting.

Leaf Area Index, in m^2 of leaves per m^2 land area), is computed from biomass, LAI is obviously less "central" in the model then W.

Assume that ΔW is a simple (and unrealistic) function of W and LAI:

$$\Delta W = K \times LAI_d \times W_d \quad (1b)$$

where the proportionality factor K would have the unit m^2(ground) m^{-2}(leaf) d^{-1}. K would be a parameter. It would probably be crop specific and adjustable by the user of the model. Next to crop parameters, there are also soil and other parameters.

Finally, input variables are those which characterise external action on the system: they include essentially the weather and management.

The order of the calculations[6] would thus be:

1. Start with W_d, the biomass at the beginning of day d
2. Compute LAI_d from biomass W_d, as well as all other variables that depend on W
3. Compute $\Delta W = K\ LAI_d\ W_d$
4. Compute the biomass at the beginning of the next day $W_{d+1} = W_d + \Delta W_d$
5. Start again from step 1 at the beginning of the next day.

Outputs are simply the variables which the user decides to look at. Some of them will be used for model verification and validation, others, like yield, are of immediate practical relevance.

[6] This is in fact a difficult issue when models are complex and subdivided into modules (Supit et al., 1994). The state variables are usually treated as global variables (always accessible throughout the programme), while other variables tend to be "local".

2.2 Ecophysiological aspects

2.2.1 The Soil-Plant-Air Continuum, or SPAC[7]

The “movement” of many physical variables like heat, liquids, electricity etc. can be described by a relation linking a flux and a driving force, as in

$$\text{Flux} = -K \times \text{driving force} \qquad (2)$$

The minus sign of the proportionality constant K indicates that the flow is “downhill” (the meaning of the negative sign will become more obvious below). The constant K is often called “conductance” and it expresses how easily flow responds to a given driving force. If we take the example of water in pipes, we can observe that narrow pipes offer more resistance to the flow than large ones. Therefore, the relation above can be rewritten as

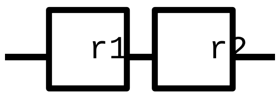
$$\text{Flux} = \frac{\text{driving force}}{r} \qquad (3)$$

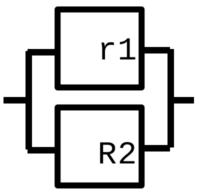
where r =1/-K. The equation now shows a clear analogy to Ohm’s law, the law governing the flow of electric current in wires. In fact, the rules adopted to describe fluxes of gases and water vapour between plants and environment follow Ohm’s law (see Box 1).

BOX 1 : OHM’S LAW

The intensity **I** of the electric current (flow) between two points **1** and **2** is the ratio of the potential difference between the points **∆P = P1 - P2** and the resistance r of the wire between the points.

When resistors are connected, the resulting current can be computed by taking into consideration the relations below:

Resistors in series  r = r1 + r2

Resistors in parallel  1/r = 1/r1 + 1/r2

If we apply this to water flow in plants, we can write that the uptake of water through the root surface is given by

---

[7] This section is largely based on Hillel (1971) and Kramer (1983).

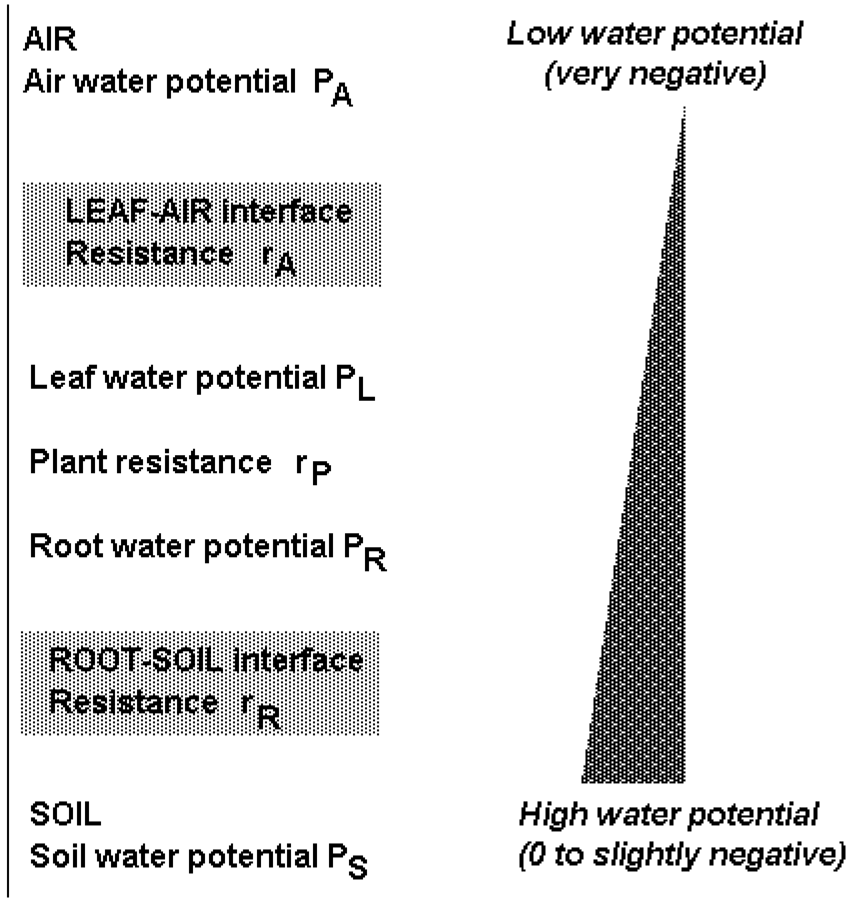
$$\text{Water uptake} = \frac{\text{Water potential in soil} - \text{Water potential at root surface}}{\text{Soil resistance}} \qquad (4)$$

which we can rewrite, using the symbols defined in figure 1, as

$$\text{Water uptake} = \frac{P_S - P_R}{r_R} \qquad (5)$$

The water potential is a measure of how strongly water is bound to its medium. The binding energy can be expressed in energy units per mass units (joule kg^{-1}) or, alternatively, as energy units per volume (joule m^{-3}) which is equivalent to a pressure (1 Pa is equivalent to 1 J m^{-3} and to 1 N m^{-2}). Refer to the section on units for details on the conversions (after the exercises of chapter 7). The unit of r_R depends on the units adopted for P_S - P_R. It usually has the dimension of s m^{-1}.

Figure 1 : A simple representation of flow of water in the SPAC



If the potential is very low (very negative), water is bound very strongly to the constituents of its medium, and it will move to another medium only if its potential is still lower (more negative).

Obviously, as there is no significant accumulation of water in a growing plant, but rather a steady flow[8], and the amount of water transpired equals the amount absorbed through the root. We can thus write

$$\text{Water flow} = \frac{P_S - P_R}{r_R} = \frac{P_R - P_L}{r_P} = \frac{P_L - P_A}{r_A} \quad (6)$$

In the older literature and in soil science texts, water potential is often expressed in pressure units (bars and pascals, and their multiples and subdivisions, in particular the MPa).

Soil water potentials are of the order of -0.1 to -15 bars (-10 to -1500 J Kg^{-1}), corresponding approximately to field capacity and to permanent wilting point. The water potential values found in leaves are around -2000 J.Kg^{-1} (equivalent to -2 MPa). The water potential (also referred to as tension, suction, etc.) tends to be high in the soil (not very negative and close to close to 0), and very low in the atmosphere (very negative). Of the values of potential difference used in the equation above (P_S - P_R, P_R - P_L and P_L - P_A), the last is very significantly larger than the others, sometimes by a factor of hundred, thus indicating the importance of the atmospheric water demand). Typical values are 1000 J Kg^{-1} for P_S - P_R and P_R - P_L but 50 KJ for P_L - P_A.

The water potential of air[9] can be approximated by

$$P_A = \frac{R_g T_K}{V} \ln \frac{e}{e_0} \quad (7)$$

where R_g is the gas constant, T_K the absolute temperature, V the partial molal volume of water, e the actual water vapour pressure and e_0 is the saturation water vapour pressure at temperature T_K. e/e_0 is thus the relative humidity.

Substituting the constants in the above equation (Rg = 8.31 J mol^{-1} K^{-1}, V=0.018 Kg mol^{-1}, T_K = 273.15 + T_C) leads to

$$P_A = 461.66(273.15 + T_C) \ln \frac{e}{e_0} \quad (8)$$

This reduces to

$$P_A = 1.35\, 10^5 \ln \frac{e}{e_0} \quad (9)$$

[8] The amount of water held in plant tissues is normally very small compared with the amounts transpired.

[9] With SI units (Kg,m,s,K), this expression is equivalent to a pressure in Pa (Energy RT, divided by a V). The Nernst equation states that one mole of water has an energy of $R_g T_K \ln(e/e_0)$, equivalent to the sum of the energy of the bonds. To express this to energy per weight (J Kg^{-1}), it must be divided by the molar mass of water (0.018 Kg).

J Kg-1 at a temperature of 20°C. As an example, the water potential corresponding to 80% relative humidity ($\ln(e/e_{0})=\ln(0.8)=-0.223$) at 20°C is -30105 J Kg^{-1}, while it drops to -217.8 KJ Kg^{-1} at 20 % moisture.

According to Kramer (1983) this equation greatly exaggerates the drop in potential in the vapour phase between leaf and atmosphere. For instance, halving relative humidity decreases vapour pressure by about 50%, but reduces the equivalent water potential gradient nearly 25-fold.

There is no need, in this context, to insist on the components of the water potential. For instance, the soil water potential is traditionally subdivided into osmotic, pressure (or matric), capillary and gravitational.

In fact, the potential of free water (for instance the solution used for hydroponic crops) and the potential of leaves when they are in the dark is nil.

In addition, plants can actively control their transpiration in response to their environment, for instance by adjusting the opening of their stomata (figure 5, 2.2.4). Plants do not only evaporate water, but also assimilate carbon, which is also absorbed through the stomata. This is only one of the numerous interactions between the various physiological functions of crops (2.2.3 for details). The resistances as well vary a lot, even over short time intervals. For instance, soil resistance is a function of soil water content and root development.

The leaf and air resistances are controlled by stomatal opening, water pressure deficit and air movement, as in the equation below

$$Transpiration = \frac{C_{leaf} - C_{air}}{r_{leaf} + r_{air}} = k_u \frac{e_{leaf} - e_{air}}{r_{leaf} + r_{air}} \qquad (10)$$

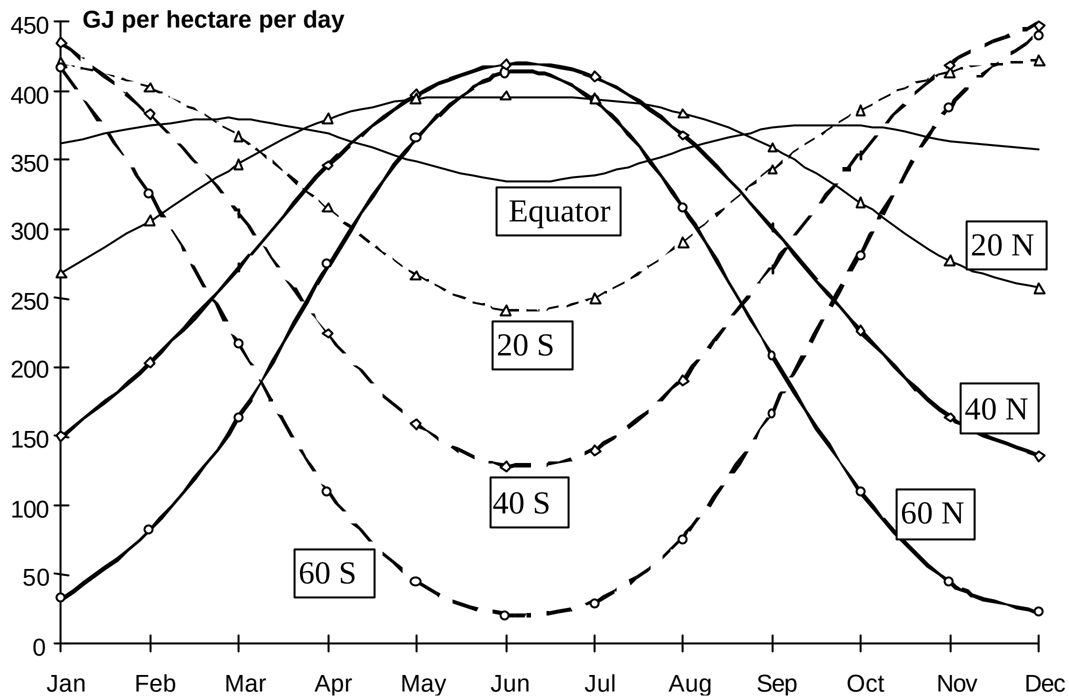
where C_{leaf} and e_{leaf} are the water vapour concentration and vapour pressure, respectively, at the evaporating surfaces within the leaf and r_{leaf} is the additional diffusive resistance of the leaf. Transpiration is in Kg (water) m^{-2} s^{-1}, the concentrations C are in Kg (water) m^{-3} and the resistances are in m s^{-1}. As the vapour pressures are in hPa, the factor k_u is symbolically added to account for the differences in units between e and C.

2.2.2 CO_2 assimilation[10]: conversion of radiation energy to biomass energy

The radiant energy reaching the upper limit of the atmosphere on a horizontal surface is known as Angot's value (R_A). It is also the amount of solar energy that would reach the ground in the absence of the atmosphere.

Figure 2 shows that its average value is about 300 GJ Ha^{-1} day^{-1} between -60° degrees southern latitude and 60° northern latitude, where most of the world agriculture is concentrated. When R_A is expressed in energy per year, the average becomes 300 x 365 = 109500 GJ Ha^{-1} $year^{-1}$ which we can round to 100 TJ Ha^{-1} $year^{-1}$. The detail of the calculations to obtain figure 2 is given in the exercises under 7.2.

Figure 2 : Global radiation at the upper limit of the atmosphere as a function of month and latitude



Only about half the radiant (solar) energy R_A that reaches the upper limit of the atmosphere actually reaches the ground (as R_I) where it is available, among others, for plant photosynthesis.

This is expressed by the well known formula by Ansgtröm:

$$R_I = R_A\,(a + b\frac{n}{N}) \qquad (11a)$$

[10] Sections 2.2.2 and 2.2.3 are mainly after Russel (1977), de Wit et al. (1978) and van Keulen and Wolf (1986).

where a and b are the empirical "Angström coefficients" which vary as a function of type of climate, and n/N is the sunshine fraction, i.e. the actual hours of bright sunshine divided by daylength. Values of a and b are close to 0.25 and 0.45 for dry tropical areas (a is often taken as 0.29 cos φ, where φ is latitude). When n/N=0 (complete overcast), all light is diffuse. The maximum value for R_I is about 70% of R_A.

The classical energy balance is usually written

$$R_I (1-s) - B = H = P + G + A + E \qquad (11b)$$

(all variables in units of W m^{-2} or J s^{-1} m^{-2}) were s is the albedo (about 0.15 to 0.40: 15 to 40 % is reflected and radiated back in the atmosphere) and B is the outgoing long-wave radiation leaving the surface[11]. As indicated, R_I.s + B make up about 50 % of R_I. The difference H (the net radiation) can be used for other processes such as photosynthesis (P, energy stored in biomass chemical bonds), the evaporation of water from crop and soil (E), and for heating the crop and the ground below it (G), as well as heating the air in contact with the soil and the crop. The latter energy is known as "sensible heat" (A).

The maximum proportion of the net radiation H that can be used for photosynthesis P is about 15 % over short periods of time, provided that the crop is well supplied with water and perfectly managed (P / H < 0.15). Over weeks or crop cycles, the efficiencies are usually below 2 %, and 1% is often regarded as an average for the fraction of the net radiation that is actually converted into biomass energy, to the extent that the net radiation is often regarded as the sum of just evaporation by crops and soil (i.e. evapotranspiration: latent heat) and sensible heat (equation 61).

Although photosynthesis does not play a significant role in the radiation balance, it constitutes the source of all solar energy stored on earth, and the only source of all food. Photosynthesis is directly driven by light. Net carbon dioxide absorption during photosynthesis follows a characteristic light response curve (figure 3) given by de Wit et al. (1978) as a function of absorbed photosynthetically active radiation (PAR), R_{HC} (see 3.1.1)

$$F_n = F_d + (F_m - F_d)(1 - \exp(-\frac{E_{lc}.R_{HC}}{F_m})) \qquad (12)$$

Where the symbols have the definition and units given in table 1.

Note that equation (12) gives short-term net assimilation in Kg CO_2 Ha^{-1} (leaf) $hour^{-1}$, thus assuming a huge horizontal leaf with an area of 1 Ha. The radiant flux in the 400-700 nm range corresponds to the so-called Photosynthetically Active Radiation (PAR), roughly equivalent to 50% of global radiation at ground level. The Efficiency at the light compensation point is the slope of the F_n curve at the light compensation point.

---

[11] B stands for Brunt, the name of the scientist who computed B as a function of air temperature (σT^4), air moisture and n/N.

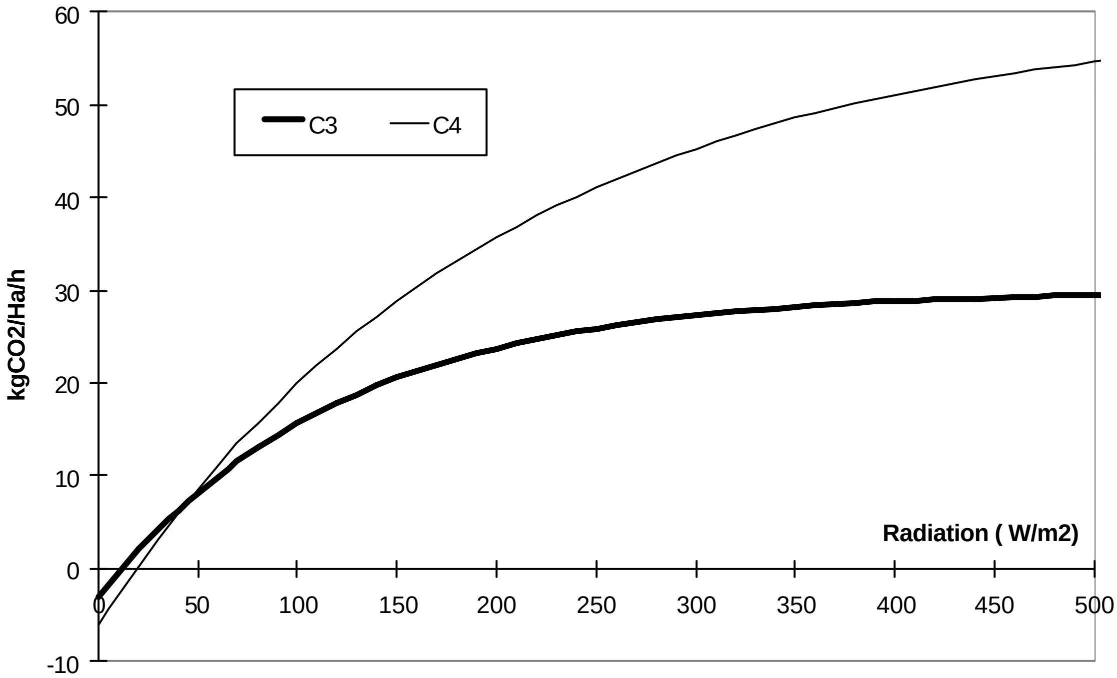
Table 1: Some characteristics of photosynthesis as driven by light, as a function of the C3/C4 type[12].

			C3-plants	C4-plants
Net assimilation	Kg CO_2 / Ha leaf / hour	F_n		
Maximum rate of net assimilation	Kg CO_2 / Ha leaf / hour	F_m	30 (15 to 50)	60 (30 to 90)
Net assimilation in the dark	Kg CO_2 / Ha leaf / hour	F_d	-3	-6
Absorbed radiant flux in the 400-700 nm range	joule / m^2 / s	R_{HC}		
Efficiency at light comp. point	Kg $C0_2$ / Joule	E_{lc}	0.25	0.30
Temperature-dependent F_m ?			No	Yes

The curve below illustrates the equation. Above the light compensation point, assimilation exceeds respiration, and there is thus a net biomass accumulation . C3 plants respond better at low intensities, but rapidly reach light saturation; C4 plants, which are more typical of tropical regions and include millet, sorghum, sugar cane and maize, continue increasing the assimilation over a much large range of radiation.

[12] The majority of plants fall into one of the C3 or C4 categories according to the number of carbon atoms of one of the first acceptors of CO_2 during photosynthesis. C3 plants respond well to increased atmospheric CO2, while C4 plants, mainly tropical grasses (maize, sorghum, sugarcane. millet) or halophytes, respond better to higher temperatures. Most agricultural plants (cereals, legumes, vegetables) are adapted to lower temperatures and sunshine; they belong to the C3 group. WUE tends to be higher in C4 plants.

Figure 3 : Net assimilation of carbon dioxide per hectare of leaf in C3 and C4 plants as a function of absorbed PAR (R_{HC}). The values read from the graph for C3 plants at 400, 40 and 4 W m^{-2} are 28.82, 6.35 and -1.92 KgCO_2 hectare^{-1} hour^{-1}, respectively. For 220 and 100 W m^{-2}, they amount to 24.72 and 15.66 KgCO_2 hectare^{-1} hour^{-1}.



2.2.3 From leaf to canopy

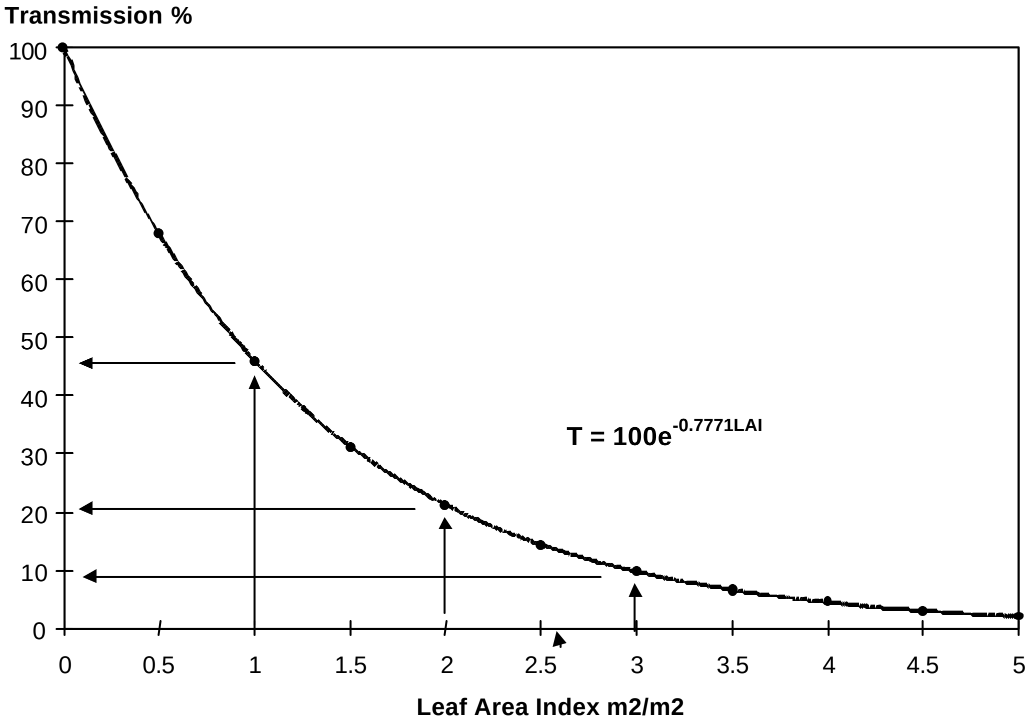
There are some major methodological difficulties linked with the translation of the net photosynthesis at the level of a leaf (as above) to photosynthesis of an actual crop. This is a typical scaling problem, of which there are many examples in the general area of climate impact on agriculture !

We mentioned above that the equation, as written and with the units used, describes photosynthesis of a huge leaf having an area of 1 Ha. This is to say that the ratio between the leaf area and the ground area is exactly one, i.e. the Leaf Area Index, or LAI, is 1. For actual crops and wild vegetation, values significantly higher than 1 can be found.

In the next paragraphs, we follow the description of the scaling problem as given by van Heemst (1986). We assume that the discussion below refers to photosynthetically active radiation (PAR, the portion of the visible between 400 and 700 nm).

10 % of the PAR that hits the leave is reflected (mainly in the green part of the spectrum: this is why leaves are green), 10 % just crosses the leaf, another 10% is absorbed by various other pigments that play no part in photosynthesis, and the remaining 70% is absorbed by the photosynthetic machinery in the leaf.

Figure 4 : Transmission of radiation in a canopy as a function of Leaf Area Index.



If we assume that the incoming radiation (the above-mentioned 70%) amounts to 400 W m^{-2}, then the resulting photosynthetic rate will be 28.82 $KgCO_2$ $hectare^{-1}$ $hour^{-1}$ for a C3 plant, according to figure 3. If we assume that there is a second leaf under the first, it will receive only about[13] 10 % of the energy received by the first leaf, resulting in a net assimilation of 6.35 $KgCO_2$ $hectare^{-1}$ $hour^{-1}$. The total for the two leaves would thus be 35.17 $KgCO_2$ $hectare^{-1}$ $hour^{-1}$.

If we added a third leaf, its net assimilation would be negative, thus not contributing anything to photosynthesis but rather consuming the assimilates of the other leaves, a situation which would not be very “sustainable”.

In actual crops, leaves are not superposed, but preferentially oriented according to different angles: in some plants almost all leaves are horizontal (planophile distribution, like in many water plants or in plants where leaves constitute a rosette), while in others they tend to be erect (erectophile species, like most grasses). In practice, most plant canopies are somewhere in between. Of special interest in crop modelling is the so-called spherical distribution, a variant of the erectophile leaf distribution where the angles of leaves follow the same distribution as on a sphere.

The result of the multitude of leaf angles in the canopy is that light is more evenly distributed over the leaves, although it still undergoes an attenuation as one moves from the top into the canopy.

Figure 4 shows an example of radiation transmission by a canopy as a function of LAI, measured starting at the top of the canopy: when LAI is 0, 100 % of the incoming energy is available. If we move down into the canopy until LAI reaches 1, only about 45 % of the incoming energy is available at the surface of the soil, at LAI = 2, this is reduced to about 20%, and so on until transmission asymptotically reaches 0 at high LAI values.

The phenomenon can alternatively be described in terms of extinction or attenuation (computed as 100 - transmission) and according to the formulation of Beer’s law

$$R = R_0 \, e^{(-k \ LAI)} \qquad (13)$$

where R is radiation at “depth” LAI in the canopy and R_0 is the incident radiation at the top of the canopy. k is the extinction coefficient. Note that the extinction coefficient is larger for PAR than for visible light (compare with equation 40).

In theory, it is thus easy, knowing LAI and the extinction coefficient, to compute the actual photosynthesis. Referring to figure 4, we note that 45 % of the light is still available at the lower face of the first leaf (LAI = 1). This means that 55% has been absorbed in the first layer. Of course, we know that part of this will be lost, but we will ignore this for the time being. The second layer thus receives 45 % of the incoming radiation, and transmits 20 (of the incoming radiation) to the lower layers, thus retaining 25%.

It is now possible to compare the photosynthesis of the two layers with the one-layer crop and the “superposed leaf” crop: still assuming that the available energy was 400 W m^{-2}, the first layer has absorbed 55% of 400, thus 220 W m^{-2} , and the

---

[13] About 10 % because some of the 10% that leaves the first leaf will be reflected etc. by the second leaf. Strictly, only 70% of the 10% transmitted should be taken into account.

second 25% of 400, thus 100 W m^{-2}. The corresponding CO_2 assimilation amount to 24.72 and 15.66, thus a total of 40.38 $KgCO_2$ hectare^{-1} hour^{-1}.

To summarise, we have examined three situations:

- one leaf, with a net assimilation of 28.82 $KgCO_2$ hectare^{-1} (leaf) hour^{-1}
- two superposed leaves, yielding 35.17 $KgCO_2$ hectare^{-1} (leaf) hour^{-1}
- "normal" leaves absorbing 40.38 $KgCO_2$ hectare^{-1} (leaf) hour^{-1}

It is clear that the real-world situation is the most efficient. Of course, in the words of van Heemst (1986, p. 18), the *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 light interception also varies according to the growth of the crop (Rosema et al., 1998a). In the early stages, it can be assumed that the amount of light intercepted is proportional to biomass. This corresponds to the exponential growth phase, which persists until the surface is completely covered by vegetation.

In practice, there does not appear to be a simple analytical solution to the computation of canopy photosynthesis based on leaf photosynthesis. An interesting feature is that the multi-layered canopies are a mechanism to expose more leaves to less intense radiation, i.e. non-saturating radiation. One of the consequences is also that when figure 3 is drawn for actual crops (i.e. $KgCO_2$ hectare^{-1} (field) hour^{-1} instead of $KgCO_2$ hectare^{-1} (leaf) hour^{-1} as above), the linear part of the curve extends into higher radiation intensities.

There are many techniques to estimate total canopy assimilation; they differ by the vertical resolution in the canopy (number of layers, from 1 to many) and by the time step adopted (typically from hours to 1 day), and by other details. WOFOST, for instance (Supit et al. 1994), adopts three "horizons" in the canopy, corresponding to 0.11 LAI, 0.5 LAI (mid-height) and 0.89 LAI, close to the ground. The total canopy assimilation is obtained as the weighted average of the three "typical" horizons above. WOFOST also computes light distribution and rates of assimilation at different depth separately from direct and diffuse light.

Needless to say, the "other details" constitute the very core of the actual complexity of the models and largely condition the input parameters required to operate them. They also seriously complicate the model validation.

2.2.4 Links between CO_2 assimilation and water use

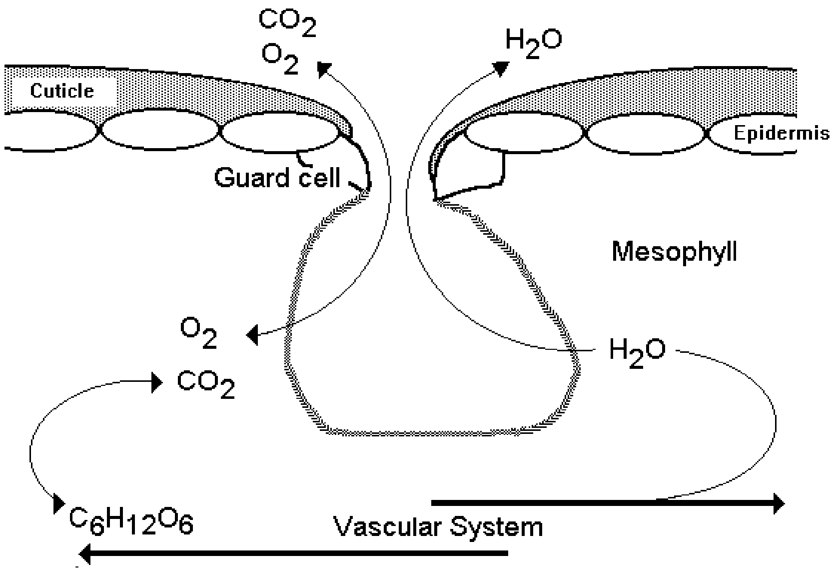
The exchange of gases (oxygen, CO_2 and water vapour) between plants and the atmosphere occurs through the stomates[14].

Stomates are a structure at the surface of the leaves (and other green plant organs) composed of two specially formed cells (guard cells) enclosing a little

[14] Also called stomata (plural) and stoma (singular).

opening, the stomatal aperture (Figure 5). The cuticle is a wax-like substance covering the epidermis, i.e. the outer layer of cells literally paving the surface of plant organs. The cuticle is almost impermeable, so that 80 to 90 % of the gases are actually exchanged through the stomates. Their diameter is about 20 μm and their density averages 300 per mm^2 , although it may reach 1200 in some plants (Kramer, 1983). The anatomy of the guard cells is such that they open when they are turgid, and that they "automatically" close in the case of loss of cell water pressure, for instance in the event of water stress.

Figure 5 : Schematic representation of a stomate and the movements of CO_2, O_2 and H_2O which take place between leaf and atmosphere.



The rates of diffusion of CO_2 and of H_2O is controlled by an Ohm-like equation (van Keulen and van Laar, 1986; also refer to Box 1, 2.2.1):

$$V_{CO_2} = \frac{(CO_2)_{ext} \quad (CO_2)_{int}}{r_{CO_2}} = \frac{\text{Ä}CO_2}{r_{CO_2}} \qquad (14a)$$

$$V_{H_2O} = \frac{(H_2O)_{int} - (H_2O)_{ext}}{r_{H2O}} = \frac{\Delta H_2O}{r_{H2O}} \qquad (14b)$$

where round brackets denote concentrations (Kg m^{-3}); V is the rate of diffusion (kg m^{-2} s^{-1}) and r is the resistance to CO_2 and to H_2O diffusion in s m^{-1}, respectively.

r_{CO2} is the sum of several resistances: r_a the resistances of the boundary layer, the layer of air immediately in contact with the leaf; r_c, the stomatal resistance, and r_m the mesophyll resistance, the mesophyll being the "spongy" tissue[15] where photosynthesis takes place. The mesophyll resistance is usually larger than the sum of the two others; the standard value of r_m is often taken as 440 s m^{-1}.

The stomatal cavity is normally saturated with water vapour, hence the diffusion is normally toward the atmosphere when air moisture is less than 100%.

---

[15] "Spongy" because there are lacunae between the cells to favour the movement of gases between the cells and the stomates.

Due to the different molecular weights[16] of CO_2 and H_2O we have

$$r_{H_2O} \quad 0.64 r_{CO_2} \qquad (15)$$

for the gas phases (r_a and r_c). Regarding the mesophyll resistance, things are a bit more complicated (Kramer, 1983). The surface of the stomatal cavity is covered by a film of water, which opposes no resistance to the penetration of water, but when it comes to CO_2, r_m is significant[17].

The relation between V_{C02} and V_{H20} can be expressed in several ways. One is the transpiration coefficient which expresses the amount of biomass produced relative to the amount of water evapotranspired. The orders of magnitude are about 200 Kg to 500 Kg of water for 1 Kg of biomass.

Another way to express the relation is the Water Use Efficiency WUE:

$$WUE = \frac{\frac{\Delta CO_2}{r_{CO2}}}{\frac{\Delta H_2O}{r_{H2O}}} = \frac{\frac{\Delta CO_2}{r_c + r_a + r_m}}{\frac{\Delta H_2O}{0.64(r_c + r_a)}} = \frac{0.64 \Delta CO_2}{\Delta H_2O} \times \frac{r_c + r_a}{r_c + r_a + r_m} \qquad (16)$$

This equation shows that, if weather is relatively windy so that $r_a \approx 0$ and ΔCO_2 is reasonably constant, water use efficiency depends mainly on air moisture and on the relative value of r_c and r_m.

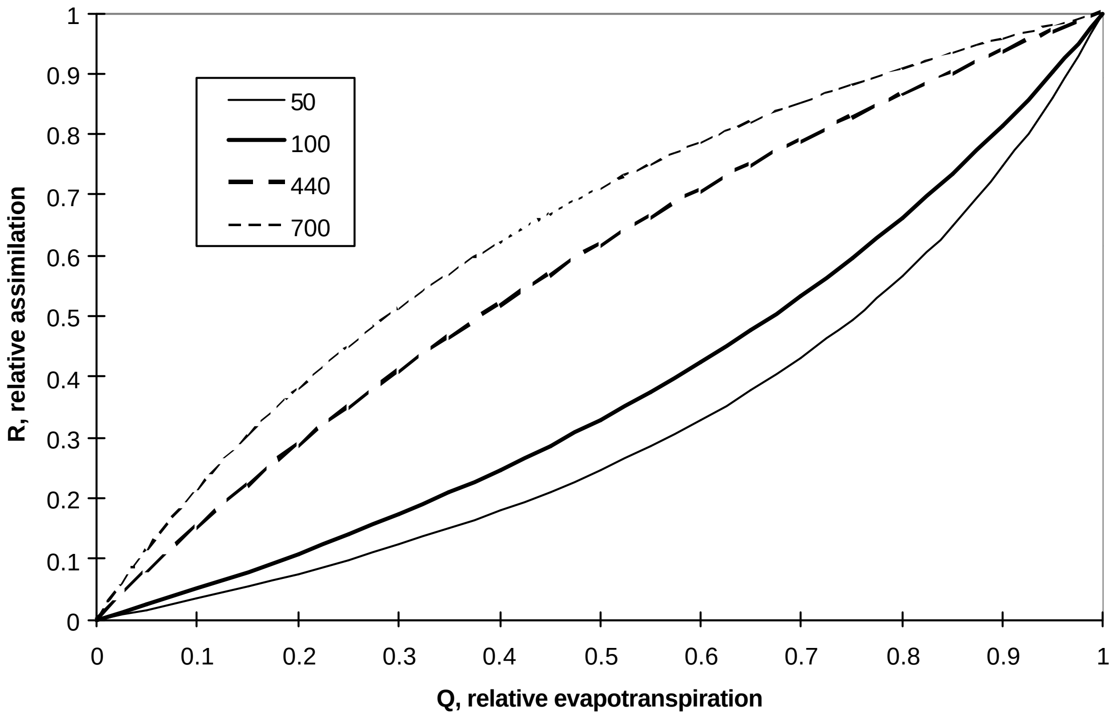
de Wit was among the first who recognised in the mid fifties that there is a direct link between transpiration and plant productivity. Transpiration can be limited due to short supply of water in the root zone, or by the amount of energy required to vaporise the water. It can be said that plants growth (biomass accumulation) is driven by the available energy, but that plants pay for the energy by evaporating water. This one of the basic functions implemented in all crop models.

Figure 6 : Plot of R_{ass} versus Q, as function of different mesophyll resistances (r_m=50, 100, 440 and 770 s m^{-1}). r_a was assumed to be 50 s m^{-1}.

[16] The speeds of diffusion are proportional to the square roots of the molecular weights of the gases.

[17] There are also biochemical limitations connected with the photosynthetic machinery.

.



Maximum evapotranspiration (LE_m)[18] and maximum assimilation (F_m) occur when the stomates are completely open , in which case one can assume that r_c is negligible ($r_c \approx 0$).

Rosema et al. (1998b) define the relative evapotranspiration as $Q = LE / LE_m$ and the relative assimilation as $R_{ass} = F / F_m$. It can be shown that

$$R_{ass} = \frac{Q}{Q + a(1 - Q)} \qquad (17)$$

where

$$a = \frac{1.8\,(1+\gamma)r_a}{r_a + r_m} \qquad (18);$$

$\gamma \approx 2.4$ is a dimensionless constant and the resistances are in s m^{-1}; r_a depends on windspeed .

A plot of relative assimilation R_{ass} as a function of relative transpiration Q is given in Figure 6. It appears that, when Q values are relatively high (at least Q>0.6), and if the effect of r_a can be assumed to be constant, the relative assimilation is directly related to relative evapotranspiration.

The relation between biomass production and evaporation is crop specific. In CropSyst, Stöckle et al. (1997a) use the form

[18] LE, is thus the evaporative heat loss (J m^{-2} d^{-1}), the product of E, the rate of water loss from a surface (kg m^{-2} d^{-1}) and L, the latent heat of vaporisation of water is 2.45 10^6 J kg^{-1} .

$$\Delta W_T = \frac{K_{BT} T}{VPD} \qquad (19)$$

where ΔW_T , the water limited growth, is in Kg (biomass) m^{-2} d^{-1}, K_{BT} is the crop specific biomass transpiration coefficient in kPa Kg (biomass) Kg^{-1} (water), T is transpiration (Kg water m^{-2}. d^{-1}) and VPD stands for **daytime** vapour pressure deficit in kPa. The order of magnitude of K_{BT} is 5 kPa kg biomass for 1 m^3 of water.

2.3 Model components

2.3.1 Assimilation and respiration

When considered from a purely geochemical point of view, plants constitute marked carbon anomalies: spatial peaks of carbon concentrations (40 to 50% of the dry matter; about 5% of living plant fresh weight) extracted from an atmosphere containing about 360 ppmv of CO_2, equivalent to 700 mg CO_2 m^{-3} (air)[19] or about 200 mg C m^{-3} (air).

The order of magnitude of CO_2 assimilation is the following:

One square m of leaf can produce

1 g of sugar in one hour

According to the well known chemical equation of photosynthesis:

$$6\ CO_2 + 12\ H_2O + h\nu \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O \qquad (20)$$

where $h\nu$ indicates light. The simplicity of this equation should not mislead the reader into believing that the conversion[20] of CO_2 into the energy rich and chemically unstable sugars during photosynthesis is a simple process[21].

The equation can also be expressed in terms of absolute amounts

$$264\ g\ CO_2 + 216\ g\ H_2O + h\nu \rightarrow$$

$$180\ g\ C_6H_{12}O_6 + 192\ g\ O_2 + 108\ g\ H_2O \qquad (21)$$

or relative weights

$$1.5\ CO_2 + 1.2\ H_2O + h\nu \rightarrow 1\ C_6H_{12}O_6 + 1.1\ O_2 + 0.6\ H_2O \qquad (22)$$

This can be expressed as follows:

- to produce 1 g of sugar, 1.5 g of CO_2 is required, which is the amount contained in about 2 m^3 of air, or
- the CO_2 of 1 m^3 of air would be exhausted in 30 minutes.

---

[19] Refer to the section on units for the conversion from ppmv to weight per volume (appendix at the end of the exercises).

[20] Technically, this conversion is a chemical reduction.

[21] The steps are (1) cyclical photo-phosphorilation during which light interacts with chlorophyll and increases the energy level of a couple of electrons that will eventually return to chlorophyll over a chain of redox-catalysers, while at the same time losing their energy which is stored in chemical bonds in a chemical known as ATP; (2) photolysis of water: water molecules are split, making O_2 available while hydrogen is stored and additional ATP is synthesised. Note that the oxygen resulting from photosynthesis stems from water and not from CO_2 ; (3) one CO2 molecule is bound to a C_5 compound ($CO_2 + C_5 \rightarrow C_6$) to yield a C_6 molecule which will undergo a bewildering chain of splits and additions, fuelled by the above-mentioned ATPs and the stored hydrogen, eventually yielding $C_6H_{12}O_6$ while the ATPs are being recharged in steps (1) and (2). The process requires a permanent supply of CO2, water and energy.

Needless to say, photosynthesis can only proceed at the above-indicated rate if a substantial renewal of air actually takes place (which is to say air is replace twice per hour). Actual plants have Leaf Area Indices which exceed 1, and therefore higher wind speeds are required.

If we consider a field of 1 Ha, the above rate ("one square m of leaf can produce 1 g of sugar in one hour") amounts to 10 Kg of sugar and 15 Kg of CO_2. If, in addition, we assume that the LAI of the plant is 5 m^2 (leaf) m^{-2} (ground), than the assimilation rate could amount to the high but realistic value of about 75 Kg CO_2 Ha^{-1} $hour^{-1}$ (assuming linearity between 1 and 5 LAI).

The energy required to produce 1 mole of sugar, considering the various losses that take place in the photosynthetic machinery, activation energies etc., the process requires ≈4400 KJ mol^{-1} of light energy[22] (the amount of energy refers to the moles, not molecules), but when 1 mole of sugar is "burnt", as in

$$C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O \rightarrow 6\ CO_2 + 12\ H_20 + 2880\ KJ\ mol^{-1} \qquad (23)$$

2880 KJ mol-1 are produced[23]. The efficiency of the process is about 65 % (Pilet, 1967). Note that oxygen is required, but, given its abundance in the atmosphere, it is normally not limiting.

The sugars may be used in several different ways by the plants:

1. conversion to structural elements (cellulose, wood, fats) which are necessary for plant growth and development; when plants die and decay, it is the structural elements that last longest. Note that we refer to structural elements at the micro-level (scale of the cell). Macro-structural aspects will be covered later under partitioning 2.3.3;
2. polymerised into starch and more or less temporarily stored;
3. used as a source of energy to "operate": synthesise other cell chemicals like proteins and fats, to maintain its structure and functions, to absorb chemical elements through the root system, etc.

The process through which energy is mobilised is respiration, often subdivided into "maintenance" respiration and growth respiration.

Based on the treatment of the subject by van Heemst (1986), we can state that the daily dry matter increase ΔW (Kg (DM) Ha^{-1} d^{-1}) of a crop with a standing biomass of W (Kg (DM) Ha^{-1}) is given by

$$\Delta W = Eff_g \left(\frac{1}{1.5} F_{CO_2} - W\ Resp_m\right) \qquad (24)$$

where F_{CO2} /1.5 is the gross sugar assimilation [Kg (sugar) Ha^{-1} d^{-1}] derived from the CO_2 uptake; Eff_g is the conversion efficiency of sugar into DM [Kg (DM) Kg^{-1}

---

[22] According to Pilet (1967).

[23] Note that, if the complete oxidation of sugar takes place in a living organism, the energy produced is also less, among others because some energy (activation energy) has to be spent to start the reaction.

(sugar)] , $Resp_m$ is the relative maintenance respiration rate [Kg (sugar) Kg^{-1} (DM) d^{-1}]. The factor 1.5 comes from equation 22.

Orders of magnitude of $Resp_m$ depend on the main storage chemicals in the plant under consideration. For the starchy roots and tubers, where little conversion to sugar is required, values are about 10 [g (sugar) per Kg of biomass]. Slightly higher values (15) are given for cereals (which are richer in protein), and oil crops are at 30. Eff_g varies from 0.75 [Kg (DM) Kg^{-1} (sugar)] to 0.70 and 0.50 for the same crops as above, respectively (van Heemst, 1986). The preceding data provide one of the reasons why tubers tend to out-yield cereals in DM terms.

$Resp_m$ appears to be much more temperature dependent than, for instance, F_{CO2}. In the physiological range of temperatures, it doubles every 10°C (a first approximation only; see section on phenology and sums of Degree-Days 2.3.2). Here again, there is a direct link with the common observation that high night-time temperatures are not conducive to high yields.

2.3.2 Phenology

Phenology qualitatively describes the successive stages in the development of plants, from seed germination to flowering to maturity. Since the stages (also called phenophases) are very plant dependent, it is difficult to define a universal system to describe phases, as only the main stages (germination, differentiation of flowers, flowering, seed formation, seed filling, maturity) are common to almost all flowering plants. Additional stages like branching, stem elongation, rosette formation, etc. all come between germination and flowering, but have no degree of generality. BASF, Bayer, Ciba-Geigy and Hoechst (BBCH) have developed a unified coding system that attempts to cover all crops from cereals[24] to beans, potatoes, vegetables and grape vines (Strauss et al., 1994).

Phenology can be modelled based on vernalization, photoperiod, thermal response and intrinsic earliness (Cao and Moss,1997), most of which are plant specific. The Intrinsic earliness is conditioned by the genetic features of the plant, and it has constituted a main target for breeders, as earliness is one of the mechanisms to avoid (evade) several difficulties linked with adverse factors like drought or early fall frost. Photoperiod and vernalization are qualitative responses of seeds or young plants that require the exposure to a cold period of a certain length and intensity before they can develop properly.

The accurate determination of phenology has a important economic role *per se*, for instance in all impact assessments and planning of farm operations (for instance labour requirement at harvesting time, or the determination of frost risk at critical crop stages; D'Antuono and Rossini, 1995). All models include a phenology component. Although they differ usually by few technical details, some phenology models are know to perform better than others. For instance, Piper et al. (1996) compared SOYGRO V5.42 and CROPGRO V3.0 for their ability to predict phenology of soybean accurately. The role of phenology goes often beyond the mere qualitative assessment phases (e.g. determination of the start of flowering or the end of root growth). Many models use a direct link between phenology and LAI, so that the whole process of assimilation becomes in fact dependent on the accuracy of the phenology (Chapman et al., 1993, and the QSUN sunflower model).

Crop phenology plays an important part whenever several species interact, either “naturally”, as in the case of weeds, insects or pathogens, or as a result of management. The phenology of pests and diseases is essential when assessing risks or evaluating losses (Rickman and Klepper, 1991), or in the optimisation of multiple cropping systems by selecting cropping sequences and their management (Tsai et al., 1987)

2.3.2.1 Photoperiod

Plants can be categorised as long-day plants, short-day plants and day-neutral plants. Flower differentiation is initiated in long-day plants by a threshold of day length below which the plants will not flower. Above the threshold, there is an

[24] Even within the groups, there is little homogeneity. For instance, some crops tiller (sorghum, wheat) while others do not (maize)

optimum daylength. Similarly, short-day plants will not flower is the day exceeds a threshold. To some extent, the photoperiodic response is independent of growth: if plants are grown outside the optimum time of the year, they may flower in very early stages (millet) or never flower at all if the proper daylength is not available.

2.3.2.2 Vernalization

Vernalization can be seen as the need for seeds or plants to be exposed to a cold threshold between T_1 and T_2 ($T_1 < T_2$). It also constitutes a mechanism to avoid frost damage. Temperatures below T_1 will kill the plant, while if temperature stays above T_2, plants will not develop. This may be combined with the duration of exposure: a shorter exposure is sometimes sufficient close to T_1, while the vernalization duration is much longer close to T_2.

2.3.2.3 Effect of temperature on phenology

Temperature plays a very directly observable effect on the rate of development of plants and cold blooded organisms. As regards crops, the effects are significant not only in temperate countries, but in tropical countries as well (examples for rice are given by Dingkuhn, 1995, and Mahmood, 1997).

The most common method to determine the effect of temperature is the often criticised method of temperature sums, also known as SDD, Sum of Degree-Days (Chang, 1974), or thermal time. The method assumes that the amount of heat (measured by temperature) required for a plant to develop from planting to stage S is a constant.

Starting from planting[25], the following sum is computed

$$SDD_S = \sum_{\text{Planting day}}^{\text{Day on which stage S is reached}} (T - T_b) \quad \text{where} \quad \begin{array}{c} T - T_b \text{ is taken as } 0 \text{ when } T < T_b \\ T \text{ is taken as } T_u \text{ when } T > T_u \end{array} \qquad (25)$$

T is average daily temperature, T_b is the base temperature below which no development takes place, and T_u is an upper threshold temperature above which it is assumed that temperatures ceases to have an effect on development. For instance, the sum of temperatures from sowing to emergence could be 100°, meaning that, with a base temperature of 10°, the plant would emerge after 10 days at 20°.

Among the criticisms to this approach, one can list the following:

- it assumes that growth varies linearly with temperature. While this may hold as a first approximation within a limited range of temperatures, it is well known that actual rates go through a maximum. The linearity assumption is closely related to the concept of Q_{10}, the factor by which the speed of a chemical reaction

---

[25] Or from some conventional date before planting is the planting date is to be determined in temperate and cold climates.

increases if temperature is raised by 10°C, as in the equation

$$Q_{10} = \frac{rate\ of\ \ reaction\ at\ (T + 10)^{\circ}}{rate\ of\ \ reaction\ at\ T^{\circ}} \qquad (26);$$

- it assumes that the temperatures T_b and T_u are constants and do not change over the cycle;
- the timing of warm spells is indifferent, whereas it is well known that the timing of abnormal temperatures does matter;
- the effects of other quantitative and qualitative factors is not taken into account (radiation).

On the positive side, we note that

- there is huge corpus of data showing that the concept provides useful indications as long as temperatures remain within the "normal range";
- the approach gives a very simple solution to the problem of some stresses. It is well known that plants like sorghum, when water stressed, may considerably delay their development (Ben Mechlia and Carroll, 1989, illustrate the fact for oranges). The introduction of a high threshold T_u can somehow account for this, as water stress periods are also characterised by high temperatures.

Over the years, many equations have been proposed to substitute the SDD method, for instance the well know biometeorological time scale of Robertson (1968).

In practice, the proposed equations often have too many parameters, or, like the SDD, do not perform well around the extremes. Interestingly (but not surprisingly), there is a marked scale effect: when equations describing chemical processes, or micro-physiological ones are transposed to the field, they usually cease to perform properly. The equation below, recently published by Xinyou Yin et al. (1995) seems to give reasonable results under field conditions (which does not mean that it would yield useful results at a regional scale).

The graph below (figure 7) illustrates the behaviour of a more sophisticated model proposed by Xinyou Yin et al. (1995), based on the beta distribution. The development rate DR is given by

$$DR = e^{m}\,(T - T_b)^{a}\,(T_u - T)^{b} \qquad (27)$$

where T_b and T_u are the base and upper values. μ is a size parameter, while α and β are shape parameters. Refer to the exercises (7.3) for details.

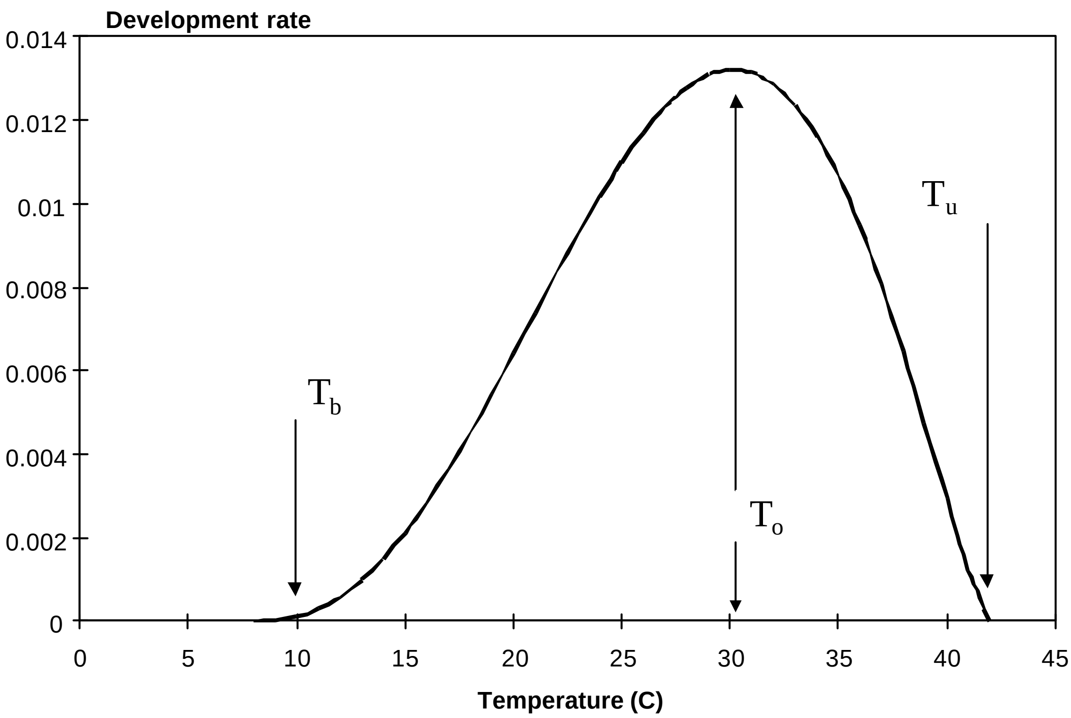
For a given phenological interval (planting to emergence, of heading to maturity, etc.), the development rate is the reciprocal of the time in days to complete the phase.

The curve culminates at T_o (o for optimum). T_o is a function of the other so-called cardinal temperatures:

$$T_o = \frac{a\ T_u + b\ T_b}{a + b} \qquad (28)$$

The maximum development rate R_o is computed by substituting T_o in the equation for DR above.

Figure 7 : Variation of development rate (Rice IR8, from sowing to flowering) as a function of temperature using the Beta model of Xinyou Yin et al. (1995). T_b is taken as 8°C and T_c is 42°C. The other parameters are μ = -15.6721; α = 2.5670; β = 1.3726.



2.3.3 Biomass partitioning

Like respiration, biomass partitioning, i.e. the distribution of the formed biomass among organs (leaves, roots...) is done at an energetic cost, which is one of the reasons why assimilation and partitioning are often discussed jointly.

Partitioning is a crop characteristic. Many models include thus a “partitioning table” which contains the necessary information. At early stages (just sown seed), the biomass stored in the cotyledons is used for root development and cotyledon elongation until they reach the surface of soil , when they start photosynthesising and assimilating. At this early stage, plants usually develop roots and leaves simultaneously at about the same rate. Roots then normally stop growing and most assimilates go to the formation of leaves. Eventually, grain formation and filling takes over the main role a sink of assimilates.

Figure 8 : An example of partitioning of biomass in a root crop at different development stages (based on data in McKerron, 1992)

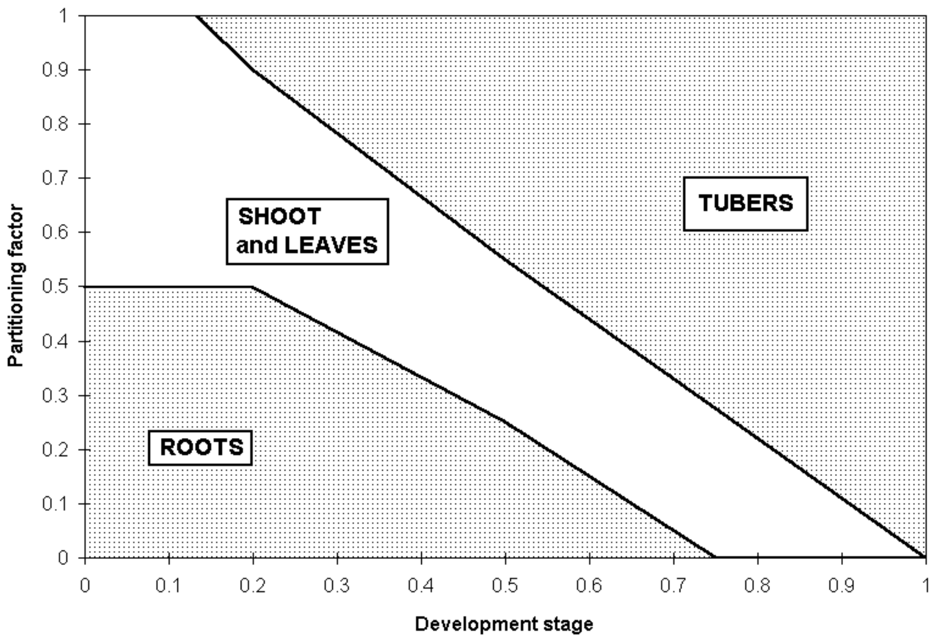


Figure 8 was drawn based on information given by MacKerron (1992). As mentioned in the above paragraph, at early stages, assimilates are evenly distributed between roots and shoots. At a relatively early stage (about 20 % through the cycle), tuber initiation takes place and new tubers start to grow. Root development will stop first, and tubers will eventually store all assimilates.

Note that biomass distribution is different from partitioning. Biomass distribution just describes in which organs the DM is actually stored at a given time, while partitioning is a more dynamic concept: it indicates to which organ the newly synthesised DM is being allocated. The harvest index, which expresses which percentage of the total biomass[26] is stored in the product (grain, fibre, sugar...) is a measure of biomass distribution at the time of harvest.

[26] In fact, for cereals the ratio sometimes refers to the quantity of product upon total above-ground biomass.

2.3.4 Root growth

The treatment of roots, if compared with the level of detail most models adopt of for light interception and the processes taking part above the ground, is best termed elementary in most cases[27].

One common approach is to assume some relation between root biomass obtained from partitioning of the photosynthetates, root weight (or root length) and the depth currently reached. The weakest points usually regard the distribution of roots over the profile, which is often assumed to be simply linear or negative exponential between the surface and the maximum rooting depth. It is amazing that validated models can predict yields and water balance rather well, while at he same time simulating rather unrealistic root distribution and biomass (for an example with CERES, see Savin and Satorre, 1994). This clearly points at other unrealistic assumptions, including in the above-ground component.

More sophisticated models do exist, which are able to simulate the relative root accumulation at certain depth due to nutrient or water distribution (Adiku et al., 1996; Asseng et al., 1997), or were calibrated against actually sampled root distributions in the soil (Pages and Pellerin, 1996).

Adiku et al. consider that the vertical extension of roots (root front extension) is more or less constant, while root proliferation, i.e. their lateral extension, is more directly conditioned by soil conditions and follows a logistic curve (which assumes a “saturation” value).

[27] For instance, the behaviour of oxygen in soils receives little attention, although it is certainly comparable in its complexity to CO_2 absorption by leaf canopies.

2.3.5 Water balance

2.3.5.1 General

The soil water balance is the universal tool to estimate soil moisture storage and its availability to plants.

Let us assume that the discussion below refers to 1 m^2. In this case, 1 mm of rainfall corresponds to 1 kg (or litre) of water.

The soil is subdivided into several layers (sometimes only one) characterised by a water holding capacity[28] (WHC); see figure 9. The order of magnitude of WHC depends on soil granulometry, composition, compaction, etc. 1 mm (water) cm^{-1} (soil) constitutes an average value. Refer to Table 2 for sample values and refer to 2.2.1 for the corresponding water potentials.

Table 2 : Some hydraulic properties of soil as a function of soil texture. Field capacity and permanent wilting point are in m^3 (water) m^{-3} (dry soil), while the bulk density is in g cm^{-3}. 0.1 m^3 (water) m^{-3} (soil) is equivalent to 1 mm cm^{-1}.

Soil texture	Field capacity	Permanent wilting point	Bulk density
Clay	0.30-0.50	0.20-0.25	1.25
Loam	0.20-0.30	0.10-0.20	1.35-1.50
Sand	0.10-0.20	0.03-0.10	1.55-1.80

Soil water content can be expressed as volumetric water content [m^3 (water) m^{-3} (soil) or, as above, mm (water) cm^{-1} (soil)] or as gravimetric soil moisture [two options, either Kg (water) Kg^{-1} (dry soil) or Kg (water) Kg^{-1} (wet soil). Other parameters frequently requested as model inputs are the bulk density which is the apparent density of dry soil [g (soil) cm^{-3} (soil)]

When water enters the soil, it fills the first layer to capacity, after which it spills over into the second layer, etc. The bottom of the last layer coincides with the maximum rooting depth. Water that spills over beyond rooting depth is usually termed deep percolation. Additional water movements are sometimes considered, for instance the rise of water from deep layers due to capillarity, and (rarely) lateral movements.

An empirical factor often used is soil bypass coefficient (0 to 1) which is useful when soils crack and fraction of the water just flows through the soil. This is one of those empirical factors which can be conveniently resorted to force a model to behave according to observation, sometimes regardless of their actual physical significance. More examples will be given under chapter 4 (4.1).

Plant roots start growing in the first layer, and gradually extend throughout the profile to occupy the whole volume up to a maximum, given either as a crop or as a soil characteristic (chemical - pH, sulphates- or physical barriers, including the presence of rock or the water table).

---

[28] Usually defined as the difference between field capacity and permanent wilting point.

Plants will gradually extract water from all the layers (transpiration). Soil evaporation occurs only from the top of the first layer, although some models make provision for air channels which are responsible for some evaporation from deeper layers.

2.3.5.2 Infiltration

One of the main difficulties in practice is the determination of the amount of water which actually enters the soil (effective rainfall R_{eff}). Part of the rainfall can be intercepted by vegetation (for instance between the leaves and the stems of cereals) or it can just be lost laterally by surface runoff (particularly on sloping terrain). In addition, infiltration rates depend on the "history" of the soil and the successive wetting cycles do not behave identically, nor are soil properties identical in the drying and wetting phases. Numerous methods have been designed to estimate R_{eff}, going from the very "theoretically correct" to the very empirical. The latter will be illustrated below.

Two popular methods are those of USDA Soil Conservation Service (USDA, 1967), and the runoff curve number approach of the USDA-SCS (USDA, 1972).

According to the first method:

$$Prec_{eff} = \frac{Prec(125 - 0.2\,Prec)}{125} \qquad for\ Prec < 250\,mm\ per\ month$$
$$Prec_{eff} = 125 + 0.1 Prec \qquad for\ Prec \geq 250\,mm\ per\ month \tag{29}$$

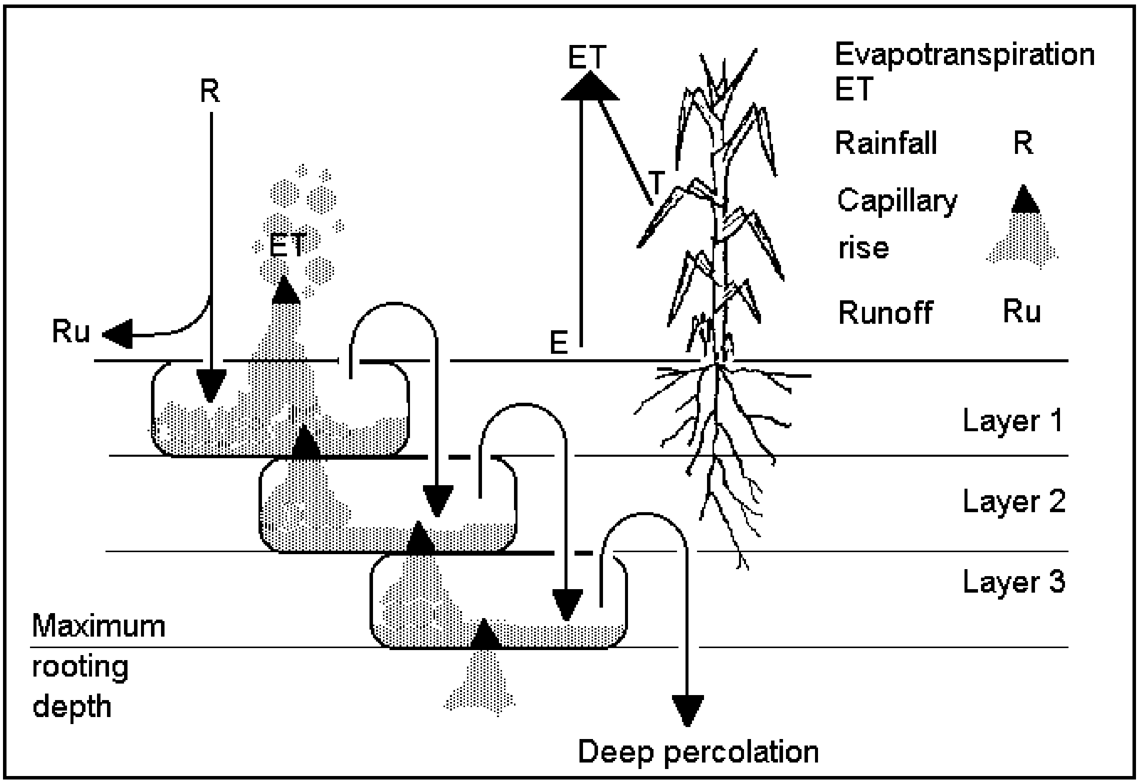
For years the USDA Soil Conservation Service (SCS; refer to Maidment, 1992) has been using an empirical approach to determine runoff, known as the *runoff curve number approach*. The method refers to one storm, hence both rainfall Prec and runoff Q refer to the accumulated values from the beginning of the storm. The derivation of the equations is quite simple; they are based, among others, on the assumption that no runoff occurs until rainfall exceeds an initial threshold (all rainfall infiltrates, is stored in the soil, percolates below it, or otherwise held in the basin).

$$Q = \frac{(Prec - 0.2S)^2}{Prec + 0.8S} \tag{30}$$

$$S = 25.4\frac{1000 - CN}{CN} \tag{31}$$

where S is the potential retention of water in the catchment area (in mm; mainly soil storage in agricultural areas) and CN is the curve number obtained from published tables as a function of general hydrological and land-use characteristics of the area.

Figure 9 : Schematic representation of water flow in a three layer soil model with no lateral movements of water in the soil.



The soil is first characterised by assigning a land use, treatment or practice, and general hydrologic condition (poor, fair, good). Examples are “fallow, straight row, poor”, or “pastures, nil, fair”, or “row crop, contoured, good”. Once the categories above have been identified, the user has to assign the area being modelled to a hydrologic soil group, defined according to their intake of water when they are thoroughly wet and receive precipitation from long-duration storms (Table 3 and figure 10).

The four hydrologic soil groups are:

Group A - Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission;

Group B - Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission;

Group C - Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission;

Group D - Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a permanent high water table, soils that have a clay pan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

Figure 10 : USDA-SCS relation between storm runoff and rainfall for curve numbers between 100 and 20 (heavy lines). Thin lines indicate the intermediate CN values (95, 85 etc.).

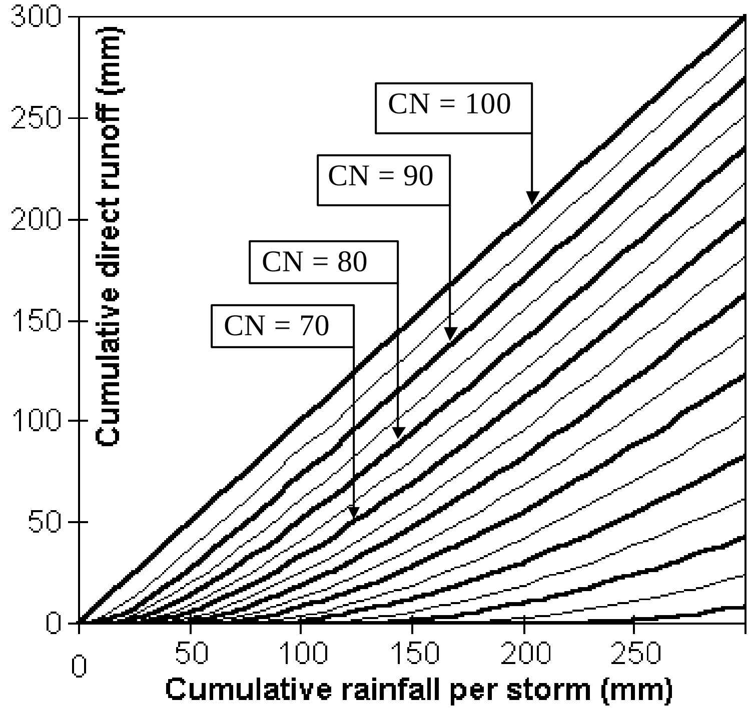


Table 3 : Examples of runoff curve numbers (last 4 columns, from A to D) as function of land use, cover or practice, hydrologic condition and soil group. The examples are from the EPIC manual (Mitchell et al., 1995) and from Maidment (1992).

Land use	**Cover, treatment or practice**	**Hydrologic condition**	**Hydrologic soil group**			
Fallow	Straight row	fair	77	86	91	94
Pasture		fair	49	69	79	84
Woods		poor	45	66	77	83
Row crop	Contoured	good	65	75	82	86
Meadow		good	30	58	71	78

Industrial			81	88	91	93
Residential	plots< 600 m^2		77	85	90	92
Residential	plots> 5000m^2		54	70	80	85

2.3.5.3 Partitioning of evapotranspiration ET between evaporation E and transpiration T; water stress

There are many “systems” to partition the evapotranspiration between evaporation from soil (or water in the case of paddy rice) and transpiration from crops. The simplest system is to assume that

$$\begin{aligned} T &= LAI \times ET \qquad \text{when } LAI < 1 \\ T &= ET \qquad \text{when } LAI \geq 1 \end{aligned} \tag{32}$$

WOFOST (Supit et al., 1994) uses a function of the LAI:

$$T_m = ET_0 (1 - e^{-K.LAI}) \tag{33}$$

where T_m is the maximum evapotranspiration rate (cm d^{1}), ET_0 is the potential evapotranspiration, K is the extinction coefficient for global radiation (dimensionless) and LAI is leaf area index in m^2 (leaf) m^{-2} (ground).

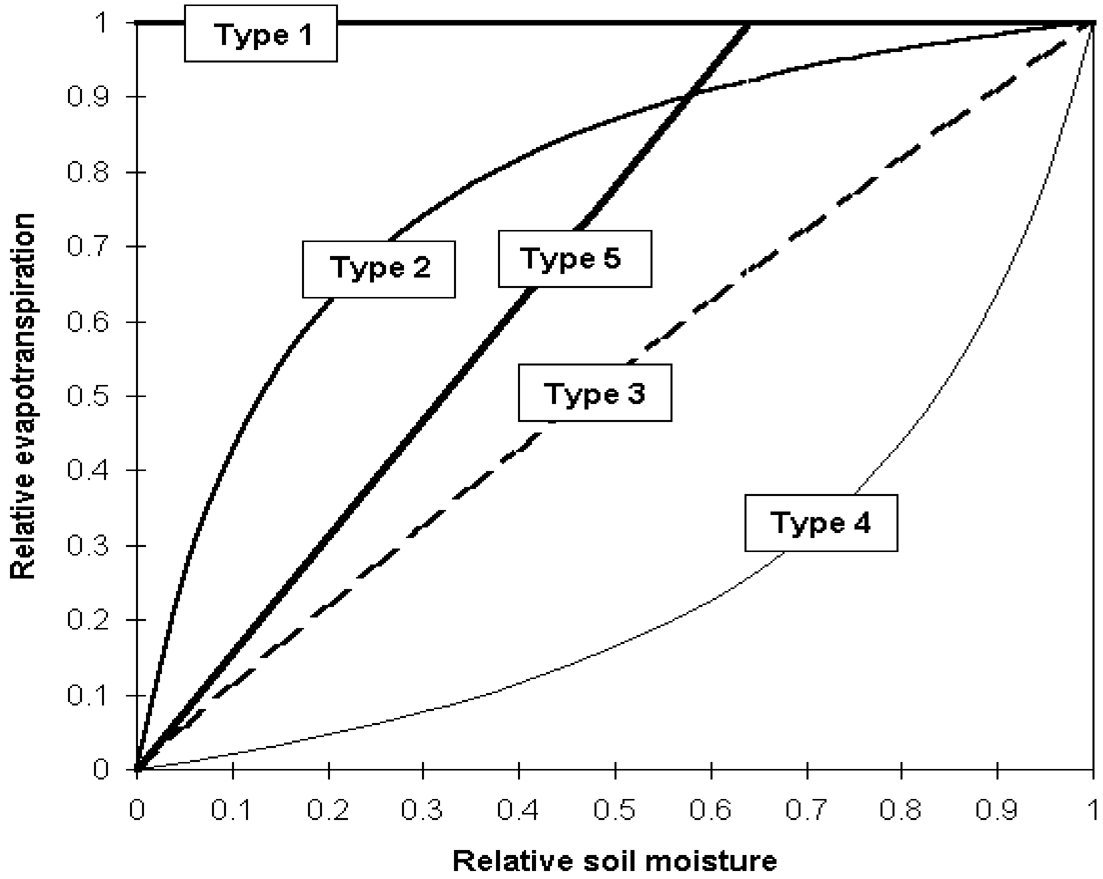
T_m is used because both transpiration and evaporation vary according to water stress, i.e. a measure of the actual water supply compared with the maximum possible supply at field capacity.

Because of the well established link between transpiration and productivity (see 2.3.3) there is a need for models to reduce evapotranspiration during stress periods. This is solved using several techniques, the most common being empirical curves relating relative evapotranspiration water to relative soil moisture, i.e. the current soil moisture expressed as the percentage depletion between field capacity and permanent wilting point:

$$H_r = \frac{H - H_{pwp}}{H_{fc} - H_{pwp}} \tag{34}$$

Different types of curves have been used; some of them are schematically in Figure 11 below.

Figure 11: Relative evapotranspiration as a function of H_r, the relative soil moisture



The less empirical approach would be to use soil water potential curves (soil suction) or soil water retention curves, but this is usually done only in the more specialised models (McCoy, 1991), probably because the potentials are difficult to sample and to derive from other soil features with some degree of accuracy (Whisler and Landivar, 1988).

Finally, ET_0 is often multiplied by an empirical coefficient to account for the fact that actual transpiration may exceed the potential values by a factor up to 20 or 30 %. The factor is called the Crop Coefficient (K_c). Kc is one of those empirical factors which should, in theory, no longer be necessary with the Penman-Monteith evapotranspiration formula. Yet, the coefficient is still very present in the literature, although, as Choudhury et al. (1994) observe, variations in soil evaporation can introduce considerable scatter in the relationship between the crop coefficient and leaf area index.

2.3.6 Mineral nutrition and nutrient management

Nutrients absorption is treated in a way which has several similarities with water, in the sense that it is driven by gradients. The approach implemented in CropSyst for nitrogen is described below (Stöckle et al., 1994).

Nitrogen constitutes between 0.5 and 1.5% of the dry matter of plants, while carbon amounts to 40 to 50%. The bulk on plant nitrogen is in proteins, which contain about 20% of N. Amounts held in plant material are usually between 250 and 1000 Kg Ha^{-1}, resulting in C/N rations between 20 (legumes) and 46. When the plants die or are ploughed into the soil, the nitrogen is gradually mineralised and released faster than C. This process is simulated by the models like CropSyst which include a nitrogen simulation module (Stöckle and Debaeke, 1997). The main source of agricultural soil nitrogen, however, is nitrogen fertiliser. Application rates are normally of the same order of magnitude as amounts exported in harvests.

Total crop nitrogen demand on day J [TD; Kg (N) Ha^{-1}] is the sum of the demand deriving from the current deficit in the plant at the beginning of J when the biomass is W [Kg (DM) Ha^{-1}] - which is deficit demand deriving from past nitrogen stress , DD) - plus the demand deriving from new growth ΔW on day J (growth deficit GD).

$$TD = DD + GD \tag{35}$$

With N_{max} being the maximum crop nitrogen concentration and N_W being the actual concentration,

$$DD = W(N_{\max} - N_W) \tag{36}$$

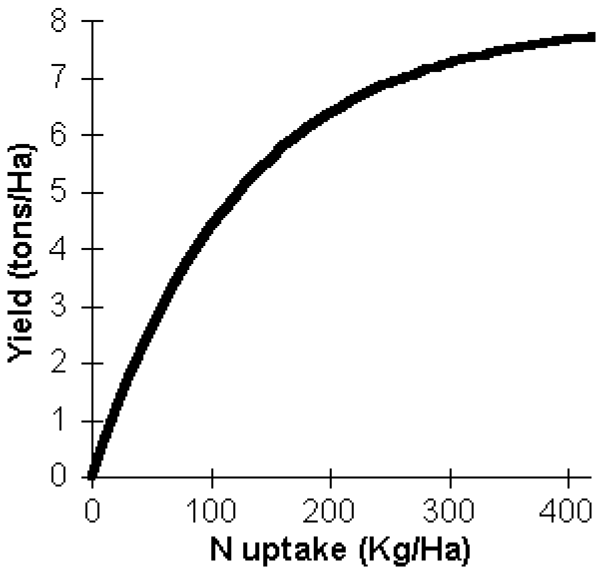
and

$$GD = N_{\max} \times \Delta W \tag{37}$$

with the following units Kg (DM) Ha^{-1} for W and ΔW, and Kg (N) Kg^{-1} (DM) for N_{max} and N_W.

Needless to say, N is taken from all soil layers and depends on the availability of nitrogen, its chemical form (NO_3^-, NH_4^+), the availability of water (as nitrogen is dissolved in water), the root length, etc. A nitrogen budget is computed, and nitrogen is allowed to move between soil layers, and sometimes to be leached out.

Figure 12: Response of crop yield (Tonnes Ha^{-1}) to nitrogen uptake [Kg (N) Ha^{-1}]



There are several techniques to quantify the effect of nitrogen uptake on yields. The response curve of yield to nitrogen is of the saturation type (figure 12). The curve can be made to condition maximum CO_2 absorption, resulting in the expected response.

An alternative approach is to partition the absorbed N into the various plant organs, usually according to their “normal” protein concentrations. As plants and their organs are characterised by a structural ratio between protein and the constituents (for instance carbohydrate), the growth can be constrained by the failure of the available N-supply to allow for the normal development of the plant organs.

CropSyst adopts the following expression for nitrogen limited growth (all biomass parameters on a daily basis):

$$\Delta W_N = \Delta W \left(1 - \frac{N_{pcrit} - N_p}{N_{pcrit} - N_{p\min}}\right) \qquad (38)$$

where ΔW is the water and radiation limited growth, N_{pcrit} is a critical nitrogen concentration, N_p is current plant nitrogen concentration and N_{pmin} is the minimum plant concentration.Δ

3. Chapter three : Overview of models

This chapter provides an overview of the types of tools available for the assessment of climate and weather impact on agriculture and plant production. They vary in their complexity from general relations to crop specific models, their scope (scale and field of application), and institutional context.

Different models have also vastly different input data and data processing requirements, and therefore their practical application implies the mastery of tools and technologies from the very simple (pencil and paper) to the very complex (computer network with automated real-time data collection).

The following 6 categories are schematically identified:

- **Global biomass models (3.1)**: descriptive methods relating biomass to environmental conditions at a very generalised scale. They are suitable for global climatological and agroclimatological studies. Their practical applications are relatively limited but for the determination of potential yield, although their relevance for fundamental and research aspects is beyond doubt;
- **Vegetation models (3.2)** attempt to describe vegetation behaviour, over various scales, from global to local. This is a field which groups rather different models, and an area where modelling is probably more difficult than in other fields, among others because of the larger number of species involved;
- **Statistical models (3.3)** are not covered in detail; they are just mentioned here as they still constitute a major tools for many crop-weather impact assessments. So-called statistical models are simply formulae linking some agronomic parameter, for instance yield with other factors, environment-, climate-, economics- or management-related. If the variables are chosen properly, statistical "models" can perform efficiently at little cost;
- **Empirical models for regional applications (3.4)**: models requiring relatively few inputs which can be used for monitoring and forecasting crops over large areas. This includes very "applied" models;
- **Simulation models (3.5)**: mostly process-oriented models which actually attempt to simulate the actual interactions between plants and their environment based on chemical, physical, physiological and anatomical data and principles covered in chapter 2. Due to their detailed nature, they constitute essential research tools for understanding crop response, and their most obvious applications at the very fine spatial resolution, i.e. the field.
- **Other models (3.6)**: this category covers methods of weather impact assessments that do not fall into any of the previous categories

3.1 Global Biomass models

The "models" listed below are simply equations which relate environmental parameters to biomass production. They are typically based on annual climatic values and there main function is to describe empirically how primary production varies according to main climates.

A second function, the main one in fact to the approach by Kumar and Monteith (1981), is to determine the yield which can be achieved (potential yield) under the current solar energy supply. Actual yield will be much less in practice, due to the interference by such factors as poor water supply, pests, sub-optimal management, etc.

3.1.1 Potential biomass

Kumar and Monteith (1981) have presented a simplified method to estimate conversion efficiency of solar radiation into biomass, based on earlier work by Monteith (Bégué et al., 1991).

The climatic potential of dry matter accumulation (DM, g m^{-2} $year^{-1}$) is given, in absence of limiting factors (for instance water stress or pest attacks), by

$$DM = H \times Eff_H \times Eff_c \times Eff_a \tag{39}$$

where H is the global net radiation (50 TJ/year per Ha, or 50 10^6 MJ/year per Ha; see 2.2.2) and Eff_H, Eff_a and Eff_c are conversion efficiencies:

- Eff_H is the climatic efficiency, i.e. the fraction of photosynthetically active radiation (PAR) relative to H, usually in the range from PAR/H=0.33 to 0.5 according to location and season, although 0.5 seems to be adopted by most authors for practical applications (Lauciani and Ponticiello, 1993) ;
- Eff_c is the conversion efficiency of absorbed PAR (PARa) to biomass produced. Eff_c is very plant dependent and varies over the life cycle. Typical values are in the range of 3 g of DM per MJ for C4 plants, and about 2 g per MJ for C3 plants;
- Eff_a, the absorption efficiency depends on leaf area index (LAI: m^2 (leaf) m^{-2} (ground surface)) and canopy geometry. This parameter is also called “interception efficiency” It is thus, again, dependent on plant type.

In general,

$$Eff_a = a\,(1 - e^{-K \cdot LAI}) \tag{40}$$

where a is the asymptotic value of Eff_a and K is the radiation attenuation coefficient within the canopy. "K depends on external factors (solar zenith angle, fraction of diffuse radiation and optical properties of the soil), on the optical properties of the leaves and on the architecture of the canopy" (Bégué et al., 1991). This subject was already covered in more detail in section 2.2.2; compare also with (13).

For field crops, it is usually possible to reduce the equation of Eff_a to a simpler linear form. For millet, for example, the quoted authors found

$$Eff_a = 0.44\ LAI \tag{41}$$

during the growth period, with a maximum LAI of 1.3.

With a net radiation H of 50 10^6 MJ $year^{-1}$ Ha^{-1} (refer to 2.2.2), Eff_c = 3 g DM / MJ , Eff_a = 0.44 x 1.3 and Eff_H = 0.5 it is found that the corresponding DM accumulation amounts to

$$DM = 3 * 0.44 * 1.3 * 0.5 * 50\ 10^6 \text{ g year}^{-1} \text{ Ha}^{-1}$$

$$DM = 42.9\ 10^6 \text{ g/year per Ha or } 42.9 \text{ tonnes year}^{-1} \text{ Ha}^{-1}$$

Climatic potential DM accumulation values are thus very high, much higher, in particular, than actual crop yield.

Note that the potential yields have to be reduced to account for the fact that the economic yield (grain, sugar or fibre, for instance) is only part of the total biomass (roots and above-ground biomass). Harvest indices (i.e. the ratio between economic yield and total biomass) typically vary from 0.5 to 0.7.

Furthermore, biomass actually grows only during part of the year (limited by low temperatures in temperate climates or by water availability in semi-arid areas); a number of pests and diseases damage crops and soil physical and chemical conditions are frequently limiting.

Finally, the radiation values of 50 TJ/Ha per year corresponds to an average. Local values may differ by a factor of 0.5 to 1.5.

With a harvest index of 0.3 (grain/total biomass) and a growing cycle of 3 months (3/12, or 0.25), 42.9 tonnes Ha^{-1} $year^{-1}$ thus reduces to a significantly more modest 3.2 tonnes Ha^{-1}, a value which, for many developing countries, is still on the high side.

The "good high" national yields (tonnes Ha^{-1}) for some crops are given below (table 4), according to the FAO production yearbooks. Locally, values may be significantly higher or lower. Provided adequate inputs are made available, biomass yields could be increased significantly.

Table 4 : Some typical values of national yields

Crop	Yield (Tons/Ha)	Crop	Yield (Tons/Ha)
Sweet potato	27	**Wheat**	7
Rice	7	**Maize**	12
Millet	2	**Sorghum**	6
Irish potatoes	45	**Yams**	30
Sugar cane	120	**Sugar beet**	57

3.1.2 The "Miami model"

Very simple empirical equations, known as the Miami model were proposed by Lieth (1972, 1975). The Miami model expresses net primary production NPP as a function of macro-climatic conditions. The NPP is expressed in g (DM) m^{-2} $year^{-1}$:

$$NPP = \min(NPP_T, NPP_P) \tag{42}$$

$$NPP_T = \frac{3000}{1 + e^{(1.315 - 0.119 T_C)}} \tag{43}$$

$$NPP_P = 3000\,(1 - e^{-0.000664\,Prec}) \tag{44}$$

where T_C is average annual temperature in °C and Prec is annual precipitation in mm. According to whether T or P is limiting, the lowest value of NPP_T and NPP_P is eventually retained.

Table 5 shows some typical values of NPP as a function of T_C and P.

Table 5 : Net primary production (g DM year^{-1}) as a function of temperature and precipitation according to the "Miami model"

Temperature		**Precipitation**	
T_C	**NPP_T**	**mm**	**NPP_P**
0	635	**0**	0
5	982	**100**	193
10	1406	**250**	459
15	1846	**500**	848
20	2231	**1000**	1456
25	2521	**1500**	1892
30	2715	**2000**	2205

In 1972, Lieth and Box (Lieth 1972, 1973, 1975) have also proposed the equation below which links productivity and annual potential evapotranspiration in mm:

$$NPP_{ETP} = 3000(1- e^{-0.0009695(E-20)} \qquad (45)$$

Finally, still in the series of empirical equations, we quote the equation by Reader linking NPP (still in g DM year^{-1}) with the length of the growing period L in days:

$$NPP_L = -157 + 5.175 \; L \qquad (46)$$

3.1.3 White, Mottershead and Harrison (1992)

White, Mottershead and Harrison (1992) provide a series of graphs showing net primary production NPP (g m^{-2} year^{-1}), as a function of several annual climatic variables, such as rainfall, actual evapotranspiration and temperature. The present author has derived the following equations based on the data in White et al.

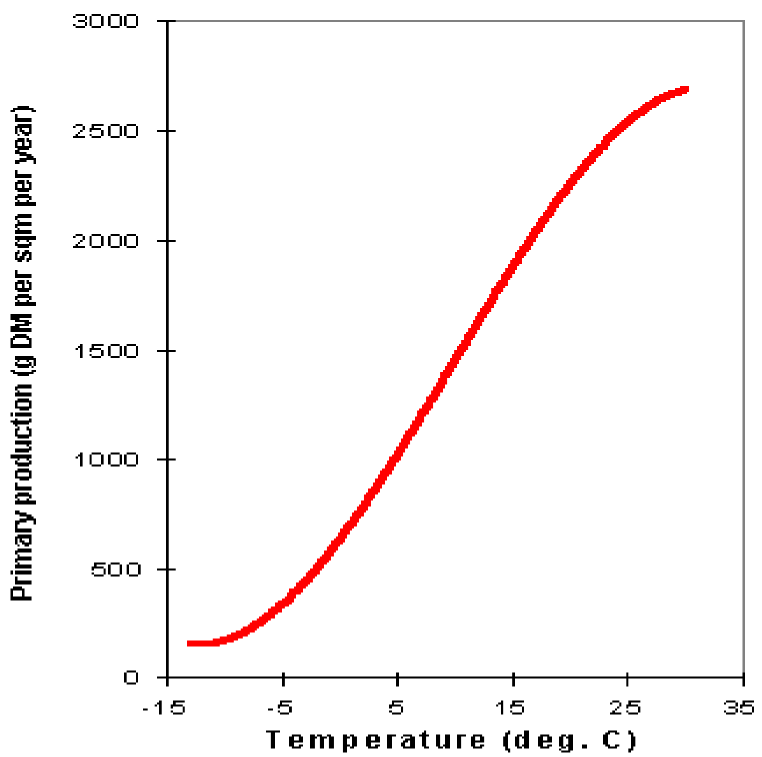
For rainfall Prec and actual evapotranspiration (ETa) the curves assume the same shape and are described by

$$NPP_X = a(1 - e^{-bX}) \qquad (47)$$

where X stands for Prec or ETa. The coefficients are given below:

	a	b
Rainfall (mm)	2909	0.000688
Actual ET (mm)	3511	0.000778

Figure 13 : Net primary production as a function of temperature according to White, Mottershead and Harrison (1992)



For temperatures (figure 13), a saturation-type curve is obtained which corresponds to the equation:

$$NPP_T = \frac{2914}{1 + 3.64\ e^{-0.128T}} \qquad (48)$$

3.1.4 The "Chikugo" model

The equation given by Uchijima and Seino (1985) and Seino and Uchijima (1992) is interesting in that in involves several terms of the water balance: radiation and rainfall. It is written

$$NPP = 0.29H . e^{\left(-0.216\ RDI^2\right)} \qquad (49)$$

where H is the annual net radiation (Kcal cm^{-2}) and RDI is the "radiative dryness index" defined as the ratio H/(L.Prec) between annual net radiation and the product of L and Prec, L being the latent heat of evaporation (580 cal/gH2O) and Prec annual precipitation in cm. RDI expresses how many times the available energy can evaporate the rainfall.

Converted to SI units, this becomes

$$NPP = 6.938 \cdot 10^{-7}\ H\ e^{\left(-3.6 \cdot 10^{-14} \left(\frac{H}{Prec}\right)^2\right)} \qquad (50)$$

with NPP in g (DM) m^{-2} year^{-1}, H in J m^{-2}, Prec in mm (equivalent to Kg m^{-2}). Refer to the exercises for more details (7.4).

3.2 Global Vegetation models (GVM)

This section groups several types of models which have in common that they deal with qualitative assemblages of several species. They describe species behaviour and interaction more in qualitative than in quantitative terms, although the underlying method may be quantitative and process-based.

Most climate classifications can be regarded as global vegetation models: in fact, it used to be one of the aims of the early climate classifiers, Köppen included, to account for the distribution of vegetation. This is clearly illustrated by the names given by Köppen to some of the climate types, for instance BS for the warm semi-arid areas (S stand for steppe) or BW for the warm deserts (W stands for the German word Wüste, i.e. desert).

Global vegetation models have undergone an increase in popularity over recent years with the renewed interest in global change and the potential impacts of global change on vegetation.

GVMs are typically based on a typology of vegetation or life forms as a function of climate. For instance, very dry and very cold climates cannot support trees. Plants adapted to very dry and warm climates have in common that they have developed mechanisms to reduce water loss, for instance water storage (as in cacti and other succulent plants), hairy leaves, low root/shoot ratios, etc. Another example: organic matter accumulates in the form of peat when production exceeds decomposition, either usually in very humid and cold climates, etc.

It is thus possible to describe the type of vegetation rather accurately based on the climatic conditions, but the simulation of species composition is till along way off, mainly because there is simply insufficient knowledge available about the ecophysiology of wild species.

One such model is a Global Vegetation Model developed by Tchebakova, Monserud and Rik Leemans. It predicts the geographic extent of biomes[29] based on climate inputs from GCMs. The model is static and is developed for a coarse resolution (0.5 deg. x 0.5 deg.).

Biomes are determined from sub-models which calculate dryness indices and potential evaporation using radiation balance equations. This model is based on an earlier model developed by Budyko which predicts vegetation patterns based on a radiation balance and dryness index.

Another well known vegetation model is BIOME3 : an equilibrium terrestrial biosphere model that has been implemented globally using a minimal set of just five woody and two grass plant types (Haxeltine and Prentice, 1996a; Haxeltine et al., 1996b). In BIOME3, leaf area is expressed as leaf area index (LAI). A small number of ecophysiological constraints is used to select the plant types that may be present in a particular climate. The model then calculates a maximum sustainable LAI and NPP for each plant type. A semi-empirical rule designed to capture the opposing effects of succession driven by light competition and natural

[29] Biomes are very broad environments, usually of world-wide importance, under the same climate. Examples for the main biomes are the tundra, temperate forests, equatorial rainforests, coastal areas...

disturbance by fire excludes grasses as a dominant plant type if soil conditions are too wet. Otherwise, the plant type with the highest NPP is selected as the dominant plant type.

At a very different scale, ALMANAC (Agricultural Land Management Alternative with Numerical Assessment Criteria) is a predictive and process oriented model , but it is also able to simulate competition between 2-10 plant species. It includes detailed functions for water balance, nutrient cycling, plant growth, light competition, population density effects, and vapour pressure deficit effects. t has enough detail to be general across locations and species but is not so complex that independent users cannot apply it to their situations (Kiniry et al., 1992). It is thus not surprising that many models restrict themselves to two or three plants: a crop in monoculture, with one or two competing weeds (Kropff et al., 1992).

The potential geographic distribution of plants, pests and diseases can be assessed using specific models such as CLIMEX. Based on gridded climatic data, such models define how conducive the conditions in a given grid-cell are for the development of a specific organism with known ecophysiological requirements. The information can then be turned into potential or risk maps using a GIS (Baker, 1996). At the field level, models incorporating weed control strategies, in combination with weed population dynamics, provide means to simulate the most cost effective control measures (Holzmann and Niemann, 1988).

3.3 Statistical "models"[30]

The most common application of statistical "models" is the use of multiple regression techniques to estimate crop yield: a regression equation (usually linear) is derived between crop yield and one or more agrometeorological variables, for instance

$$\mathrm{Yield} = 5 + 0.03\,\mathrm{Rain}_{\mathrm{March}} - 0.10\,\mathrm{T}_{C,\,June} \qquad (51)$$

with yield in tons Ha^{-1} , March rainfall in mm and June temperature in °C. Beyond their simplicity, their main advantage is the fact that calculations can be done manually, and in the fact that data requirements are limited. The main disadvantage is their poor performance outside the range of values for which they have been calibrated. They often also lead to unrealistic forecasts when care is not taken to give greater priority to the agronomic significance than to statistical significance. The equation above, for instance, suggests that low March rainfall (a negative factor) could be corrected by below zero temperatures in June (frost), which obviously does not make sense. Another disadvantage is the need to derive a series of equations to be used in sequence as the cropping season develops. For an overview of regression methods, including their validation, refer to Palm and Dagnelie (1993) and to Palm (1997a).

Many of the disadvantages of the regression methods can be avoided when value-added variables are used instead of the raw agrometeorological variables, as is done in the FAO method (see section below). Such a value-added variable would be, for instance, actual crop evapotranspiration, a variable known to be linked directly with the amount of solar radiation absorbed by the plant under satisfactory water supply conditions or light water stress (2.2.4).

---

[30] Taken from Gommes, 1998b.

3.4 Semi-empirical models for regional applications: the FAO method

There appears to be a gap between the global scale described above (3.1) and the field scale. It is suggested that the approach used by FAO and a number of developing countries for crop forecasting at the national level occupies an intermediate niche, both in terms of input requirements and ease of validation[31]. The section thus describes the FAO crop modelling and forecasting philosophy, based largely on Gommes et al., 1998.

The word "philosophy" is preferred to "methodology" because the position of FAO has been to propose a general framework of which the totality, or only some elements, can be adopted by the countries for their national crop forecasting methodology for food security. It is also felt that "philosophy" stresses the fact that, when operating in a field with many partners (economists, marketing experts, nutritionists, statisticians, demographers, *etc.*), the most serious problems are not technical but <u>organisational</u> and <u>institutional</u>: co-ordination of the participants and integration of different sectoral approaches.

3.4.1 Flow of data

The flow of data is illustrated in figure 14. The left hand side of the figure (elliptic boxes) lists the sources of the data: the meteorological network, satellites, field observers (mostly agricultural extension staff) and national services dealing with soils (e.g. soil survey), crops (ministry of agriculture services) and National Agricultural Statistics. The number of partners and the diversity of the data types creates some difficult as well as interesting problems which were described elsewhere (Gommes, 1996).

Each of the sources may contribute one or more types of data (second column, rectangles). For instance, meteorological data can be provided, in addition to the *ad hoc* national network, by remotely sensed sources. Indeed, several methods are now routinely available which are used to derive or interpolate rainfall or sunshine data from satellite information (compare with 5.1).

The same applies to some crop data, for instance planting dates, which may be estimated, under adequately known conditions, from vegetation index (NDVI[32]) time series.

Based on the meteorological and agronomic data, several indices are derived which are deemed to be relevant variables in determining crop yield, for instance actual evapotranspiration, crop water satisfaction, surplus and excess moisture, average soil moisture... The indices (variables) then enter an equation (the yield function[33]) to estimate station yield. At this stage, the data are still station-based since most input are by station.

---

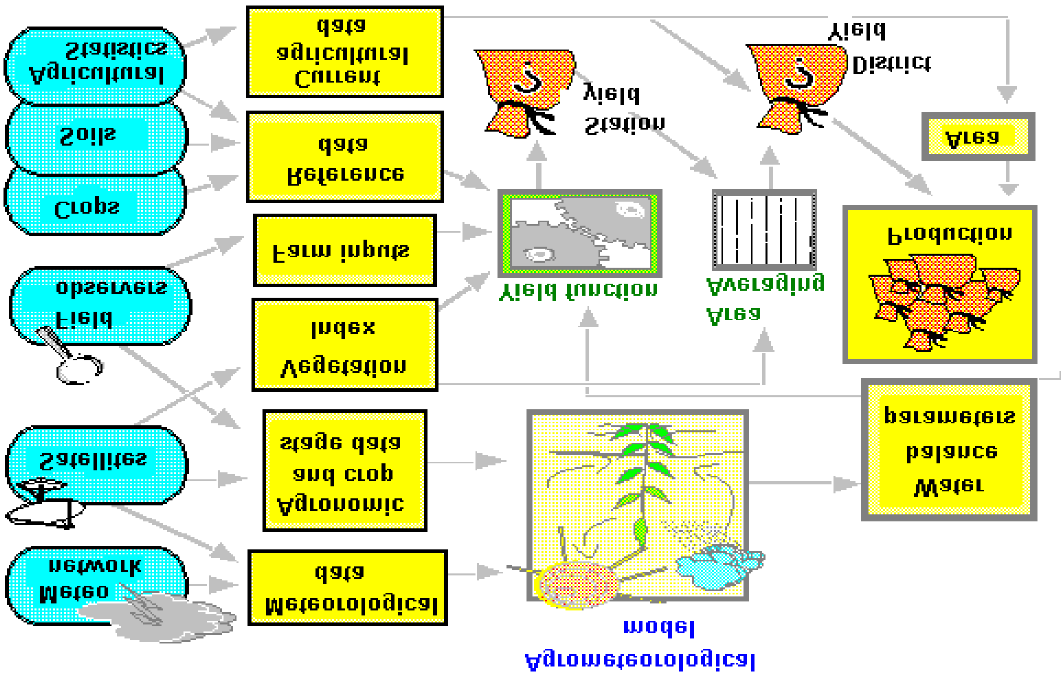
[31] Validation, in this context, covers basically the statistical calibration of the model, as the underlying processes can hardly be verified at the considered scale.

[32] Normalised difference vegetation index. A satellite index which is roughly and not too far from linearly correlated with standing living biomass. Under normal circumstances, the condition of natural vegetation and crop condition are related. Refer to 5.1.2.1.

[33] The yield function is usually an equation, linear in most variables, which was obtained by multiple regression of a combination of time series and cross-sectional data.

It is stressed that the derivation of the indices above constitute a major difference with the process-oriented models: they constitute some of the variables that will be used in an empirical multiple-regression type “model”, to estimate yields, as described under 3.3. However, because they derive from an agrometeorological analysis, they constitute highly value-added variables.

Figure 14 : The flow of data in FAO-promoted crop forecasting systems for food security.



Station yields are then area-averaged using, for instance, NDVI as a background variable (see 5.3.3), possibly adjusted with other yield estimated provided by national statistical services, multiplied by planted area to yield a district production estimate[34].

As indicated, according to countries, variants to this general scheme can be introduced at almost every step. The technical options were adopted mainly to reduce computing overhead and bypass, for the time being, some problems which are still difficult to handle in the context of developing countries. More details will be given below, but simple, even elementary solutions are sometimes preferable to complex solutions for which the necessary inputs are not available and must virtually be guessed. It is also suggested that a codified system and reproducible approach, even if very far from perfect, is preferable to no system.

To illustrate the previous point: many countries estimate crop production[35] by calling a meeting of knowledgeable people (grain board, statistics,

---

[34] In practice, the situation is slightly more complicated as “station yields” have themselves been calibrated against agricultural statistics which are given by administrative units.

[35] In most developing countries there are not many alternatives to agrometeorological crop forecasting, with or without remote sensing inputs. Some countries in the Sahel conduct rapid

agrometeorological services) and, through bargaining, eventually reach an agreement on the current crop production estimate. No specific methodology is followed, and strong political bias - conscious or otherwise - is often a basic ingredient in the forecast.

Under such circumstances, any “system” which will avoid political bias and ensure at least a reasonable degree of consistency from year to year and from place to place is to be preferred.

3.4.2 Technical options

The main technical options adopted in the FAO crop forecasting philosophy are the following:

- agrometeorological and remotely-sensed data are integrated at all levels whenever possible: at the level of data (rainfall, phenology) and at the level of products (area averaging of yields);
- gridding is done after modelling[36], under the assumption that there exist variables, such as NDVI, which are at least qualitatively linked to crop condition **in a given area**. If this assumption does not hold in quantitative terms over large areas is not relevant for the interpolation procedures adopted. This also assumes that such factors as soil fertility and the effect of greater soil water holding capacity is captured by NDVI;
- the time step mostly adopted is the dekad: all calculations are done at a ten-daily step
- results are calibrated against agricultural statistics through empirical yield functions. It is clear that the accuracy of the forecasts cannot possibly be better than the agricultural statistics used to calibrate them. There is thus some uncertainty about the accuracy (see 4.5), 10% to 30% is probably a good guess. At the scale at which FAO works, e.g. districts, provinces, etc., models developed at the field level do not apply. The “agrometeorological models” mentioned in figure 14 are thus usually very simple. They aim more at assessing growing conditions through value-added “water balance parameters” then actually simulating crop-weather-soil interactions. It is, therefore, justified to use empirical

---

estimates based on interviews with farmers. Other countries have developed biometric systems based on measured crop indices (plant density, maize cob size). In some countries agricultural statistics are so uncertain that the agrometeorological forecasts are taken as final yield and production figures. The agrometeorological approach usually gives best results in semi-arid areas where the water deficit is the main limiting factor. It performs poorly in some mountainous areas where (i) farming does not follow a homogeneous pattern, (ii) coverage by the weather stations is insufficient and (iii) water surplus, or pests and diseases, tend to be the main limiting factor(s). Simple statistical (trend) models perform very poorly in semi-arid countries, where the inter-annual variability of yields reaches very high values. This being said, after an initial spell of enthusiasm, the hope to use direct correlations between satellite indices and yields as a forecasting tool, was gradually abandoned. The methods worked only in few countries, if given the help of additional data collected at ground level.

[36] Gridding of actual data, for instance weather data for short time intervals, is the typical example where we feel that the available techniques have not reached the a level of reliability which would justify our transferring the methodology to national services in developing countries.

yield functions which, in addition, avoid to touch on the most difficult issue of geographic scale effects;

- tools are modular, i.e. the crop forecasting system uses a number of software tools that carry the analysis from the data to the final production estimate (see Gommes, 1995, for a more detailed account of the software). Depending on the local conditions, national services can choose between different tools (for instance for area averaging). Any specific tools can be changed without touching the whole structure of the system: the system remains light and easily upgradable and maintainable. This is facilitated by standardisation[37] through common file names and structures and early reduction[38] of RS images (Snijders, 1995). What this means is that the users, who are responsible for carrying out the analyses and the forecasts, need not worry about the technical (remote-sensing technical) aspects of satellite inputs.

[37] This issue was addressed by a recent meeting organised by FAO (FAO, 1995).
[38] Image reduction here refers to the corrections (geometric, collocation, radiometric, etc.) which must be made on the images before they can be used for applications.

3.5 Simulation models

3.5.1 Sources of information

The information below, in addition to original scientific publications, is also taken from several internet sites which have now become one of the easiest non-technical sources of information about models. There are several sites specialising in ecological and agronomic models. Most are searchable, sometimes with keywords, which greatly facilitates the identification of suitable models. The sites also provide links to the specific home pages dedicated to the models, their authors and other relevant information.

Many models and other agrometeorological tools are downloadable from the WWW and distributed as freeware. In some cases, only the older versions are freely available, "older" meaning that either the model has been improved - in which case better functionality may be expected from the newer versions - , or aesthetic improvements were made, like moving the model to a different operating system (read: from DOS or UNIX to the successive versions of Windows). It is unfortunate that so much effort and resources are now diverted from actual modelling work to follow the fashion and pace imposed by operating systems!

Some of the best WWW sources for models are listed below:

- ECOBAS (ECOlogical models dataBASE) site of the University of Kassel, Germany, with a comprehensive list of ecological models, from all fields of environmental science, but with many agricultural models

  http://dino.wiz.uni-kassel.de/ecobas.html

- CAMASE (**C**oncerted **A**ction for the development and testing of quantitative **M**ethods for research on **A**gricultural **S**ystems and the **E**nvironment) site at Wageningen Agricultural University (Netherlands), with the searchable register of agro-ecosystem models. There is also a printed version of CAMASE register (Plentinger and Penning de Vries, 1995)

  http://www.bib.wau.nl:80/camase/

- CIESIN-USDA. CIESIN is the Consortium for International Earth Sciences Information Network. The site has the details of a study carried out on behalf of USDA to evaluate the relevance of US models for global change impact assessments. Although the geographic and thematic scope of the site is narrow, it has comprehensive information for the models that are covered and constitutes a main source for parts of the present overview

  http://www.ciesin.colostate.edu/USDA/LOOKmodels.html

- CEAM, Center for Exposure Assessment Models of US Environmental protection agency

  http://www.epa.gov/epa_ceam/wwwhtml/software.htm

Note that there are also some commercial sites producing models, such as the ones given in the footnote[39].

3.5.2 Scope of models

Process-oriented simulation models have been developed for many different purposes and uses (Boote et al., 1996). They all have a preferential (i.e. native) domain of application (crop, scale, climate...) where they perform best. There are many examples showing that models should be taken beyond their original domain only with great caution.

Note that the items below refer to the specific purpose for which models have been developed, not to the areas of potential application. For instance, very little interest is dedicated by the research community to regional crop models, i.e. models that apply at scales starting just above the farm, but often going well beyond into districts and provinces or large pixels (say 50 x 50 km). Such models require specific input data (for instance 10-daily or monthly data) but other inputs may be much more difficult to interpret in physical terms (e.g. regional planting date!). There are also few models that indicate clearly for which purpose they were developed, like the peach tree model of De Jong et al. (1996), a “model for

This being said, the following general areas of application can be identified:

- research, to understand the actual behaviour of plant-environment and, in the more complex cases, plant-plant-environment interactions. Models offer also one of the methods to determine the order of magnitude of some variables and crop constants which are not accessible to experimental determination.
- training at all levels, to illustrate the behaviour of crops when exposed to varying environmental conditions and management options. This is probably the only area where fancy user interfaces are required, as in some farm simulation games based on sound physical, eco-physiological and economic principles;
- management at farm-scale, and other operational applications: to assist farmers to improve the planning and timing of their operations. With the advent of precision farming, a completely new class of applications is being considered.
- regional applications, mostly in the area of planning. This sector of activities, often at the margin of agriculture proper (e.g. river basin management) is under-developed.

The two last, regional and operational applications, are also characterised by their data requirements, i.e. real-time, or near real-time data are required, which adds a significant constraint.

[39] http://www.std.com/vensim/VBROCH.HTM, http://www.powersim.com/, http://www.greenhat.com/,
http://www.ranchvision.com/.

3.5.3 Input data[40]

The list of input data used by crop models grows with model development and with the introduction of new data types and sources. The data belong to the categories of weather and climate, crop ecophysiology and phenology, agronomy , pedology and terrain, as well as economic data. The data are characterised by specific sources, both technical and institutional, and by sampling frequencies. It is also stressed that, according to the scope of the model (see above: research, training, management and planning), the input data may vary (Hough et al., 1998).

Model sophistication is paralleled by the sophistication of input requirements and the level of spatial detail , but no necessarily by the accuracy of the outputs. The empirical rule seems to be that monthly data are adequate with statistical “models” operating at a synoptic scale (roughly 1°x1° grids) (Sakamoto et al., 1977) while the scale of the field requires daily data.

Sometimes there are several versions of the same model, with different input requirements, or the same model can use the data which are actually available. For instance, CropSyst accepts three levels of weather inputs:

- option 1 : daily rainfall , maximum and minimum temperature ;
- option 2: daily rainfall , maximum and minimum temperature, radiation;
- option 3: daily rainfall , maximum and minimum temperature, radiation, maximum relative humidity, minimum relative humidity and windspeed;

according to data availability, the model will use a simple temperature based model (option 1), Priestley-Taylor (1972; Option 2), or Penman-Monteith (Penman, 1948; Monteith, 1965; option 3). It is well understood that option 3 is the preferred one, but the model can still operate with limited data, which is an advantage.

WOFOST 6.0, the version implemented in the EC Crop Growth Monitoring System (CGMS) of the MARS project normally uses daily weather data on a 50 km x 50 km grid. It also includes an option to use average (monthly) weather data. Daily data are then derived through interpolation, except rainfall, which is generated using a built-in mathematical rainfall generator.

The pre-processing of data is a crucial issue in operational crop modelling, and includes data aggregation and disaggregation, the estimation of missing data and the related problem of the spatial interpolation of agroclimatic data (see 5.3).

As described in chapter 5, there is now a tendency to rely more and more on remotely sensed data (RS data). There are several reasons to that, among others the following:

- RS data provide a global spatial coverage in their native format, while most ground data must go through a error-prone spatial interpolation procedure;
- several types of weather data and, to some extent, crop data, can be determined based on RS sources, for instance radiation, surface temperatures, vegetation indices, phenology and even, according to some authors, even disease impact on crop condition (Nilsson, 1997);

[40] This is covered with more detail in chapter 5 (5.1 and 5.2).

- RS data are usually reliable and easy to obtain, as the number of institutional partners is limited and data collection and dissemination is largely automated;
- RS data already allow to skip several steps in some model components. For instance, if RS could reliably estimate actual crop evapotranspiration and phenology, the models could do without the calculation of those variables, or the variables could be adjusted based on the RS observations. Needless to say, RS inputs are more useful at the regional scale, although there is a potential to derive local values from pixel values, a procedure usually simpler than computing area-wide values from point data.

Among other “new” sources of data is weather radar (Hough, 1998; see 5.2), the spatial resolution of which (kilometric pixels) is usually adequate for local studies if used in combination with ground data.

3.5.4 Sub-models

In this context, the wording “sub-model” does not refer to actual model components, but rather to very specialised models of physiological processes which are too complex to be included in operational models; they contribute to improving the coarser approaches by giving better insight into the processes and by the development of more realistic simplifying assumptions. An example would be a model like 2DLEAF which simulates the processes of CO_2, O_2, and water vapour diffusion in an intercellular space and boundary layer, evaporation from cells' surface, assimilation of CO_2 , and stomatal movements (Pachepsky and Acock, 1994; Acock, 1994).

Another example is the Root Zone Water Quality Model (RZWQM; Nokes et al., 1996): a computer model developed to simulate water, chemical, and biological processes in the root zone of agricultural management systems, or the programme given by Jones et al. (1991), although the level of detail is significantly less than in 2DLEAF. For a detailed biophysical root model, refer to McCoy (1991).

3.5.5 Associated models and tools

“Associated models” are not directly part of the crop simulation model, but they tend more and more to be part of the “package” (see for instance DSSAT and CropSyst below).

Most popular models now have an “associated” Random Weather Generator, a programme that generates synthetic weather series for a given location[41]. They are extremely useful for many applications, from risk evaluation to crop forecasting. Related software are the “weather disaggregators”, i.e. weather generators which produce realistic data for short rime series based on aggregated values, for instance daily rainfall based on monthly data. The difference between a RWG and a weather disaggregator is that the RWGs read historical data and then produces weather data with the same statistical properties as the training series, while a weather disaggregator requires the historical data, **and** the aggregated data.

---

[41] RWG outputs are obviously based on the statistical properties of real world weather data from the same location.

Of the associated models and tools, Geographic Information Systems have now become ubiquitous. GIS techniques, normally in conjunction with geostatistical software, are used to prepare the spatial input data for the regional applications; they are used after model runs to format and present the output and analyses.

Finally, particularly for the regional applications, it is necessary to estimate planting dates. This an be done using a variety of techniques, from actual observations to the very empirical approaches ("farmers plant when 60 mm of rain have fallen in 4 days, and the 4-day period is not followed by more than 8 consecutive dry days in the two following weeks") to sophisticated models involving soil trafficability and short range weather forecasts.

3.5.6 Software/hardware Implementation

Crop modelling, and most numerical applications in natural sciences became actually possible because of the development of computers, and it is interesting to compare the sophistication of current work with the methods and approaches prevailing 15 to 20 years ago (Weiss, 1981; Gommes 1983 and 1985).

The volume by Weiss is interesting in that it shows that most problems being dealt with today in crop-climate relations were already on the agenda in 1981, almost twenty years ago: problems of scale, real-time collection of data and modelling etc. There are, however, several newcomers in the field of crop-climate simulation: GIS and the related issue of the spatial interpolation of agroclimatic data, and random weather generators. The issue of geostatistics applied in agriculture was so remote that one of the papers quoted by Sakamoto and LeDuc (1981) estimated the station density requirement to use a process-oriented sorghum model for regional evaluations. The density was found to be 500 km^2, or a grid of stations distant 22 km from each other.

Obviously, few real-world networks are actually so dense, and there is no doubt that excellent spatial interpolations could be obtained with the network density mentioned above.

Still in the same volume Jordan and Shieh (1981) write that *we seem to be close to the productivity limits for manual programming in procedural languages like FORTRAN and PASCAL*. While the statement is no doubt correct, it is worth mentioning that PASCAL, and particularly FORTRAN are still being used, even if little new code is actually written in those languages. As often noted, this situation is due to the huge library of scientific subroutines that exist in FORTRAN, because the compilers are largely bug-free and the language is still very efficient at "number-crunching", and finally because the it is now easy to use old code under the more modern languages and user interfaces.

The most common languages thus appear to be FORTRAN, PASCAL and C++, and many models - such as those of the Wageningen school -, are mixed-language programmes because of their long history. The code of the CropSyst model is written in Pascal (DOS version) and C++ (Windows and Windows 95 versions). There are still QuickBasic programmes (QB-Maize model), and apparently only few models appear to be written in only one language (Sigma+, a cotton simulator, appears to be a pure C++ model). Many models exist for several platforms (operating systems) but the author did not yet come across a model written in JAVA nor the specialised modelling languages such as SIMULA and DYNAMO. WOFOST 6.0, for instance, is available in PC (DOS), VAX/VMS and UNIX versions. Special software is available for model building (Stella, SB Modelmaker).

To some extent, the above situation is heartening in that it shows the vitality of the crop modelling world, but also the smooth passage to more modern computing environments.

Finally, we note that many models can be run in automatic and interactive mode.

3.5.7 Model complexity and balance

This section is based on the very interesting paper presented by Jones, Thornton and Hill at a recent meeting on crop yield forecasting in Villefranche-sur-mer (Jones et al., 1997).

The authors arbitrarily group model components into the 6 processes listed below[42]; each process/component was assigned mark from 0 to 3, where 0 stands for purely black-box empirical approaches and 3 represents a sub-model constructed in depth with a level of discrimination approaching plant organs, such as the models we have mentioned under sub-models above (3.5.5):

- phenology, which varies from direct observation (1) to sums of temperatures (Degree-Days: 2) and models with an intrinsic timing mechanism (3);
- assimilation: the complexity comes mainly from the way light distribution in the canopy is dealt with;
- partitioning and respiration;
- root growth, varies from 1 when roots are assumed to homogeneously occupy a volume of soil to 3 when root growth is controlled by soil feedback, like water availability;
- water management : from 1 for one-layer soils with simple rules to partition ET into E and T, to 3 in multi-layered soils and water uptake is a function of root growth;
- nutrient management: 1 does not go beyond fertiliser response curves; class 3 considers the dynamics of uptake and re-mobilisation, mineralisation of OM, etc.

We suggest that it may now be necessary to include a sevenths "component" which would include the ability of a model to take realistic management into account. This would go from 0 (stand alone model) to 3 in the more complex suites of models simulating rotation, all farm operations etc.

The model complexity index MCI is defined as the average of the complexity CC_i of the components. The model balance index (MBI) is computed as

[42] This is almost the structure adopted under 2.3 for model components.

$$MBI = 1 - \frac{\sqrt{\frac{\sum_i (CC_i - MCI)^2}{6}}}{MCI} \quad (52)$$

where the index i indicates the 6 components.

The extreme values that are possible for MBI are -1.23... (very unbalanced and low complexity with values 0 0 0 0 0 3) to 1 (very balanced model: all CC_i identical, except when MCI = 0[43]). The average value expected for MCI is 1.5, and 0.27 for MBI[44]. Note that the balance of (3 3 3 3 3 0) is 0.55, a value much higher that for (0 0 0 0 0 3) as the MBI tends to be higher in complex models.

While recognising that the procedure just described is a subjective one, it is interesting to note that the most complex model studied by Jones and his colleagues is WHEAT (MCI = 2.8) followed by PNUTGRO (MCI = 2.7), and by CERES-maize and CERES-wheat (both at MCI = 2.3). The lowest complexity was found in an early version of RICEMOD (MCI = 0.8) , while version 3.00 of the same model reaches 1.8.

Regarding balance, there tends to be a qualitative correlation with MCI. The lowest MBI was TOBACCO (-0.28), followed by SIMREW (MBI = -0.10) and the above-mentioned early version of RICEMOD.

According to the authors, EPIC, ALMANAC, NTRM and WOFOST compare with CERES.

It would be interesting to critically evaluate the concept of MBI with a view to reducing its subjectivity, possibly by taking into account the number of inputs and parameters. Most models studied by Jones et al. are, as indicated, relatively early versions, and the number of inputs is amazingly low when judging by the more recent models (see 4.1 in this document) where inputs and parameters are often counted by the hundreds (Jones list an average of about 5 weather inputs, 10 crop inputs and 2 to 10 soil inputs per soil layer). A revision of their paper should cover more models (in particular the WOFOST family) and take into account the number of inputs and parameters, as well as the number of internal variables. We suggest that due attention should also be given to the *ad hoc* parameters, modular construction and the ability to evolve.

3.5.8 Some details on specific models

3.5.8.1 CropSyst[45]

CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface, and with a link to GIS software and a weather generator (Stöckle, 1996). Link to economic and risk analysis models is under development.

---

[43] In which case it will be difficult to talk about a model at all!

[44] The average MBI value is only indicative. It was obtained by Monte-Carlo simulation.

[45] The section is quoted from the WWW site maintained by C. Stöckle at the university of Washington,
http://www.bsyse.wsu.edu/cropsyst/

The model's objective is to serve as an analytical tool to study the effect of cropping systems management on crop productivity and the environment. For this purpose, CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. These are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilisation, pesticide applications, soil and irrigation water salinity, tillage operations, and residue management.

An advanced user-friendly interface allows users to easily manipulate input files, verify input parameters for range errors and cross compatibility, create simulations, execute single and batch run simulations, customise outputs, produce text and graphical reports, link to spreadsheet programs, and even select a preferred language for the interface text.

Simulations can be customised to invoke only those modules of interest for a particular application (e.g., erosion and nitrogen simulation can be disabled if not desired), producing more efficient runs and simplifying model parameterization. The model is fully documented (Stöckle and Nelson, 1994, and successive updates) , and the manual is also available as a help utility from the CropSyst interface. CropSyst executable program, manual, and tutorials can be retrieved directly over the Internet (http://www.bsyse.wsu.edu/cropsyst)

Additional references to the model include Pala et al., 1996; Stöckle et al., 1994; Stöckle et al., 1996; Badini et al., 1997; Stöckle and Debaeke, 1997, and Pannkuk et al., 1998.

3.5.8.2 WOFOST 6.0

3.5.8.2.1 The de Wit family of models of Wageningen Agricultural University (Netherlands)

WOFOST originated in the ambit of an interdisciplinary study on the potential world food production by the Centre for World Food Studies (CWFS; WOrld FOod STudies provides the etymology of WOFOST) in co-operation with the Wageningen Agricultural University, Department of Theoretical Production Ecology (WAU-TPE) and the DLO-Centre for Agrobiological Research (CABO-DLO, currently AB-DLO), Wageningen, the Netherlands.

After cessation of CWFS in 1988, the development of the model has been continued by the DLO Winand Staring Centre (SCDLO) in co-operation with AB-DLO and WAU-TPE.

WOFOST is just one of the members of the family of models developed in Wageningen by the school of C.T. de Wit. Related models are the successive SUCROS models (Simple and Universal CROp growth Simulator), ARID CROP, Spring wheat, MACROS and ORYZA1 (rice). A history of the 'pedigree" of WOFOST is given by Bouman et al., 1996. Refer to Bouman et al., 1995, for an overview of the models of the "School of de Wit".

3.5.8.2.2 WOFOST

As indicated, WOFOST belongs to the "Wageningen family" (van Diepen et al., 1989; Supit et al., 1994; Hijmans et al., 1994; van Kraalingen et al., 1991). The model does not appear to have its own WWW site, but information can be found under the ECOBAS[46] site of the University of Kassel, Germany

http://dino.wiz.uni-kassel.de/model_db/mdb/wofost.html

WOFOST version 6.0 is a mechanistic model that explains crop growth on the basis of the underlying processes, such as photosynthesis and respiration, and how these processes are affected by environmental conditions. The model describes crop growth as biomass accumulation in combination with phenological development. It simulates the crop life cycle from sowing or emergence to maturity. Meteorological data (rain, temperature, windspeed, global radiation, air humidity) are needed as input.

Other input data include volumetric soil moisture content at various suction levels, and other data on saturated and unsaturated water flow. Also data on site specific soil and crop management are required. Time step for simulation is one day.

A distinction is made between potential production and water limited production as approximations for production ceilings under irrigated and non-irrigated conditions respectively. The crop growth model is generic including model parameters for: Wheat, Grain Maize, Barley, Rice, Sugar Beet, Potato, Field Bean, Soy Bean, Oilseed Rape and Sunflower. In version 6.0 the crop parameter values represent specific crop characteristics such as temperature sums and day light that were adopted to regional conditions throughout Europe. Other versions exist for tropical regions, and there is even a version to simulate tulip growth and development..

3.5.8.3 EPIC

EPIC, the Environmental Policy Integrated Climate (formerly Erosion Productivity Impact Calculator), and SWAT , the Soil and Water Assessment Tools can both be found and downloaded from of the Blackland Research Center (Temple, Texas) which belongs to TAMUS (Texas A&M University System). EPIC is well documented and has been used in a number of publications (Williams and Berndt, 1977; Williams et al., 1989; Sharpley and Williams,1990; Williams et al., 1990).

The models home page is at the TAMU:

http://brcsun0.tamu.edu/epic/

http://brcsun0.tamu.edu/swat/swat

The description below is drawn from the EPIC version 5300 fact sheet (Mitchell et al., 1995).

The objective of the model is to

- assess the effects of soil erosion on productivity;

---

[46] Most of the present information stems from the ECOBAS site.

- predict the effects of management decisions on soil, water, nutrient, and pesticide movement and their combined impact on soil loss, water quality and crop yields for areas with homogeneous soils and management[47].

The model components include:

- A detailed soil water balance, including lateral subsurface flow and snow melt (rarely found in other models), water and wind erosion ;
- Detailed N and P budget (loss in runoff, leaching, including for the organic phases, mineralisation and uptake);
- Pesticide fate and transport;
- Crop growth and yield for over 20 crops;
- Crop management (drainage, irrigation, fertiliser application;
- Economic accounting and
- Waste management.

EPIC operates at 1-daily steps and is driven by soil, weather, tillage and crop parameters data supplied with the model. Soil profile can be subdivided into up to ten layers.

The model's first steps go back to 1980; it is being continuously updated and adapted to a variety of uses and situations, in particular climate change studies, farm-level planning and soil-loss assessment. There is an Australian sugarcane model (AUSCANE) derived from EPIC. Like the other popular models, EPIC now comes with a weather generator.

The main application of EPIC remains in erosion studies, and thanks to the weather generator, the model can be run for thousands of years to capture the effect of this very slow process.

3.5.8.4 DSSAT and CERES[48]

3.5.8.4.1 DSSAT, Decision Support System for Agrotechnology Transfer

"CERES" is the banner product of the DSSAT family, which also includes GRO (BEANGRO, SOYGRO and PNUTGRO), SUBSTOR and CASSAVA. The family of models is managed by IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) and sponsored by mainly by USAID and the USDA-CSRS. Version 3 was released in 1994 (Hoogenboom et al., 1994) and version 3.5 in 1998.

DSSAT is a decision support system that is designed to aid farmers in developing long-term crop rotational strategies. Fifteen crop simulation models (CERES-Wheat, maize, rice, sorghum, millet, barley, sunflower, sugarcane,

---

[47] Note that this limitation is a very real one and applies to almost all process-oriented models. Few, however - including the developers - confine the use to their model to homogeneous areas.

[48] Information about all the DSSAT/CERES products is available directly from the listed WWW site at the University of Hawaii (http://everex.ibsnat.hawaii.edu/). The site provides links to the related products.

chickpea, tomato and pasture; SOYGRO, PNUTGRO, BEANGRO, SUBSTOR-potato) are accessible in DSSAT. The crop models were developed to assess the influence of weather and management practices on crop growth and development.

One interesting feature of DSSAT is the development of standards for data collection and formats for data acquisition and exchange. This allows any crop model of the family to share and access common soils and weather data. Each of the models are processed-based and simulate the daily growth and development of crops as influenced by daily weather. Multiple season simulation provides cumulative probability analysis for risk management.

Among the listed models of the family, several have been integrated into a higher level modelling environment known as CropSys (Crop Systems), for instance those of the CERES-type. The models currently in CropSys include: CERES-Barley, CERES-Maize, CERES-Millet, CERES-Rice, CERES-Sorghum, and CERES-Wheat.

3.5.8.4.2 CERES (Crop Environment Resource Synthesis[49])

CERES comes in a variety of “brands” usually named after the crop being simulated, for instance CERES-Maize, CERES-Wheat and CERES-rice, while more distant relatives have more independent names (SOYGRO). CERES is a deterministic model used to simulate growth, soil, water and temperature and soil nitrogen behaviour at the field scale for one growing season. They are very popular models which have been used in the recent year to evaluate the effect of global change conditions on field crops.

Potential dry matter production is calculated as a function of radiation, leaf area index and reduction factors for temperature and moisture stress. Six phenological stages are simulated, (based primarily on Degree-Days), and leaf and stem growth rates are calculated (depending on phenological stages). Available photosynthate is initially partitioned to leaves and stems, and later for ear and grain growth. Any remaining photosynthate is allocated to root growth. However, if dry matter available for root growth is below a minimum threshold, grain, leaves and stem allocations are reduced and the minimum level of root growth occurs.

Separate routines calculate water balance, including runoff, infiltration, saturated and unsaturated water flow and drainage. Mineral nitrogen dynamics and nitrogen availability for crop uptake are also calculated.

The model provides information on above-ground dry matter, nitrogen content, grain dry matter and nitrogen content, summaries of water balance and soil mineral nitrogen.

Refer to the following for additional details and examples of applications: Jones and Kiniry, 1986; Wu et al. 1989; Adams et al., 1990; Bachelet and Gay, 1993.

[49] A nice acronym: the Latin word *ceres* designates harvests, wheat and bread; from Ceres, the Roman goddess who taught men agriculture.

3.6 Other process-oriented models

There are many crop specific models, as well as models usable for a larger range of crops, for instance legumes. For a short list of models by crops, refer to Jones et al., 1997. Many models, as indicated, are now part of a more comprehensive package including several auxiliary decision making tolls. An example is GOSSYM, a cotton growth model. Its main originality is its association with COMAX, an expert system (Whisler and Landivar, 1988). Refer to the sources indicated above (3.5.1) for details, i.e. mainly CAMASE and ECOBAS.

3.7 Rule-based systems

Rule-based systems include the whole spectrum from simple descriptive thresholds to expert systems. We suggest that they are particularly useful in assessing qualitative and indirect effects of weather on crops. The first part of this section on descriptive models is taken from Gommes (1998b).

The simplest descriptive methods are those that involve one or two thresholds. A hypothetical example is given in the table below (Table 6).

Table 6 : Hypothetical example of wheat yield (Tons/Ha) dependence on two climatological variables, with 95% confidence interval.

	June average sunshine hours per day	
	6 hours and less	more than 6 hours
March total rainfall		
75 mm and less	5 ±1	6±2
More than 75 mm	8±1	10±2

Descriptive methods are non-parametric. It is sufficient to identify the environmental (agrometeorological) variables that are relevant for the crop under consideration. This is normally done with statistical clustering analysis on a combination of time-series and cross-sectional data. Once the groups have been identified, it must be verified that yield averages corresponding to different clusters significantly differ from each other.

One of the reasons why simple descriptive methods can be very powerful is that climate variables do not vary independently and constitute a “complex”[50]. For instance, low cloudiness is associated with high solar radiation, low rainfall, high maximum temperatures and low minimum temperatures. Each of the variables affects crops in a specific way, but since they are correlated, there is also a typical combined effect, which the non-analytical descriptive methods can capture.

The descriptive methods have a number of advantages: (i) to start with, no assumption is made as to the type of functional relationship between the variables and the resulting yield; (ii) the clustering takes into account the fact that many climatological variables tend to be inter-correlated, which often creates methodological problems, at least with the regression methods described above (3.3); (iii) confidence intervals are easy to derive and (iv) , once developed, the descriptive methods require no data processing at all; their actual implementation is extremely straightforward.

Many “El Niño” impacts on agriculture which are currently debated could best be treated by descriptive methods: El Niño effects on agriculture result from a long

---

[50] This is not unrelated with the typical “weather types” described by meteorologists.

→ Global atmospheric circulation → Local weather → Local crop yield) where each step introduces new uncertainties. As mentioned above, this chain of interactions can also be seen as a "complex" starting with the El Niño - Southern Oscillation (ENSO) index. In southern Africa, for instance, warm El Niño events are associated with an premature start of the rainy season, followed by a drought at the time of flowering of maize, the main crop grown in the area. This pattern usually results in good vegetative growth, followed by drought induced crop losses. Cane et al., (1994) have found good relations between El Niño parameters (i.e. the very beginning of the causal chain) and maize yields in Zimbabwe, which constitutes a good illustration of the concepts described in this section on "descriptive" methods.

Descriptive methods have also been used successfully to estimate the quality of agricultural products such as wine. Given that the concept of "quality" is difficult to describe in quantitative terms[51], the non-parametric approach of the is probably the most suitable.

Expert systems are more complex (Russell et al., 1997). They use the techniques of artificial intelligence to infer the impact of environmental conditions on crop yield. To do so, they require a base of data, a knowledge-base and an "inference engine" which is the software which constitutes the interface between the data and the users. A knowledge base includes all the normal database functions, but has additional functionality in terms of the way questions can be asked. For instance, a knowledge base "knows" synonyms, it knows orders of magnitude ("low yield"), understands contexts (general information, e.g. properties of a group of plants, for instance grasses) and is normally able to perceive implicit information. Implicit information is the information normally associated with a category, like humic gleysol (pH, drainage properties, depth, texture, etc.).

The inference engine controls the reasoning used to answer queries. Knowledge bases can use the outcome of one rule as an input for another. Below we quote an example adapted from Russell (Russell and Muetzelfeldt, 1998), the author of a very detailed wheat knowledge base for Europe, which at the same time illustrates the concept and shows the usefulness of knowledge bases in crop-weather modelling:

what are the consequences of high temperatures in March on wheat yield in Spain ?

The expert system must first "understand" what is meant by *high temperatures,* next it must "know" at what phenological stage wheat will be in Spain at the said time. Finally, the programme must "understand" the concept of Mediterranean region If no specific data are available for Spain, the system will "know" that Italy, Greece and Southern France are part of the same region and that some data can be borrowed from there.

The European wheat knowledge base puts special emphasis on the identification of alarm situations, based on research and expert knowledge. As such, a knowledge base constitutes a unique monitoring tool as it is unlikely that any of the

[51] Quality of wine is described by a combination of pH, sugar contents and types, acid types, concentration of tannins, colour, etc.

other types of models will be able to perceive the more complex environmental interactions and sequences, such as the example quoted under sensitivity analysis (4.6): a succession of very warm days at the beginning of flowering of orchard crops, followed by a week of heavy rain, which will have several indirect effects, like poor pollination.

Expert systems can be combined with the traditional process-oriented models. Kamel et al. (1995) have developed a tool to support the regional management of irrigated wheat in Egypt which captures local expertise through the integration of expert system technology and a crop simulation model (CERES). The system can improve the selection of sowing date and variety, pest monitoring, identification and remediation and harvest management, and may allow better utilisation of resources, especially water.

For an easily accessible rule-based model (PLANTGRO) the reader can consult the following WWW site : http://www.ozemail.com.au/~chackett/.

4. Chapter four : Checking the quality of models

4.1 A world of many and varied variables

Process-oriented crop simulation methods are the most accurate and the most versatile of models in that they attempt to describe a crop's behaviour (physiology, development) as a function of environmental conditions (3.5). They thus tend to be less sensitive to "new" situations, i.e. situations that did not occur during the period

The current versions of models like EPIC, CERES and WOFOST use about 50 crop characteristics, around 25 parameters to describe soils, plus 40 or so management and miscellaneous parameters. In comparison, the daily weather variables, which actually drive the models, are usually just 5 or 6 (rainfall, minimum and maximum temperatures, windspeed, radiation and air moisture). The internal variables used by WOFOST amount to about 260, of which half are crop variables, 30% are soil variables and 20% are weather variables (including all the astronomic variables like daylength, Angot's value etc.).

Output variables can, in principle, be any of the internal model variables. The EPIC manual, for instance, list 180 between input parameters and output variables. In comparison, CropSyst uses "only" 50 input parameters.

All process-oriented models more or less openly use ad hoc variables to force the models to behave like the experimental data. It is not always easy to decide which variables are ad hoc without digging deeply into the operation of the models, which is possible only with the models for which detailed documentation and often the source code is available. The ad hoc variables are sometimes grouped under a category of "miscellaneous" variables, or they have names like "reduction factor", "adjusted rate", "correction factor" or "coefficient of crop yield sensitivity to water Mitchell et al., 1995) has a "factor to adjust crop canopy resistance in the Penman equation" and a "nitrogen leaching factor". One of the best examples remains the Crop Coefficient (2.3.5).

Savin et al. (1994) compared some root variables of CERES-wheat with actual conditions. While the model accurately predicted crop development and yield, it over-predicted root depth by 90 cm at terminal spikelet and by 50 cm at booting, anthesis and mid grain-filling periods. This indicates that an accurate prediction can actually be made by less than perfect models. The reasons for this can be tentatively found in the *ad hoc* coefficients that adjust for model imperfections, for instance the use of laboratory determined constants on field crops, and the fact that models are mostly calibrated against proxies, not the actual crop variables. A very common example is soil moisture: a model can correctly simulate soil moisture even if root behaviour and water relations are very far from reality, like with one-layer soil models.

Errors often mutually cancel out, and so do errors in the parameters of a model. In the example above too large a root length can be compensated for by too small an absorption rate.

4.2 Model evaluation, validation and cross-validation.

Before models can be put to work in assisting with decisions in the real-world, the user must be reasonably confident that the model describes actual crop responses to weather and management with a degree of precision that is sufficient for the intended application. The standard wording usually resorted to in this context includes validation, calibration, verification, etc. (Penning de Vries et al., 1995), but there is no consensus in their actual acceptation. Some terms (like accuracy) appear to be used only in particular contexts such as crop forecasting.

In fact, maybe with the exception of *evaluation*, the meaning of some of the words varies according to the type of model, and the concepts themselves have a subjective element.

Evaluation seems to be the most neutral term. It means nothing more than assessing the value of a model: how realistic are the model components? What is their level of detail? How many fudge factors (*ad hoc* correction factors, adjusted rates, etc.) had to be introduced by the model developers to make it behave adequately. What do model developers actually call an adequate behaviour? How balanced is the model (see 3.5.7)? Evaluation is the qualitative mental exercise, based on subjective perception as well as, but not necessarily, on quantitative tests (validation, calibration), that will eventually lead a potential user to declare the model fit for his intended purpose.

Validation is more difficult. There is no such thing as a definitive or final validation of a model. A model must be **validated** at the same spatial scale and with the same type of data as those that will be available in operational work. In other words, validation is the sequence of tests and checks that convince the user that the model is valid for the intended purpose. If a model has been validated for many different circumstances, the potential user can decide that it may perform properly even under his own conditions, but he should not take it for granted.

Cross-validation is the comparison of one model against another taken as standard.

4.3 Verification

According to Penning de Vries et al. (1995) the term designates the inspection of the internal consistency of the model and its software implementation. In practice, verification is very difficult to carry out, as it implies the access to the computer source code and the full model documentation. Most successful models go through a number of versions (sometimes starting twenty years ago) and are, in practice, permanently “under construction”.

Some of the recent models have reached such a level of complexity that it is almost impossible to verify them but for their authors. Fortunately, for most reputable models, the source code is actually available freely over the internet or, at request, from the authors. This will at least allow the potential users to examine the algorithms.

The best practice, therefore, is to develop models in successive “stable” versions, which are fully documented and published, while the authors develop and debug the forthcoming version. As many scientists usually work on different parts of the model, the most efficient approach is to develop the models components in separate and largely independent modules. This will also facilitate verification and allow users to select the level of complexity and the specific algorithms of their simulations by choosing the appropriate modules.

We are still far away from this approach, among others because of the diverging traditions of modelling schools (Wageningen, CERES), and because fully modular models pose some very challenging technical problems.

4.4 Calibration

Calibration and fine-tuning are the same concept. Assuming that the author or the user of a model is satisfied with the algorithms, the next step is to submit the model to the ordeal by real-world data: the model is run repeatedly with actual inputs to see if it mimics reality sufficiently well. The actual data are usual referred to as calibration data or training data. The greater the variety of training data, the greater the chances that the model will be well behaved under new conditions.

Calibration is done differently for different categories of models. For models developed for educational purposes, it is sufficient if the models behaviour is qualitatively consistent.

Research oriented models are more difficult to calibrate, as all the variables of the crop-environment system should take values in agreement with reality. This is impossible to verify in practice. It is also recalled that many crop constants were obtained under laboratory conditions on single organs, and that rates observed on whole plants under actual conditions may sometimes differ by orders of magnitude from those observed under controlled environments. In addition, rates and concentrations may vary significantly between the beginning and the end of an experiment. A good example is provided by some of the current work on “double” CO_2 effects on plants: initial response is high, but the plants adapt (the phenomenon is known as down-regulation of photosynthesis; see Wolfe and Erikson, 1993; Allen et al., 1996). This is nothing but another manifestation of a temporal and spatial scale problem.

In addition to the scaling problem, we have already underlined that very often models are not calibrated against actual plant variables but against proxies, i.e. it is the result of the crop-environment interaction that is modelled rather than the processes themselves. Next to the example with soil water given above (4.1), we could mention that crop yield models are calibrated against final yields, never against daily biomass accumulation. Also note that the time step almost universally adopted for models is the day, when plant processes actually take place at much shorter scales.

In practice, models are all characterised by some parameters and thresholds the value of which is not really known nor very precisely fixed, nor constant over the life of crops (for instance, the base temperature for sums of temperatures, of leaf water potentials, etc.). It is clear that such values can be adjusted without contravening to the rules of plant physiology. Such adjustments may, however, have an effect on the final yields or other model behaviour, so that they provide one of the ways to calibrate a model.

Next come the *ad hoc* factors (4.1), often introduced because they are the only way to make a model perform realistically; they constitute the second “button” that can be used to fine-tune a model.

The calibration is thus done by trial and error, among others by plotting the errors affecting some key crop or soil variables against the model parameters. Given the complexity of models and the number of variables involved, it is virtually impossible to be certain that the best set of parameters was eventually selected. The “best” is to be understood in the double statistical and crop/physiological sense.

Needless to say, if next to statistical and physiological criteria we also adopt agronomic criteria and constraints (like using the model at a different geographic scale than the one for which it was developed), the “best” parameters may still be different.

In multiple regression models, calibration takes the meaning of finding the values of the coefficients that provide the best statistical fit to a set of experimental data (usually yields). Within the limits of the models, rigorous methods exist to optimise the values of the coefficients (see Palm and Dagnelie, 1993, and Palm, 1997a and 1997b). There is a large variety between the options to compute the regressions proper and to verify the suitability for the intended purpose, which is usually crop forecasting. One of them is known as jack-knifing, another is split-series.

Jack-knifing computes the regression with all the data but one set, and verifies that the model can forecast the yield (or other parameters) of the missing set. The same procedure is then repeated for all the sets in succession, lending the procedure some statistical weight. With split series, the sets are subdivided into two groups (often the first and the second half of a time series, but he concept is more general) and the coefficients are determined for each set. If the model is of general applicability, the coefficients should not be very different in the two groups. The procedure can be repeated with other groups of sets.

In all statistical calibration, one of the main problems is the proper balance between statistical and agronomic significance, essentially the orders of magnitude and the signs of the coefficients.

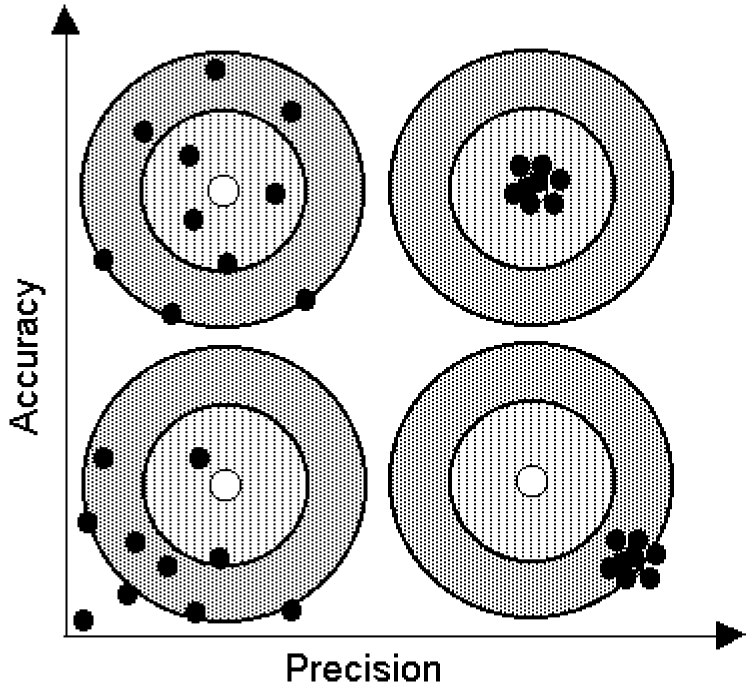
The two extremes of model calibration thus seem to be process-oriented models with trial and error calibration and empirical statistical “models” with statistically optimal calibration.

4.5 Uncertainty analysis: reliability, accuracy, precision and bias

Uncertainty analysis examines the errors in model outputs. Some authors (Penning de Vries et al., 1995) hold the view that errors in the outputs of deterministic models are due exclusively to errors in the input data and parameters.

It is suggested that things are not so simple. To start with, model outputs are outputs from computer programmes, and even after accurate model verification, it is impossible to exclude software bugs or other programming errors.

Figure 15 : A graphical representation of the differences between accuracy and precision.



Uncertainty analysis thus deals mainly with model reliability, a term which encompasses both *accuracy* and *precision.* For some unexplained reason, they are not normally part of the criteria adopted for crop modelling and they are associated more with the empirical world of crop forecasting where the objective is mainly one: ensuring that the model accurately forecasts yield. In fact the concepts make sense only of referred to a limited number of criteria.

A model output is accurate if in the long-term or under different conditions its average is close to the actual average; the difference between the averages is the bias. A model is precise if there is little dispersion of the outputs. This is illustrated in figure 15 using a presentation similar to that adopted by Sakamoto (1995).

Low accuracy is probably easier to correct that low precision; the former can be corrected through the identification of some error in the model variables or parameters. Low precision is more difficult to tackle, as its source is more likely to be in the input data, including their selection, than in the model proper. In fact, the accuracy-precision discussion is useful in that it allows some identification of the source of the errors.

Sometimes, some model output variables are accurate, while others are not. An example is provided by the adaptation of the SIMCOY maize model to Tanzania (Lyamchai et al., 1997). A number of parameters had to be adjusted; some eventually showed low errors with observations, while others retained a bias. For instance, the model estimated above-ground biomass correctly, but soil water remained significantly different from observed values.

The identification of the source of dispersion and biases can be further refined using sensitivity analysis (4.6).

It is a rather common observation that all models, be they deterministic or statistical, tends to underestimate the variability present in actual cropping. In other words: models tend to simulate average conditions more often than desired.

A systematic study by Aggarwal (1995) confirms the observation: uncertainties in outputs increase as the production system change from a potential production level to a level where crop growth was constrained by limited availability of water and nitrogen. There was an 80% probability that the bias in the deterministic model outputs was always less than 10% in potential and irrigated production systems. In rainfed environments this bias was larger.

4.6 Sensitivity analysis

Sensitivity analysis examines the response of outputs to changes in the input data and in the model parameters. This covers several different techniques.

The simplest is to plot the values of a selected output variable against a range of values of an input variable or a parameter. The shape of the resulting functional relationship is interesting in itself (linear, maximum, minimum, constant), and should makes sense from a physiological and agronomic point of view. It will appear, in many cases that the effect of one single parameter is relatively limited.

In crop forecasting, sensitivity analysis is often used to see the effect of the parameters on the errors affecting the forecasts.

A convenient way to approach sensitivity analysis is to plot the both the output variable O and the input parameters P of interest as a percentage of their normal ranges: this immediately indicates the effective role of the parameter and the fact that other factors are at work. When more that two parameters are chosen (P1 and P2), the same approach can be used. Sometimes, Monte Carlo simulation is resorted to determine which values of the parameter produce the least error. Vanclooster et al. (1995), used Monte Carlo simulation to assess the effect of uncertainty of the sensitive hydraulic properties on the calculated nitrogen balance of the WAVE model, a model to simulate water and solute transport in soils.

We conclude this section with a note on extreme events: it is unlikely that a model will ever have been tested for very unusual[52] inputs, for instance a succession of very warm days at the beginning of flowering of orchard crops, followed by a week of heavy rain with numerous qualitative impacts. It is equally unlikely that a model will be able to capture the impact of the extreme conditions.

[52] This is the definition of an *extreme* event.

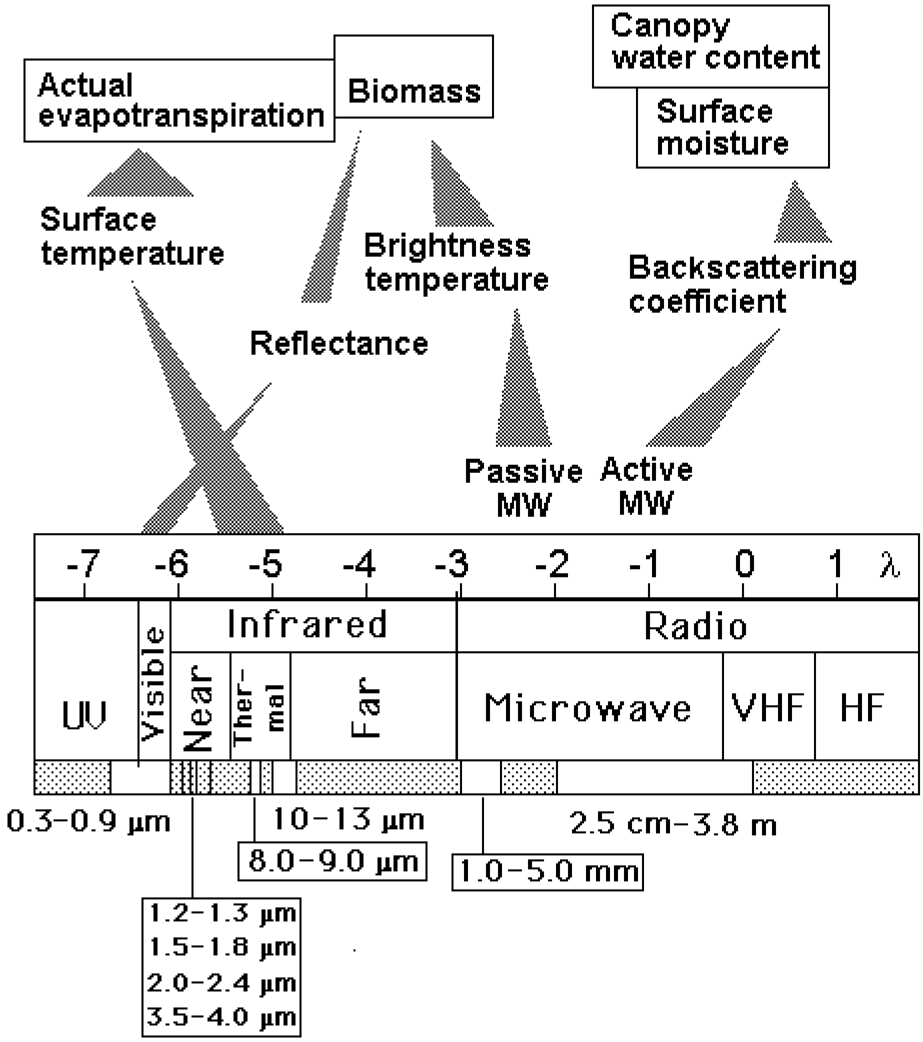
5. Chapter five : Some methods and tools for operational crop modelling

5.1 Remote sensing data

5.1.1 Why a section on remotely sensed data ?

As already mentioned under 3.5.3, remotely sensed data have become an indispensable tool in operational crop monitoring and crop modelling, at the level of data and at the level of the final products.

Figure 16 : Remote sensing sources of crop weather modelling inputs. λ indicates the exponent of the wavelength in m (- 6 corresponds to a µm, -2 to a cm, etc.). The bottom line shows the main atmospheric windows, i.e. parts of the spectrum to which there is little absorption in the atmosphere. The absorption is mainly due to CO_2 (thermal infrared) and water vapour.



The early applications focused on the use of satellite indices (essentially vegetation indices, i.e. satellite variables more or less linearly correlated with living green biomass) to monitor crops. With spatial resolutions (pixel size) of the order of the Km, it is usually possible to "see" the main agricultural areas, in developed countries. The assumption that the radiance[53] signal measured by the radiometers on board the satellites actually correspond to the crop being monitored holds only if the fields are (very) large and homogeneous.

In many circumstances, in particular in many developing countries fields tend to be small and irregular in size and shape, crops are often mixed, etc. so that the sensors measure essentially a mix of crops and natural vegetation. It is then generally assumed that crops follow greenness patterns similar to vegetation. This is a reasonable assumption in areas where vegetation shows marked seasonality, for instance in semi-arid areas. Many of the difficulties listed disappear at higher spatial resolutions.

There is now also a tendency to use satellite inputs in crop modelling (Sequin, 1992; Nieuwenhuis et al., 1996; Stott, 1996; Cleevers and van Leeuwen, 1997). In spite of current shortcomings of the proposed methods, there is little doubt that with improving spatial and spectral resolutions, progress will be made in the area of water balance components (soil moisture) and biomass estimations (LAI and conversion efficiencies).

An overview of the potential sources of data is shown in Figure 16, according to the concepts presented by Seguin (1992). More details will be found in the text below.

5.1.2 Vegetation indices

5.1.2.1 Definitions

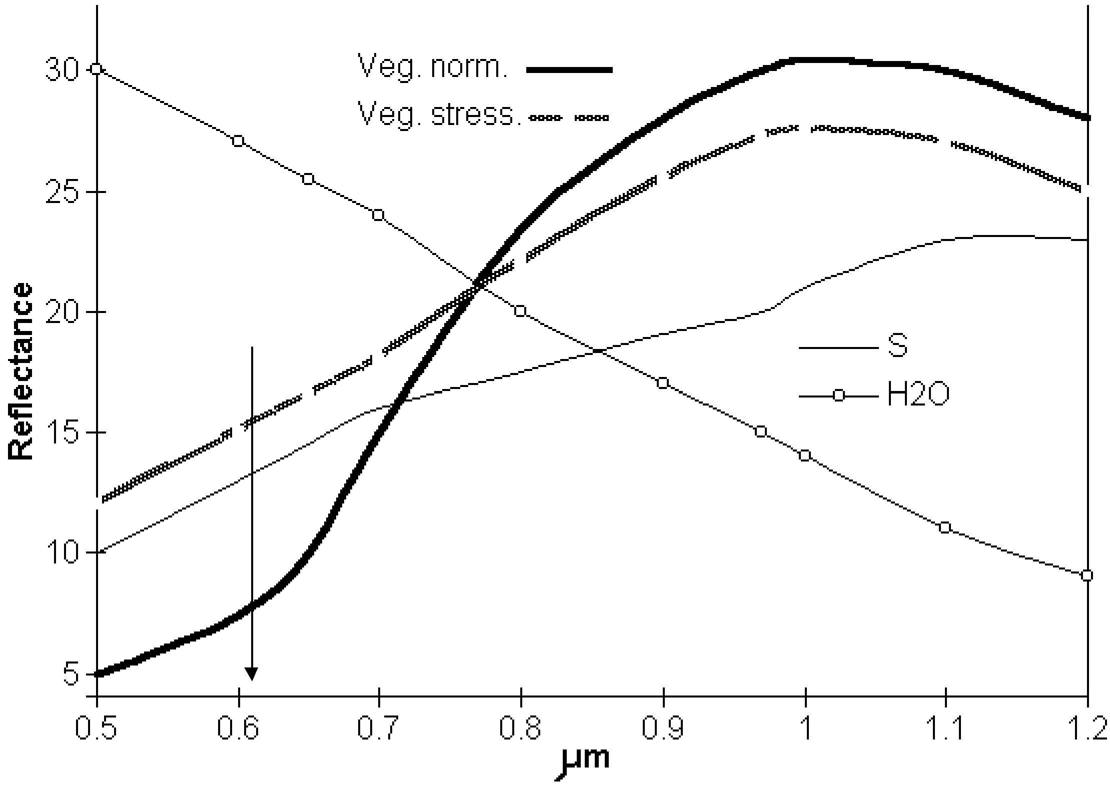
All vegetation indices are based on the fact that plants are green: they reflect a much larger proportion of white sunlight in the green part of the spectrum than in the blue and in the red. In fact, plants contain varying proportions of Chlorophyll-a (absorbing mainly the blue between 0.38-0.45 µm and the red around 0.675 µm) and Chlorophyll-b (0.41-0.47 µm and 0.61 µm). Plants reflect a much larger proportion of light in the near infra-red, so that they appear normally very bright when seen through a near infra-red filter or sensor. Figure 17 compares the reflectance[54] of different types of surfaces in the red and near infra-red.

---

[53] Radiance is the amount of energy received by a sensor (radiometer) expressed in power units (W or J s^{-1}). The term is sometimes used to express flux density, expressed in W m^{-2} sr^{-1}. In practice, the sensors onboard an aircraft or a satellite measure electrical currents which are converted into radiances using calibration tables.

[54] The reflectance is the percentage of the incident radiation (including light) that is reflected. The word is also sometimes used to indicate the intensity of reflected radiance.

Figure 17 : Reflectance spectrum[55] of stressed vegetation , vegetation in good health (veg. Norm), soil (S) and water H_2O. The arrow indicates the second (red) peak of absorption of chlorophyll.



It is obvious that the spectra of the different surfaces illustrated in Figure 17 are characteristic for the surface and constitute their “spectral signature”. In principle, it should thus be easy to identify the surfaces simply by comparing their reflectance.

Things are not so easy, for several reasons. To start with, the spectral signatures are obtained experimentally on the ground under known conditions of irradiance[56]. The radiance measured by satellites have undergone qualitative changes (wavelength) and changes in intensity in the atmosphere. Further, the irradiance varies as well as a function of atmospheric conditions and angle of incidence (which is to say: the time of the day).

Many vegetation indices are thus “normalised” to correct for at least the most obvious atmospheric and soil effects, as in the popular normalised difference vegetation index (NDVI): it is defined as

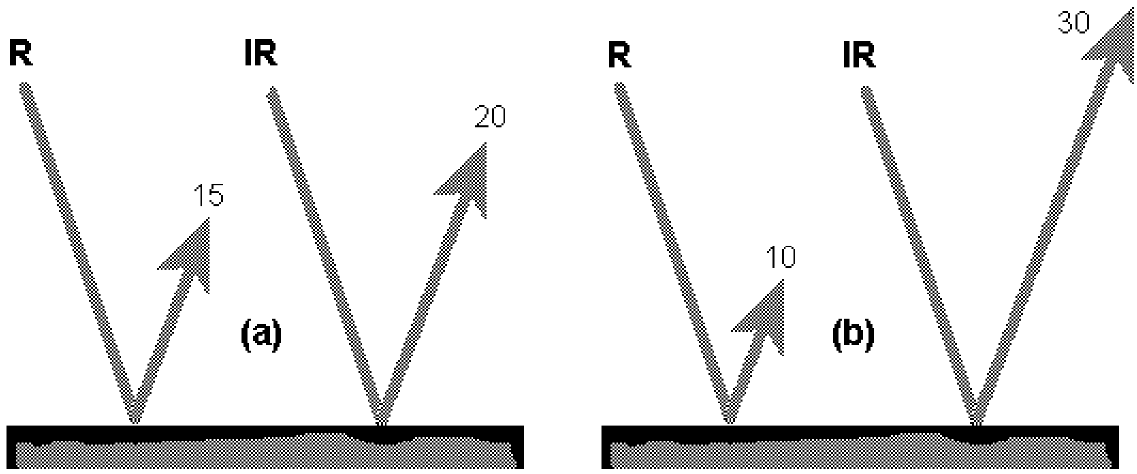
$$NDVI = \frac{NIR - R}{NIR + R} \qquad (53a)$$

where NIR stands for the reflectance in the near infra-red region (roughly from 0.8 to 1.1 µm) and R is the reflectance in the red part of the spectrum. Examples of the calculations are given in Figure 18.

---

[55] The remote sensing jargon also calls e reflectance spectrum *spectral reflectance*.
[56] Irradiance is the incident radiance, for instance and normally as sunlight.

Figure 18 : Computation of the normalised difference vegetation index based on the red (R) and near infra-red (IR) reflectance for soil (a) and vegetation (b).



$$NDVI = \frac{20 - 15}{20 + 15} = 0.14 \qquad NDVI = \frac{30 - 10}{30 + 10} = 0.50$$

$$WDWI = 30 - 10\,\frac{20}{15} = 16.67$$

In theory NDVI varies from -1 to 1; in practice, values for water are negative, bare soil covers the range from 0 to 0.12, where sparse vegetation starts.

NDVI can be computed whenever red and near infra-red reflectance (i.e. reflected radiance) are available, from such satellites as the LANDSAT-TM, SPOT and NOAA-AVHRR.

The most popular source for satellite NDVI is the NOAA series polar-orbiting sun-synchronous[57] satellites, starting with TIROS-N (1978). The most recent satellite of the series (NOAA-14 at 833 Km) was launched in 1994, but NOAA-11 (launched 1988) and NOAA-12 (launched 1991) are still operating.

Their AVHRR (Advanced Very High Resolution Radiometer) measures radiance in 5 wavelength bands, also known as “channels”:

- Channel 1 (visible): 0.58 - 0.68 µm, mainly used for daytime cloud/surface and vegetation mapping;
- Channel 2 (NIR): 0.725 - 1.10 µm; surface water, ice, snow melt, and vegetation mapping;
- Channel 3 (SWIR; Short Wave IR): 3.55 - 3.93 µm; surface temperature, night-time cloud mapping;

[57] Polar-orbiting sun-synchronous: the satellite is on an orbit passing over the pole, and it is synchronised with the sun, i.e. for a given location it passes every day at the same times. The period of a circular orbit is easy to calculate: for an altitude h in thousand Km (i.e. 580 km = 0.58 Mm), the period T in hours is given by $T=0.0875\sqrt{(6.37 + h)^3}$.

- Channel 4 (TIR, thermal infra-red): 10.50 - 11.50 μm; surface temperature, day and night cloud mapping;
- Channel 5 (TIR): 11.4 - 12.4 μm; surface temperature, day and night cloud mapping.

NDVI is computed by calculating the ratio of the VI (vegetation index, i.e., the difference between Channel 2 and 1) and the sum of Channels 2 and 1. Thus NDVI = (channel 2 - channel 1) / (channel 2 + channel 1), using a series of corrections (geometric, radiometric and declouding).

The products are available in three different formats: HRPT, LAC and GAC:

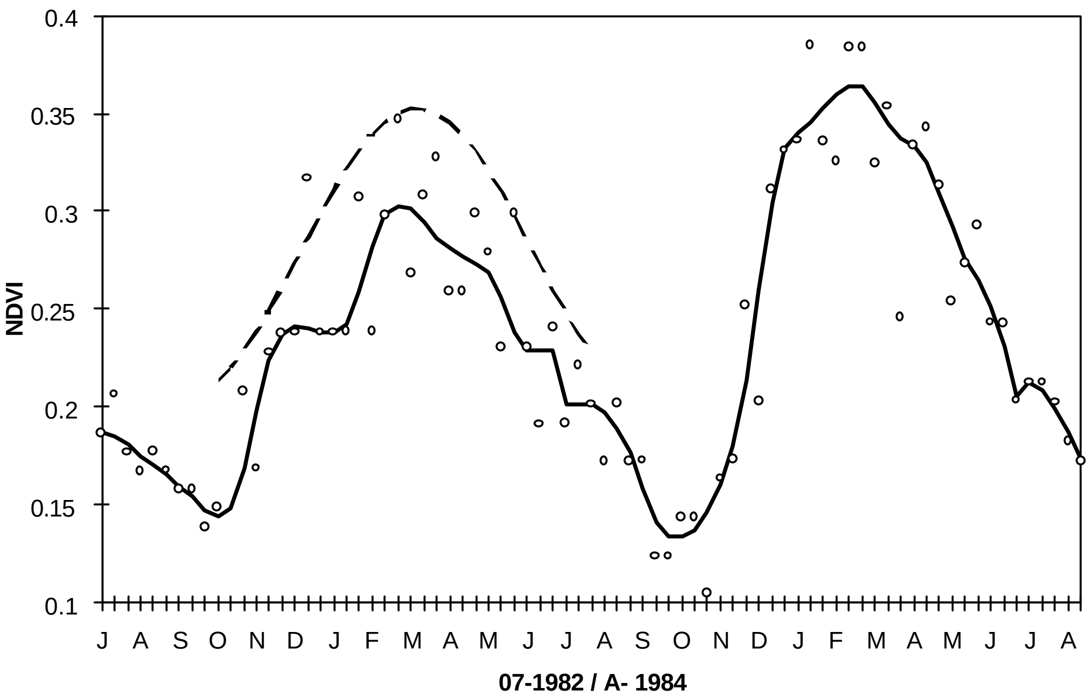
- HRPT, High Resolution Picture Transmission. HRPT data are full resolution image data transmitted to a ground station as they are collected. The resolution is 1.1 km at the satellite nadir;
- LAC, Local Area Coverage. LAC are full resolution data that are temporarily stored onboard for subsequent transmission to the ground. The resolution is the same as HRPT, but LAC data have been stored prior to their transmission;
- GAC, Global Area Coverage. GAC data are derived from a sample averaging of the full resolution AVHRR data (1.1 km by 4 km).

NDVI can be obtained at the LAC and GAC resolutions.

5.1.2.2 Vegetation indices for monitoring

There are numerous actual and potential applications of NDVI in operational crop modelling. Below (Figure 19) is an example of one of the most straightforward applications.

Figure 19 : Average dekadal NDVI in the Midlands province of Zimbabwe between July 1982 and August 1984. Next to the individual NDVI readings (circles), the dotted line is a cosine envelope approximately fitted to the 1982/83 data, while the heavy line uses another smoothing technique.



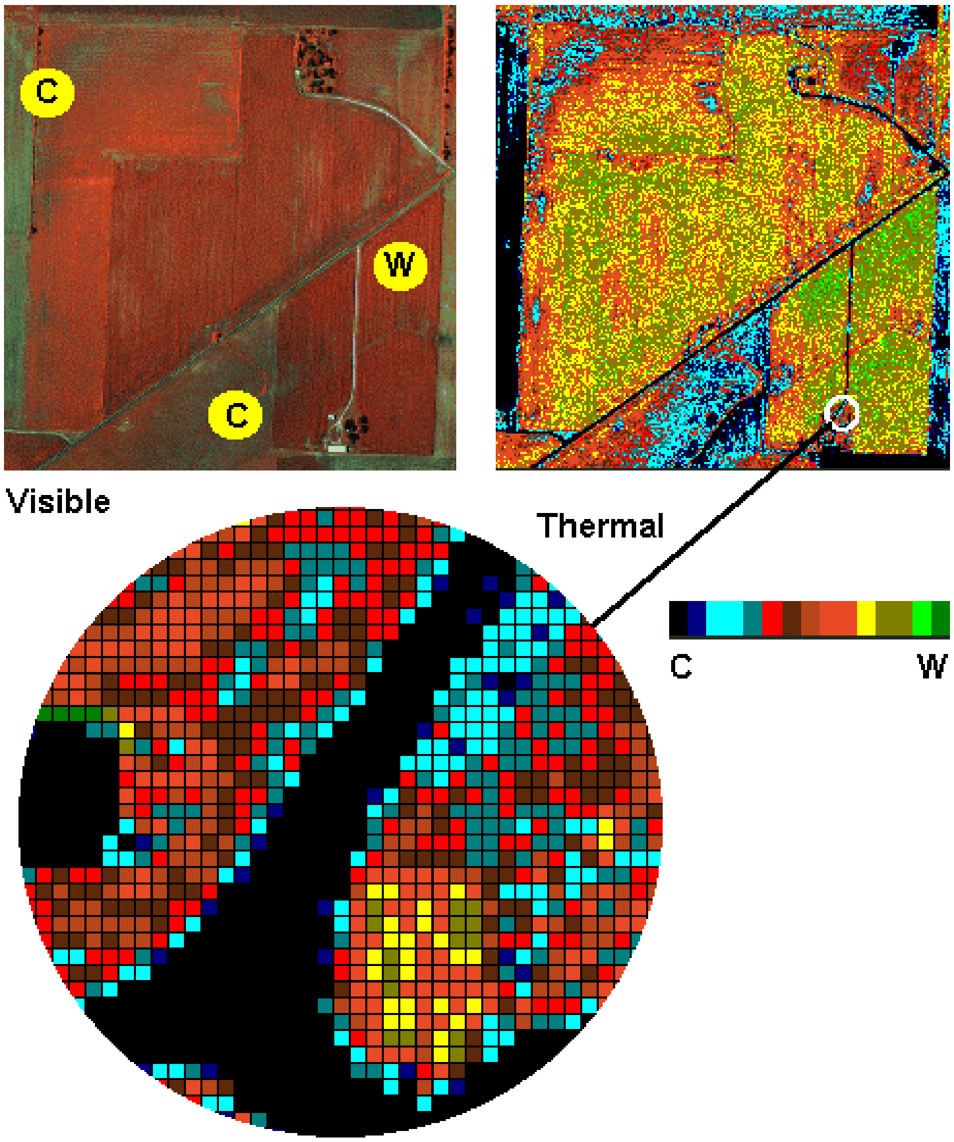
The figure illustrates the use of NDVI to derive phenological information in the absence of ground data. Note that due to the presence of clouds, many readings have to be discarded. The operational procedure is, therefore, to use only the maximum values for each pixel during a certain period (for instance ten days). This removes only part of the variability from NDVI series, as can be seen in figure 19. It is therefore also a common practice to smoothen the NDVI curves, often by drawing an envelope around the cloud of observations.

Assuming that crops and natural vegetation are synchronised, planting can be assumed to take place at dekad D when NDVI starts increasing again after the dry season, or a fixed number of dekads after D (for instance D+4), or when NDVI crosses an locally determined threshold...

NDVI and other vegetation indices can, of course, be computed at any scale. Companies in the USA have started providing very detailed NDVI maps of farms on a subscription basis.

One of the companies (Emerge[58]) provides 1-m resolution geo-referenced digital imagery covering customers' fields. See figure 20 for an example.

Figure 20 : A farm in the Midwest (USA) in July 1997. The top left figure image is a photograph (visible light), while top right photographs indicates a vegetation index coded on a thermal scale. As the grey shades do not properly reflect the original colours, the main “warm” and “cold” areas has been indicated on the left. The zoomed area at the bottom shows the metric resolution of the original product, with a road crossing the image.



This information can be printed or directly read into mapping software. The acquisition and processing techniques allow “temperature” and visible maps to be available to customers on their internet sites within 48 hours after the data have been sampled using a small aircraft. The company stresses that the maps allow farmers to visualise the variability of their field and areas of water or pest stress or

[58] Emerge, trademark of TASC, Inc., a subsidiary of Litton Industries (http://www.emerge.wsicorp.com/emerge/info.html)

otherwise sub-optimal management. Obviously the products could be use also for early production estimates in combination with ground weather stations.

We conclude this section by mentioning the derived defined by Kogan (Kogan, 1995, 1997; Unganai et Kogan, 1998) based on NDVI further normalised by comparing them with their recorded extremes:

$$VCI = 100 \frac{NDVI_i - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \quad (53b)$$

and

$$TCI = 100 \frac{BT_i - BT_{\min}}{BT_{\max} - BT_{\min}} \quad (53c)$$

VCI is the Vegetation Condition Index and TCI is the Thermal Condition Index. They vary in opposite directions. The BT are brightness temperatures computed from AVHRR channel 4 (10.3 à11.3 µm). The channel is more sensitive to drought because it is less affected by atmospheric moisture than channel 5. The analyses carried out by Kogan have shown that during drought years, BT is significantly higher than in normal years, which entails a close relationship between TCI and crop yield anomalies.

Note that Kogan (Unganai et Kogan, 1998) uses a linear combination between VCI and TCI directly estimate maize yields.

5.1.2.3 Vegetation indices used in modelling

On the more complex side, many relations have been developed to link the various vegetation indices and canopy properties (Laguette, 1995; Laguette, 1997; Laguette et al., 1998).

We have listed the following equation under "potential biomass" (3.1.1):

$$\mathrm{DM} = \mathrm{H} \times \mathrm{Eff_H} \times \mathrm{Eff_c} \times \mathrm{Eff_a} \quad (39)$$

where Eff_H is the climatic efficiency (0.5: PAR total light), Eff_c is the conversion efficiency of absorbed PAR (PARa) to biomass produced (also called the radiation use efficiency or light to biomass conversion efficiency, etc.), and Eff_a is the absorption or interception efficiency. Both Eff_a (see below) and Eff_c (5.1.3.1) can benefit from remote sensing inputs.

We have mentioned that Eff_a is related to LAI. Various authors quoted by Laguette have developed empirical relations linking Eff_a directly to NDVI, for instance

for millet:

$$Eff_a = a\,(NDVI - NDVI_{soil}) \quad (54)$$

for wheat

$$Eff_a = a\,(\frac{NIR}{R} + b) \quad (55)$$

and for rice

$$Eff_a = 1 - \left(\frac{0.9 - NDVI}{0.9 - NDVI_{soil}} \right)^2 \qquad (56)$$

The relations are usually valid for a specific phenological phase.

We have mentioned elsewhere in this manual the link between absorption efficiency and LAI (eq. 13, 2.2.3; eq. 40 and 41, 3.1.1). The equations above clearly indicate that there must be a relation as well between LAI and the vegetation indices.

An interesting method has recently been published by Bouman in 1995. The author uses still another vegetation index, the Weighted Difference Vegetation Index defined as

$$WDVI = IR_c - VIS_c \frac{IR_s}{VIS_s} \qquad (57)$$

where the indices (c and s) indicate crop and soil; IR stands for infrared[59] and VIS for visible. An example of a calculation is shown in figure 18, although the IR and VIS bands used by Bouman do not necessarily correspond to AVHRR channels 1 and 2.

For potato, Bouman found an excellent linear relationship between ground cover (%) of white potatoes and WDVI up to 50, after which the curve levelled off. For LAI in barley, the relation was found to be exponential, with good correlation coefficients as well.

Nieuwenhuis et al. (1998) list the following relation between LAI and WDVI:

$$LAI = \frac{1}{a \ \ln(1 - \frac{WDVI}{WDVI_{\infty}})} \qquad (58)$$

where α and $WDVI_{\infty}$ are empirical parameters. Nieuwenhuis and his colleagues indicate that WDVI has a higher saturation ceiling for biomass than NDVI and that, therefore, WDVI has a greater sensitivity to biomass changes. Note that the exponential relation between LAI and WDVI for Barley was mentioned already above.

5.1.3 Other data types

5.1.3.1 Surface temperature and evapotranspiration

Because of its relevance for soil water balance calculations, a lot of interest is dedicated to the related subjects of estimation of ETP and surface temperatures

---

[59] For remote sensing, the infrared wavelengths are often subdivided into near infrared (0.7-1.3 microns), middle infrared (1.3-3.0 microns) and far infrared (7.0-15.0 microns). Far infrared is sometimes referred to as thermal or emissive infrared.

using satellite data (Kustas and Norman, 1996; Bastiaansen et al., 1996). The surface temperature T_s is the temperature of the layer of air immediately in contact with the leaf, and T_a is the conventional air temperature measured in a screen.

The interest in the difference between surface and air temperatures goes back to the work on Jackson's CWSI (Crop Water Stress Index ; Jackson et al., 1981) which is defined as

$$CWSI = 1 - \frac{LE}{LE_p} \qquad (59)$$

where LE is the actual potential evapotranspiration and LE_p is the potential evapotranspiration, usually referred to a short time interval.

The concept of CWSI is identical to the FAO Water Satisfaction Index (WSI) introduced by Frère and Popov (1979) as a monitoring tool derived from a water balance calculation over the whole cycle[60].

Jackson and his colleagues found that an alternative formulation for CWSI is

$$CWSI = \frac{T_a - T_{smin}}{T_{smax} - T_{smin}} \qquad (60)$$

with T_a = air temperature and the various T_s parameters represent the surface temperature minimum and maximum values. T_s represents the effective temperature at which the processes in the leaves take place. It can be determined using the AVHRR channels 4 and 5 with the proper geometric, radiometric, atmospheric and declouding corrections using a linear combination technique (so-called split-window technique), with an accuracy of 2 to 3 degrees. The geostationary meteorological satellites like METEOSAT and GMS also have a TIR channel that can be used to estimate T_s and derive evapotranspiration (Rosema et al., 1998b).

It can be shown (Laguette, 1995, 1997) that, for a given net radiation, there is a direct link between actual evapotranspiration and T_s-T_a.

In the net radiation balance equation already discussed under 2.2.2

$$H = P + G + A + E \qquad (11)$$

the terms G and P play a minor part compared to A, the sensible heat and E, the evapotranspiration; the equation thus reduces to

$$H \cong A + E \qquad (61)$$

It appears that A is directly related to T_s -T_a, and that the partitioning of H between A and E is of the form

$$H - E = (T_s - T_a)(bT_a^3 + c)\,; \qquad (62)$$

[60] Needless say that the are marked scaling effect when passing from CWSI to WSI.

where b and c are coefficients depending on the Stefan-Boltzman constant, the turbulent exchange coefficient and the volumetric heat capacity of air.

T_s -T_a, as a measure of the sensible heat flux, indicates how much energy is available for evapotranspiration. A large difference indicates reduced evapotranspiration and stomatal closure, and therefore a reduced conversion efficiency Eff_c. A small difference indicates that water supply is adequate and that plants actually evapotranspire, that most energy goes into E , under which conditions the ratio of A to E is about 0.1. In general low temperatures thus indicate healthy and photosynthesising crops.

The conversion efficiency Eff_c can be shown to be linked to the CWSI and thus to T_s and T_a.

5.1.3.2 Cold Cloud duration (CCD)

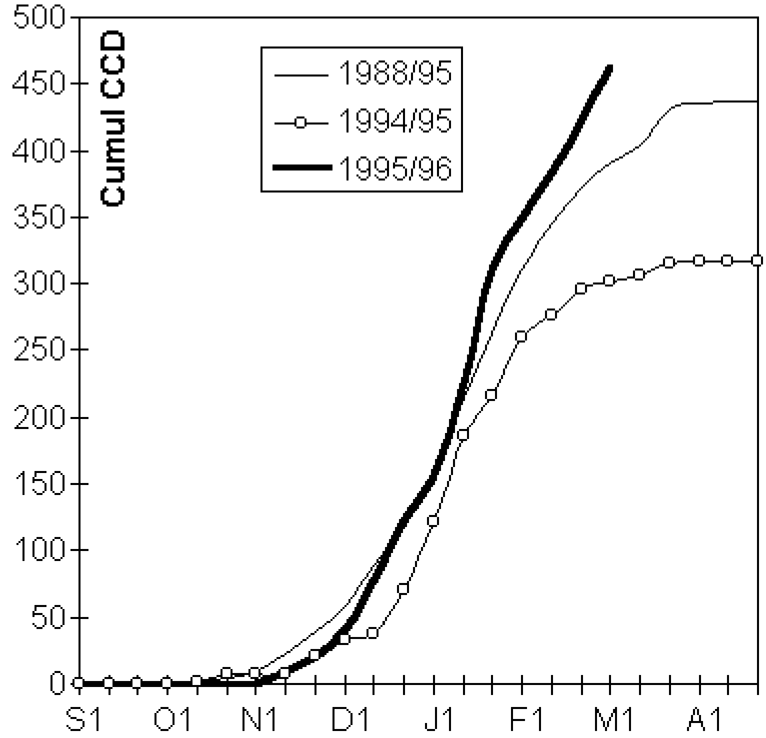
Cold Cloud duration (CCD) is determined using the geostationary satellites of the METEOSAT or GMS types. Due to the low temperature threshold corresponding to high elevations, there is relatively very little atmospheric effects to be corrected in CCD when compared with NDVI.

GMS-4 is a Japanese satellite in geostationary orbit over the equator at approximately 140E. The satellite is equipped with the Visible and Infrared Spin Scan Radiometer (VISSR) imaging sensor, which uses the spin motion of the satellite to scan the earth in the East-West direction. GMS begins a North-South scan every hour on the half hour, with four additional scans daily for wind estimation. At the vertical of the satellite, the visible (0.5-0.75 μm) channel has a resolution of 1.25 km and the infrared (10.5-12.5 μm) channel has a resolution of 5 km. This gives approximately 10,000 visible and 2,500 infrared lines and samples for each full-globe image.

METEOSAT provides weather oriented imaging of the earth. Like GMS, it covers visible and infra-red wavelengths sampled at half-hourly intervals.

CCD has been used extensively in a food security context to estimate rainfall using various techniques. It is defined, for each pixel and for a given period (usually ten days), as the number of hours during the temperature was below a “cold” temperature threshold around -40 °C, which corresponds to convective clouds with high vertical extension assumed to produce rainfall. The technique has been used to estimate rainfall with good results in tropical countries only. For a general introduction to the subject, refer to Bellon and Austin, 1986; Adler and Negri, 1988; Dugdale et al., 1991; Snijders, 1991; Guillot, 1995, Petty and Krajewski, 1996.

Figure 21: Accumulated CCD (hours) in central Malawi during two cropping seasons (1994/95 and 1995/96) in comparison with the reference period 1988/1995. The abscissa covers the period from the first dekad of September to the end of August in the following year.



Although the relation between the solar radiation reaching the ground and clouds is far from direct (Li et al., 1995), the development of more or less empirical methods is progressing, usually with much better results than with rainfall (Lourens et al., 1995; Wald, 1996; Supit and van Kappel, 1998), among others because the role of clouds in radiation interception is far more direct than in rainfall production. In addition, the methods, once they have been properly calibrated, apply in tropical and temperate countries alike.

The original approach was to try and estimate rainfall based on CCD only, assuming a constant intensity R_i (mm hour^{-1}). Because of the large spatial and temporal variability of R_i, the method is now being replaced by more or less real-time calibration against ground data, using CCD as an auxiliary variable in the spatial interpolation of raingauge measurements.

The major methodological issues regarding rainfall estimation and CCD can be listed as:

☞ rains are known exactly only for a given duration only for a very limited area around raingauge. According to the period covered (hours, days, dekads, months), the radius within which a raingauge provides a representative sample varies from a couple of hundred meters to 200 km;

- ☞ CCD indices cover a METEOSAT or GMS pixel (about 50 km^2 at the equator), and correspond to a discontinuous sample in time (one observation every 30 minutes);
- ☞ a plot of rainfall as a function of CCD thus compares two rather different variables, both of which are used as proxies for a third unknown variable, the average pixel rainfall. One of the consequences is a rather poor correlation[61] between CCD and rainfall, and usually not usable for rainfall estimation. Newer and significantly more efficient techniques are now available (see 5.3.3);
- ☞ for short time intervals (one day), an additional difficulty is the difference between the time covered by rainfall measurements (09 GMT to 09 GMT the next day) and the satellite images.
- ☞ It remains however that CCDs are associated with rainfall and that they provide a useful monitoring tool, as shown in figure 21. This figure covers one of several "homogeneous" rainfall units of the SADC region which are regularly published by the regional monitoring system.

5.1.3.3 Observations of microwave satellites

The use of satellites for the direct estimation of surface moisture involves a number of difficulties (Nemani et al., 1993).

Active microwave (or radar) satellites operating in the centimetric range of wavelengths are relatively unhindered by clouds, and satellites such as ERS-1 and JERS-1 have been providing images of the earth since the early nineties (Bouman, 1995). Radar is an active sensor in that it emits a bean or energy which is analysed after having been scattered back by the surface: is provides information about the surface, either crop canopy structure or soil surface. Regarding crops, active microwave responds well to row spacing and orientation, and even to leaf orientation. Little operational use has so far be made of the technique because of its large sensitivity to such factors as wind effects on the surface, including leaf orientation!.

Much hope is placed in the technique to estimate soil surface moisture directly, and possibly crop water content for plants with a planophile or near-planophile leaf distribution. For the estimation of soil moisture, refer to Wagner et al., 1999a, 1999b. Regarding the use of radar remote sensing, often combined with visible imagery, for crop modelling and yield forecasting, see Huete, 1988; Clevers, 1989; Le Toan et al, 1989; van Leeuwen and Clevers, 1994; Clevers, et al., 1994; Bouman, 1995; Doraiswamy and Cook, 1995; Clevers and van Leeuwen, 1996, et Clevers, 1997.

Passive microwave measure the centimetric radiation emitted by the surface. It used to determine the brightness temperature[62], or effective temperature which can be used in biomass estimations.

---

[61] Il existe une limite **théorique** au coefficient de corrélation de l'ordre de 0.7 (50% de la variabilité

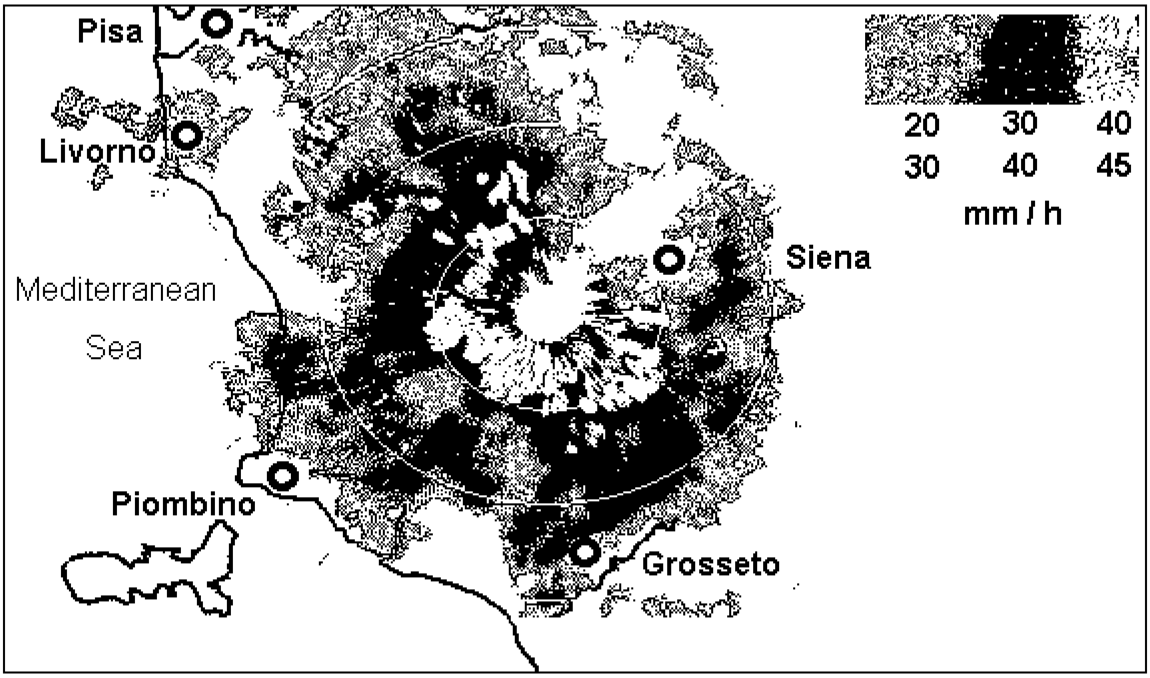
[62] Brightness temperature is the temperature of a blackbody radiating the same amount of energy per unit area at the wavelengths under consideration as the observed body.

5.2 *Weather radar*

Weather radar, like microwave satellites, operates in the centimetric range. The technique basically measures rainfall intensity within a radius of about 100 Km around the station, sometimes less. Its main advantage is that the spatial distribution of rain over short time intervals can be determined with a significantly better accuracy that with any other technique. As with satellite rainfall estimates, the best results are achieved over relatively long time intervals (days and beyond) after calibration against ground data. A reference quoted by Keane (1998) indicates that in shower conditions, a radar calibrated against two raingauges over 1000 Km^2 achieved the same accuracy as 50 raingauges.

Figure 22 illustrates a typical rainfall radar image.

Figure 22 : The thunderstorm of 5 June 1997 over Tuscany (central-western Italy) at 4 p.m. Rainfall intensities are given in mm/hour. The distance between the white concentric circles is 25 km (from LAMMA home page, Laboratorio per la Meteorologia e la Modellistica Ambientale http:// www.lamma.rete.toscana.it)



5.3 Area averaging and missing data

5.3.1 The relevance of the problem in crop-weather modelling

Spatial interpolation of missing data consists in the estimation of the unknown values at one P point in space based on the known values at neighbouring points. Area averaging is the estimation of the spatial average, within a contour, of a variable measured at several points. A typical example is the estimation of a district crop yield when the value has been actually sampled or computed at several points only, or the estimation of a temperature based on nearby stations.

The methodology of area-averaging involves the computation of the variable at regularly spaced gridpoints covering the area, followed by their averaging. This is a typical geostatistical problem.

Gridding, area averaging and the estimation of missing data from neighbouring stations are thus different facets of the same problem of spatial interpolation. Spatial interpolation has become a central issue in regional crop-weather model and yield forecasting (Landau and Barnett, 1996; Hashmi et al., 1995), to the extent that many of the comprehensive crop modelling environments like DSSAT now include tools for geostatistical analysis (Thornton et al., 1997). Gridded data are directly compatible with the Geographic Information Systems

The available methods are many; they vary in their complexity, constraints on inputs, and computer implementation. In addition to the “historical” Thiessen and Voronoi diagrams, we can mention inverse distance weighting, kriging and co-kriging, thin-plate splines, etc. For some general and climatological references, refer to Hutchinson, 1991; Phillips et al., 1992; Laughllin et al., 1993; Myers 1994; Hudson and Wackernagel, 1994; Bogaert et al., 1995; Hutchinson and Corbett, 1995. For some agricultural applications, see Booth et al., 1989; Takezawa and Tamura, 1991; Corbett, 1993; Stein et al., 1994; Klein, 1997; Tabor et al., 1984 and 1985.

The spatial interpolation can either be purely geo-statistical, or take advantage of the additional knowledge obtained from external variables. A third approach, known as mesoscale modelling, uses the physics of the phenomenon to model its spatial behaviour (Takle, 1995).

In the first category, we mention the method known of inverse distance weighting and simple kriging. In the second, the method we can list co-kriging and Satellite Enhanced Data Interpolation (SEDI).

The purely geostatistical methods treat spatial interpolation as a statistical problem: the nature of the variables being interpolated does not matter. The second methods takes advantage of the correlations between the variable to be interpolated and some other variable (external variable), for instance the well known linear decrease of temperature with elevation. If a digital terrain model[63] is available, the spatial interpolation can be significantly improved.

Two basic approaches are used to convert model outputs to regional statistics.

---

[63] A Digital Terrain Model is a grid of elevations.

In the first all input parameters are gridded and then input to the model at each gridpoint. This is the approach adopted by the EU MARS project (Dallemand and Vossen, 1995; Rijks et al., 1998). The alternative method (implemented by FAO: Gommes et al., 1998) is to run the models only with actual data, but to subsequently interpolate the yields using external variables (like NDVI) to guide the interpolation. Both methods have advantages and disadvantages in terms of reliability of input data and ease of use.

5.3.2 Inverse distance weighting[64]

The *inverse-distance weighting* is one of the most straightforward methods of spatial interpolation; it takes into account the distance d between the "known" and "unknown" points and their relative importance in the estimation. For instance, close-by points are assigned a higher weight than far-away ones. If the unknown value X_P at a point P has to be determined, the first step is to compute the distances between the point and all the points where the value X_i is known, subsequently discarding all he values beyond a certain distance and retaining only n neighbours. The user usually has the option to interpolate X_P only if the number of numbers is sufficient (for instance, n>5). The distance between P and the n other points is d_i.

$$X_P = \frac{\sum_1^n X_i d_i^a}{\sum_1^n d_i^a} \tag{63}$$

in which the exponent a is determined empirically. The method has several advantages, including simplicity and the fact that only values in the range of X_i are determined. The main disadvantages is the lack of indication of the statistical error affecting X_P.

5.3.3 Satellite enhanced data interpolation (SEDI)

SEDI takes advantage of the correlation between the variable to interpolate and an environmental variable, for instance NDVI/biomass and agricultural yields. One of the ways to approach this is co-kriging, a variant of kriging using one or more auxiliary variable and exploiting both the spatial features of the variable to be interpolated and the correlations between the variable and the auxiliary variables (Bogaert et al., 1995).

The SEDI interpolation method originated in a Harare based Regional Remote Sensing Project. It was originally developed to interpolate rainfall data collected at station level using the additional information provided by METEOSAT CCD. The methods proved powerful and versatile, and it is now regularly used to spatially interpolate other parameters as well (e.g. potential evapotranspiration, crop yields, actual crop evapotranspiration estimates, etc.).

[64] This section and the next (SEDI) are based on Gommes and Hoefsloot, 1998.

The concepts of this interpolation method and software implementing the technique have been described by Hoefsloot, 1996. The SEDI functions were recently incorporated into the WINDISP_3 software (Pfirman and Hogue, 1998)

SEDI is a simple and straightforward method for 'assisted' interpolation. The method can be applied to any parameter of which the values are available for a number of geographical locations, as long as a 'background' field is available that has a negative or positive relation to the parameter that needs to be interpolated.

Three requirements are a prerequisite for the application of the SEDI method:

1. The availability of the parameter to interpolate as *point data* at different geographical locations (e.g. rainfall, potential evapotranspiration, crop yields). In the present case of statistical variables, they were assigned a co-ordinate corresponding to the centre of gravity of the administrative unit;
2. The availability of a background parameter in the form of a *regularly spaced grid* (or field) for the same geographical area (e.g. the above-mentioned NDVI variables, altitude).
3. A monotonous relation, **at least locally**, between the two parameters (*negative or positive*; Yield/NDVI is positive, temperature/altitude would be negative). A Spearman rank correlation test can reveal whether a relation exists, and how strong this relation is.

The SEDI method yields the parameter mentioned under point 1 as a field (i.e. an image covering the whole area under consideration).

Let us illustrate the method below using rainfall and CCD: it is implemented in three steps (i) extracting CCD values from the satellite image and calculating the ratio of point and image values; (ii) gridding the ratios to form a regularly spaced grid, using any method, for instance inverse distance weighting or kriging; (iii) multiplying the grid of interpolated ratios with the grid of CCD (image) pixel by pixel to obtain an estimated rainfall grid (image).

There are several variants of the interpolation method thus described, for instance the one described by Herman et al., 1997. The authors include an estimate of orographic rain based on clouds with a relatively warm top. Note that the described methods apply only to tropical conditions.

5.4 Random weather generators

Random weather generators (RWG) are algorithms and computer programmes that generate synthetic time series of weather based on the historical data for the station being investigated. In the words of Göbel (1995), synthetic series are not forecasts of what will happen in the future but rather samples of sequences of events which might happen that way.

Such series are frequently used in Monte Carlo simulation of risk, and in crop forecasting (6.1).

RWG simulate the correlations and stochastic processes (Markov chains) that are present in the historical data. The processes are controlled by coefficients which are site specific. The coefficients driving a generator may be mapped (spatially interpolated) like any other variable, thus providing the possibility to generate synthetic weather covering large areas. Note that in most cases there is no spatial coherence in the thus generated fields.

The area of space-time synthetic weather models (Hutchinson, 1994) will gain in popularity as computing power available to individual scientist increases.

6. Chapter six : Agrometeorological applications of crop models

6.1 Crop forecasting

It can be said without much doubt that most applications of crop modelling are, directly or indirectly, linked to crop forecasting. This refers obviously to yield forecasting, as opposed to production forecasting. Some methods with a marked agrometeorological component do, however, have the potential to forecast production, like in the airborne pollen method[65] developed by Besselat and Cour (1997).

Planted areas depend to a much larger extent than yields on non-weather factor. The main factors can be listed as economic and political. For instance, In Malaysia, Tada and Morooka (1995) found that wage rate and per caput income are the key factors that exert strong negative effects on the planted area. Note that this specifically refers to planted areas. Areas actually harvested depend on environmental conditions as well.

There are, as always, a number of critical points to consider when using a model for crop forecasting. For instance, there are some differences between model fitting and forecasting (Pawer, 1993).

We have stressed elsewhere the importance of using models only at the scale for which they were developed. This hold particularly in regional forecasting where statistical crop-weather models found their first applications. The EC crop forecasting system is based on a non-crop specific version of WOFOST (Dallemand and Vossen, 1995; Vossen and Rijks, 1995; Supit, 1997a) run with daily data interpolated to large pixels (50 x 50 Km), which is subsequently calibrated against agricultural statistics. Vossen and Rijks list the main methodological issues as

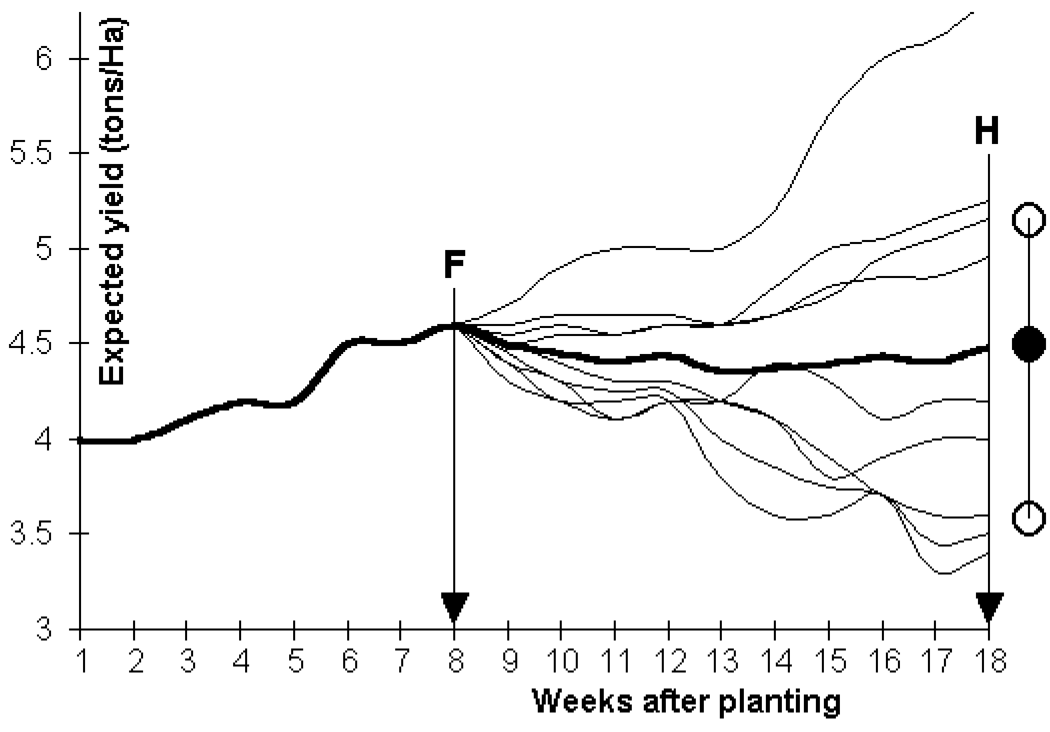
- a change of scale;
- a limited precision of input information, in particular the fact that the weather data do not necessarily represent the main cropping areas, uncertainties on phenology, etc. We could add the fact that inputs are n longer real data but spatial averages;
- some missing data, for instance rooting depth (this factor is rarely critical in some humid climates where water supply is usually sufficient);
- insufficient spatial resolution of inputs ;

[65] The method applies mostly to high value and mostly wind pollinated crops such as grapes. Airborne pollen is sampled and calibrated against production in the surrounding area. The method is currently under-developed regarding the physico-physiological emission and capture of pollen by plants as a function of environmental conditions, transportation of pollens by air, the trapping efficiency including trap behaviour and effect of atmospheric agents, sp. rain.

- insufficient knowledge of agro-pedo-meteorological growth conditions and yield for the various regions of Europe;
- poor timeliness of some of the inputs.

It is suggested that an additional point could be mentioned, maybe the most serious one: the very long “distance” between the raw weather data and the final yield estimate at the regional scale. The “distance” would be measured in terms of pre-processing (indirect estimation of radiation, area averaging for many variables, etc.) and the processing by the internal machinery of the models. The reporter suggests that many process-oriented models are too complex for regional applications. Sensitivity analysis normally refers to model parameters, not to the input data, in particular the weather data which are “given”. It would be most interesting to artificially contaminate the input data with a random factor or increasing magnitude to see what fraction of estimated detrended yield can actually be assigned to weather. The suggested answer is that the yield values would not be very dependent on some of the weather inputs.

Figure 23 : Yield forecast F at week 8, and harvest H at week 18. The black dot represents the estimated value, together with its confidence interval.

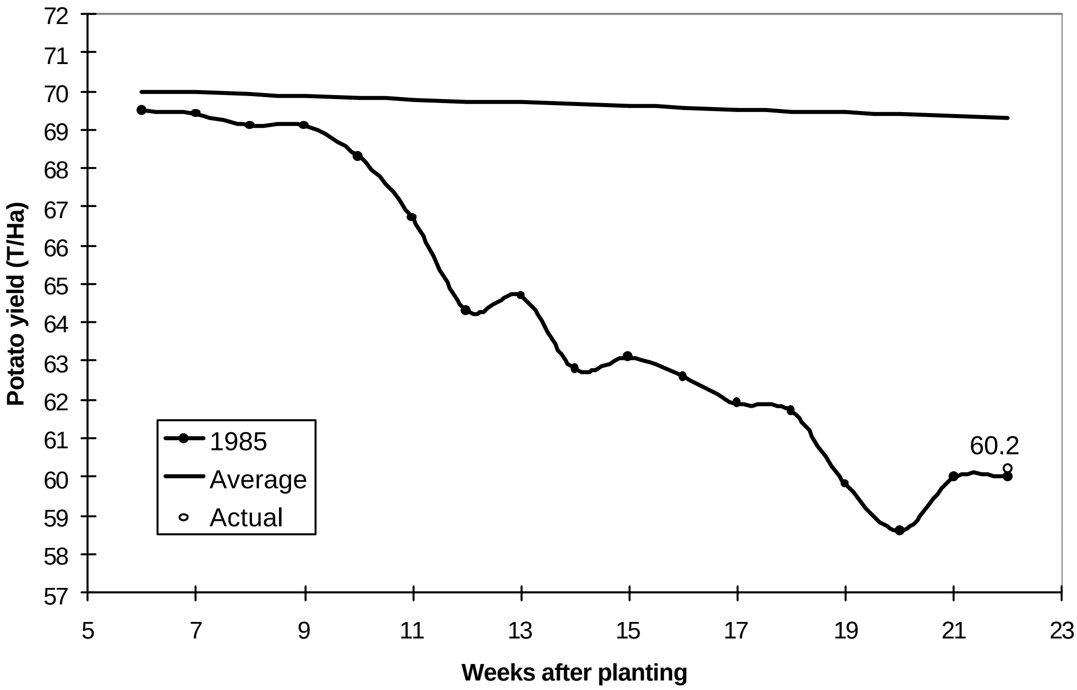


The main difference between crop modelling *per se* and yield forecasting is the fact that a forecast needs future data, i.e. an estimation of weather data between now, the time of the forecast, and the harvest. This is illustrated in figure 23. Several techniques can be used: either one uses “normal” weather, or the historical data that have occurred between F and the time of harvest, or one uses a random weather simulator. The two last approaches are preferable in that they provide not only a yield estimate, but also a confidence interval.

In particularly favourable conditions, when more reliable long range forecasts are available, a run can be done with no actual observations long in advance. Meinke and Hammer (1997) use an ENSO forecast to extend the range of their models. This information is available shortly after sowing a crop and at least 3-5 months before harvest.

An actual example of the evolution of a Irish potato forecast is shown in Figure 24, based on a figure given by MacKerron (1992).

Figure 24 : Evolution of a white potato forecast using actual 1985 data and the long-term average (after MacKerron, 1992).



There are a number of practical problems associated with the calibration of a model for forecasting purposes, mainly because the calibration set corresponds to a time series, where marked trends may be at work. There are several techniques to resolve this problem when there is no weather trend, such as the one that occurred in the West African Sahel between 1960 or so and 1984.

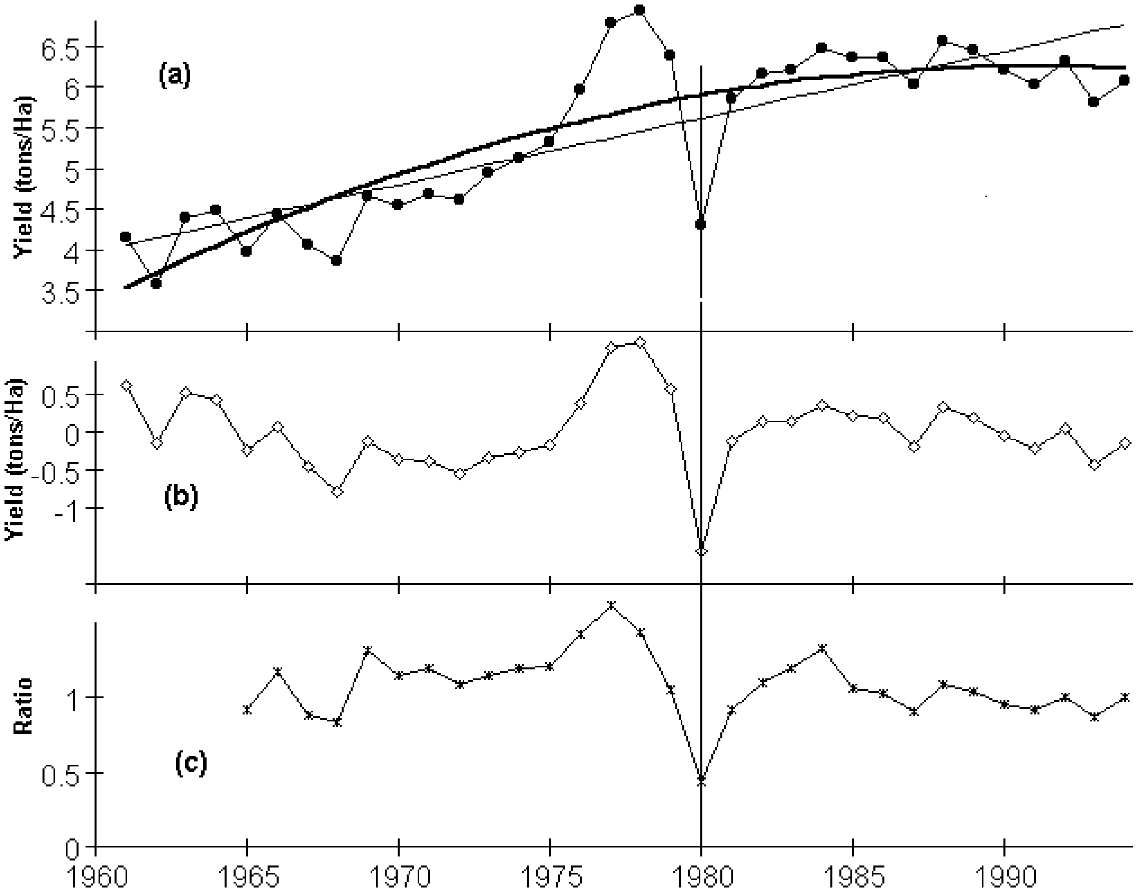
One can, for instance, detrend the yield series (Figure 25). The example (Korean Republic) shows a typical upward trend due to improved technology (varieties, management, inputs) as well as the linear and quadratic trend. The coefficients of determination[66] amount to 0.74 and 0.71, respectively. The coefficient achieved with the “best” trend model (a sigmoid, not shown) amounts to 0.80. Within the remaining 20%, weather accounts probably to about half.

The sharp drop in 1980 was due to severe low temperatures around the heading stage through early ripening stage. Tong-il varieties, high yielding hybrids, are very sensitive to abnormal cool temperature at that stage due to the failure in pollination. In the late 70s, the weather had been mostly favourable to rice cultivation, especially to Tong-il type (Byong-Lyol Lee, personal communication).

[66] The coefficient of determination is the square of the coefficient of correlation. It expresses which percentage of the variance is accounted for by the trend.

The middle curve shows the detrended yield (using the quadratic trend). This is the yield that will be used to calibrate a regional crop forecasting model. The lower curve shows the ratio between the yield of the current year and the average of the yields of the 4 preceding years, assuming that the trend is not significant over such short period. The advantage of this approach is that no trend has to be determined, and no hypothesis has to be made about the shape of the trend.

Figure 25 : Yield of total paddy in the Korean Republic between 1960 and 1994 (based on FAO statistics). The top curve (a) indicates the actual yields with their linear and quadratic trends; the middle curve (b) is the detrended yield, i.e. the difference (residual) between actual yield and the quadratic trend; the lower curve (c) shows the ratio between the yield of year N upon the average of the 4 years from N-1 to N-4.



When there is a marked trend in the weather variables, it is probably better not to detrend the time series, but to add time as one of the variables in the calibration process (Swanson and Nyankori, 1979; Vossen, 1990), which we can write as

$$Y_y = Y_0 + f_1(y) + f_2(simulation) + e \qquad (64)$$

where Y_y is the yield of year y computed from a function f_1 of time and a function f_2 of simulation model outputs (Supit, 1997b). An additional reason for adopting this approach is that management is both time and weather dependent. For a more detailed discussion of the concepts, refer to the quoted paper by Supit (1997b).

Equation 64 corresponds exactly to what we referred to under 3.4.1 and 3.4.2 as a yield function.

6.2 Farm-level applications

6.2.1 Response farming applications

"Response farming" is a methodology developed by Stewart (1988), based on the idea that farmers can improve their return by closely monitoring on-farm weather and by using this information in their day to day management decisions. The emphasis is here on the use of quantitative current data which are then compared with historical information and other local reference data (information on soils etc.). This is a simple variant of the what-if approach. What about planting now if only 25 mm of rainfall was received from the beginning of the season? What about using 50 Kg N-fertiliser if rainfall so far has been scarce and the fertiliser will increase crop water requirement and the risk of a water stress?

The method implies that, using the long-term weather series, decision tools (usually in tabular or flowchart forms) have been prepared in advance. They are based on

- the knowledge of local environmental/agricultural conditions (reference data[67]);
- the measurement of local "decision parameters" by local extension officer or farmer;
- economic considerations.

We suggest that crop weather models can improve response farming in two different ways. To start with, the decision tables can probably be somewhat improved by using simulation models to better understand the impact of past weather on past crops. Next, models could be run on the farm to carry-out the what-iffing, although this is hardly imaginable in developing countries.

In the latter, the decision-tools must be prepared by National Agromet Services in collaboration with Agricultural Extension Services and subsequently disseminated to farmers. The third operation will be the most difficult in practice (WMO/CTA, 1992).

A similar concept to response farming is flexcropping; it is used in the context of a crop rotation where summer fallow is a common practice, especially in dry areas, like the Canadian prairies. Rotations are often described as 50:50 (1 year crop, 1 year fallow) or 2 in 3 (2 years crop, 1 year fallow). The term flex crop has emerged to describe a less rigid system where a decision to re-crop (or not) is made each year based on available soil moisture and the prospect of getting good moisture during the upcoming growing season (Zentner et al., 1993; Peter Dzikowski and Andy Bootsma, personal communication).

Weisensel et al. (1991) have modelled the relative profitability and riskiness of different crop decision models that might be used in an extensive setting. Of particular interest is the value of information added by the availability of spring soil moisture data and by dynamic optimisation. The simulation has shown that flexcropping based on available soil moisture at seeding time is the most

---

[67] A simple example of this could be, for instance, a threshold of air moisture or sunshine duration to decide on pest risk, or a threshold of salt content of water to decide on irrigation-salinity risk. Normally, other parameters (economic) also play an important part.

profitable cropping strategy. The authors stress the importance of accurate soil moisture information.

6.2.2 Farm management and planning (modern farming)

Farmers have been using weather forecasts directly for a number of years to plan their operations, from planting wheat to harvesting hay and spraying fungicides! Models, however, have not really entered the farm in spite of their potential. The main causes seem to be a mixture of lack of confidence and lack of data (Rijks, 1997).

Basically three categories of applications can be identified:

- what-if experiments to optimise the economic return from farms, including real-time irrigation management. This is the only area where models are well established, including in some developing countries (Smith, 1992);
- optimisation of resources (pesticides, fertiliser) in the light of increasing environmental concern (and pressure);
- risk assessments, including the assessment of probabilities of pest and disease outbreaks and the need to take corrective action..

Contrary to most other applications, on-farm real-time operations demand well designed software that can be used by the non-expert, as well as a regular supply of data.

In theory, some inputs could be taken automatically from recording weather stations, but the reporter did not come across many specific examples. What comes closest is probably a publication by Hess (1996). The author underlines the sensitivity of an irrigation simulation package to errors in the on-farm weather readings.

Systems have been described where some of the non-weather inputs come from direct measurement (Thomson and Ross, 1996). Model (PNUTGRO) parameters were adjusted as the system was used based on soil water sensor responses to drying. An expert system determined which sensor readings were valid before they could be used to adjust parameters.

Irrigation systems have a lot to gain from using weather forecasts rather than climatological averages for future water demand. Fouss and Willis (1994) show how daily weather forecasts, including real-time rainfall likelihood data from the daily National Weather Service forecasts can assist in optimising the operational control of soil water and scheduling agrochemical applications. The authors indicate that the computer models will be incorporated into decision support models (Expert Systems) which can be used by farmers and farm managers to operate water-fertiliser-pest management systems.

Cabelguenne et al. (1997) use forecast weather to schedule irrigation in combination with a variant of EPIC. The approach is apparently so efficient that discrepancies between actual and weather forecasts led to a difference in tactical irrigation management.

We conclude this section with an interesting example of risk assessment provided by Bouman (1994) who has determined the probability distribution of rice yields in the Philippines based on the probability distributions of the input weather data. The uncertainty in the simulated yield was large: there was 90% probability that simulated yield was between 0.6 and 1.65 times the simulated standard yield in average years.

6.3 Institutional users

6.3.1 Impact assessment

The term impact assessment covers the evaluation, mostly in quantitative terms, of extreme environmental conditions, including extreme weather, on agriculture.

There is now much talk about future impact assessments in the ambit of global change studies. Many studies do in fact use the same crop models as the one described in this paper (3.5), after having made provision for the increased CO_2 concentrations that will occur in the future if current trends persist, which is likely in the foreseeable future.

About all popular crop models have been used in studies of climate change impact: GLYCIM (Haskett et al., 1997), ORYZAI and SIMRIW (Matthews et al., 1997), CERES-rice and CERES-wheat (Karim et al., 1996), WOFOST (Wolf and van Diepen, 1995), EPIC (Easterling et al., 1992)... The effect of elevated CO_2 is often taken into account through its effect on water use efficiency and/or radiation efficiency. Toure et al. (1995) have conducted a comparative study of 4 models (including EPIC and CERES) used under climate change conditions.

The approach is almost invariably that global circulation model (GCM) outputs, usually corresponding to 2 x CO_2 are fed into the models[68]. As GCM climate is very far from weather, the climate change simulation includes an additional step of deriving a set of estimated weather. Together with scaling problems, this happens to be a major source of uncertainty about the impact projections as, assuming that the zonal averages output by GCM are reliable, the conversion to local climate with an added variability are not.

Models are not very suitable to assess the impact of extreme factors that physically damage plant organs, exposing the plants to increased pathogen and pest attacks and disrupting the normal functions of the plants.

Gommes and Nègre (1990) indicate that analytical models can be used to simulate the plant processes (recovery and regrowth) after mechanical damage has occurred. A good example is given by Moore and Osgood (1987) in their studies on yield forecasting after cyclones. Cyclones break a large proportion of the stalks in sugar cane fields. For instance, hurricane "Iwa" which struck Kauai island (Hawaii, November 1982) broke up to 25% of the stems and damaged up to 76% of the leaves, which consequently affected the 1983 and 1984 harvests and sucrose yields.

The model estimates the rate of recovery of the damaged plants in view of their age at the time of the cyclone, the extent of the damage, and the classical agrometeorological parameters. The mechanical damage has, however, to be

[68] Other methods include historical and geological analogues.

estimated separately, and constitutes one of the inputs in Moore and Osgood's approach.

6.3.2 Warning systems, especially for food security([69])

Warning systems are of many types. Many of them address both individual and institutional users, although the main target of warnings for food security is usually governments. Other types of warnings include fire warning, pest warning, warning of periods of high water consumption or pathogen impact, etc.

In many developing countries, farmers still practice subsistence farming, i.e. they grow their **own food**, and depend directly on their **own food** production for their livelihood. Surpluses are usually small; they are mostly commercialised in urban areas (the urban population constitutes about 30% of the total population in Africa). Yields tend to be low: in Sahelian countries, for instance, the yields of the main staples (millet and sorghum) are usually in the range of 600 to 700 Kg/Ha during good years. Inter-annual fluctuations are such that the **national** food supply can be halved in bad years or drop to no production at all in some areas.

This is the general context in which food surveillance and monitoring systems have been established in a number of countries on all continents since 1978; their name varies, but they are generally known as (Food) Early Warning Systems (EWS). They contribute to:

- informing national decision makers in advance of the magnitude of any impending food production deficit or surplus;
- improving the planning of food trade, marketing and distribution;
- establishing co-ordination mechanisms between relevant government agencies;
- reducing the risks and suffering associated with the poverty spiral.

EWS cover all aspects from food production to marketing, storage, imports, exports and consumption at the level of families. Monitoring weather and estimating production have been essential components of the system from the onset, with an direct and active involvement of National Meteorological Services.

Over the years, the methodology has kept evolving, but crop monitoring and forecasting remain central activities:

- operational forecasts are now mostly based on readily available agrometeorological or satellite data, sometimes a combination of both. They do not depend on expensive and labour intensive ground surveys and are easily revisable as new data become available;

[69] Largely taken from Gommes, 1997a. Although pests and diseases are not the object of this section, it is worth noting that many models developed in the general field of plant pathology can often be associated to the crop-weather models in impact assessments and warning systems. For an overview of such models, refer to Seghi et al., 1996. Most of them are typical developed country applications, where both data availability and good communications permit their implementation in a commercial farming context.

- **forecasts** can be issued early and at regular intervals from the time of planting until harvest. As such, they **constitute a more meaningful monitoring tool than the monitoring of environmental variables** (e.g. rainfall monitoring);
- forecasts can often achieve a high spatial resolution, thus leading to an accurate estimation of areas and number of people affected.

Due to the large number of institutional and technical partners involved in EWS, interfacing between disciplines has been a crucial issue. For instance, crop prices are usually provided as farmgate or marketplace prices, food production and population statistics cover administrative units, weather data correspond to points (stations) not always representative for the agricultural areas, satellite information comes in pixels of varying sizes, etc. GIS techniques, including gridding, have contributed towards improving links in the “jungle” of methods and data (Gommes, 1996).

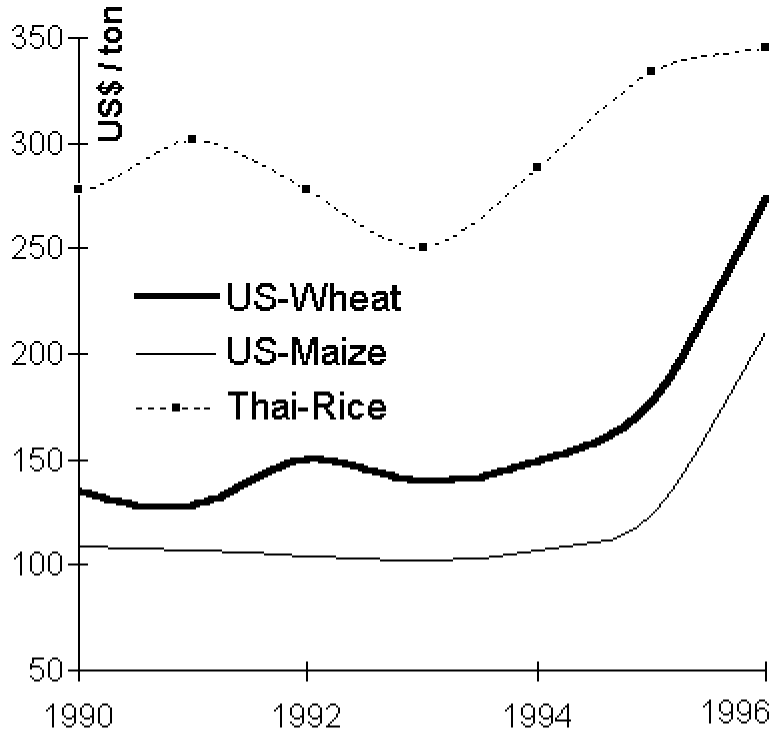
6.3.3 Market planning and policy

Market planning depends crucially on the advance knowledge of the likely volume of future harvests: prices fluctuate as function of the expected production[70] (read: forecast production), with a large psychological component. In fact, prices depend more on what traders think the production will be than on actual production (Marcus and Heitkemper, 1997). Accurate forecasts are, therefore, an essential planning tool. Accurate forecasts can also often act as a mechanism to reduce speculation and the associated price fluctuations, an essential factor in the availability of food to many poor people .

Figure 26 shows that the wheat prices increased from about 150 US$/ton in 1993 to about 275 US$ at the end of 1995. The main causes where the policy of both the US and the EU to reduce stocks (stocks are expensive to maintain), and a poor prospect of the 1995-96 winter wheat in the US and EU. Maize, a summer crop, was affected by “contagion”. Had the forecasts been more accurate and reliable, it is clear that the prices would have remained more stable: they culminated around May 1996, and returned to normal values thereafter.

Figure 26 : Recent variations of wheat, rice and maize prices between 1990 and 1996 (fixed 1996 CIF[71] US$ prices). The tics on the X-axis represent the beginning of the respective years.

[70] The main factors affecting prices are world production forecasts, speculation, weather, stocks and the time of the year.
[71] Cost Insurance and Freight.



A similar, but more dramatic situation occurred in 1977 with coffee prices when they reached their all-time high due to low stocks and frost in some of the main producing areas in Brazil (Brazil produces about 28 % of the world output of which more than half comes from São Paulo and Minas Gerais).

Commercial forecasts are now available for a subscription. CROPCAST (CROPCAST, 1994), for instance, provides estimates not only for yields, but also for production, areas, stocks, crop condition and futures prices.

At a more local scale, many food processing plants depend on the production in their area, and such production is linked to the seasonality of production for most crops (canning of fruit and vegetables, sugar from sugar beet, cotton fibre processing, oil from sunflowers and oil palm[72], etc.). It is important that not only the volume to be processed be known in advance, but also the timing.

Next to forecasting yields and production, there is thus a second category of forecasts regarding phenology, especially maturity date: many fruits are still harvested by hand, and the logistics of hiring the labour, storing and transporting the produce, and marketing it is best planned as long as possible in advance. The application has the largest potential for high-value fragile crops like grapes (Due et al., 1993; Riou, 1994), vegetables[73] (Bazlen et al., 1996) and flowers (when they are grown in the open).

---

[72] Oilpalm and other palms pose a series of very specific forecasting problems due to the very long lag between flower initiation and harvest. This period usually covers 3 years and more. In addition, probably more than in other plants, qualitative factors are very critical, for instance the effect of temperature on sex differentiation (only female flowers produce seeds, thus oil). See Blaak (1997) for details.

[73] The paper by Bazlen also includes an example of a "biometric" forecast combined with a more classical agrometeorological approach. In biometric forecasts, some characteristic size is

A new category of forecast has been gaining importance over the recent years: forecasting quality of products. This regards not only the very impressionistic[74] wine market (Desclée, 1991; Ashenfelter et al., 1995; Jayet and Mathurin, 1997), but also some cereals entering an industrial process where, for instance, starch/protein ratios should ideally remain within a relatively narrow range.

6.3.4 Crop insurance

Crop insurance is one of the main non-structural mechanism to reduce risk in farming: a farmer who subscribes an insurance is guaranteed a certain level of crop yield , equivalent, for instance, to 60% or 70% of the long-term average yield. If, for reasons beyond the control of the farmer, and in spite of adequate management decisions, the yield drops below the guarantee, the farmer is paid by the insurer a sum equivalent to his loss, **at a price agreed before planting**.

Crop insurance can be resorted to only when there is sufficient spatial variability of an environmental stress (e.g. with hail), but remains extremely difficult to implement for some of the major damaging factors, such as drought, which typically affect large areas, sometimes whole countries.

One of the basic tools for insurance companies is risk analysis (Abbaspour, 1994; Decker, 1997). Monte Carlo methods play an important part in this context, either in isolation or in combination with process-oriented or statistical models. As noted under the related subject of impact assessment (6.3.1), almost all major models have been put the use in a risk assessment context: for instance WOFOST (Shisanya and Thuneman, 1993), AUSCANE (a sugar cane model; Russel and Wegener, 1990) and others (de Jager and Singels, 1990; Cox, 1990).

Many of the papers presented at the international symposium on *climatic risk in crop production: models and management in the semi-arid tropics and subtropics* in July 1990 in Brisbane are relevant in the present context.

Crop insurance is not very developed in many Third World countries. This is best explained by the fact that many farmers live at subsistence level, i.e. they do not really enter commercial circuits (compare 6.3.2). Rustagi (1988) describes the general problematique rather well. For instance, insurance companies will accept to insure a crop only if the farmer conforms to certain risk-reducing practices, e.g. early planting. The identification of the “best” planting dates constitutes an direct application for process-oriented crop-weather models. The quoted paper by Shisanya and Thuneman (1993) used WOFOST to determine the effect of planting date on yields in Kenya.

An interesting example regarding both the forecasting of the quality of products and insurance is given by Selirio and Brown (1997). The authors describe the methods used in Canada for the forecasting of the quality of hay: the two steps include the forecasting of grass biomass proper, then the forecasting of the quality

---

measured on a plant at a typical time (eg. cob length in maize) and used as a forecasting variable, alone or in combination with other factors.

[74] “Impressionistic” because next to quality proper (defined by pH, tannin content, sugar, colour, etc.) the manipulation of demand plays a prominent role, particularly during average and mediocre years (see Ashenfelter et al., 1995).

based essentially on the drying conditions. One of the reasons why models have to be used is the absence of a structure that measures, stores and markets forage crops that is comparable to grain crops. In addition, field surveys are significantly more expensive to carry out than forecasts.

7. Chapter seven : Exercises

7.1 Familiarisation with spreadsheets and graphs: plot some functions

Almost all exercises make use of a spreadsheet. The students are invited to plot some functions to familiarise themselves with the tools.

7.1.1 Response curve to light of net photosynthesis

Plot net carbon dioxide absorption during photosynthesis as a function of light response for C3 and C4 plants.

$$F_n = F_d + (F_m - F_d)(1 - e^{-\frac{Elc.Rv}{Fm}}) \quad (12, 2.2.2)$$

7.1.2 **Light absorption in a canopy**

The exercise assumes that R_0 = 570 W m^{-2} and that LAI varies from 0 to 5 m^2 (leaf) m^{-2} (ground). The extinction coefficient will be originally set to 0.8. Define a named cell K, plot the function on the same sheet and examine the effect of varying K on the transmission rate.

$$R = R_0 e^{(-k\ LAI)} \quad (13, 2.2.3)$$

7.2 Compute Angot's value

Angot's value is the amount of energy (J m^{-2} day^{-1}) reaching a horizontal surface the upper limit of the atmosphere. On a given day, it depends on the solar constant S_c and the actual height of the sun.

If the sun stays close to the horizon, the total energy is less than when the sun moves high into the sky. If z is the zenith angle (the angle formed by the local vertical and the sun), the energy is largest when z=0 (cos(0°)=1) and smallest when the sun is at the horizon (cos(90°)=0), so that the total energy R_A over the day is

$$R_A = S_c \int_{z\ at\ sunrize}^{z\ at\ sunset} \cos(z)\, dz \quad (65a)$$

When cos(z) is replaced by its analytical expression, the following is obtained

$$R_A = S_c \times (D \times SS + \frac{24}{p} CC \sqrt{1 - \tan^2(l)\tan^2(d)}) \times 3600$$

(65b)

Figure 2 under 2.2.2 illustrates the behaviour of R_A as function of latitude and month (expressed in Gigajoules per hectare per day).

R_A is computed from the solar constant S_c in W m^{-2} (or J m^{-2} s^{-1}), the daylength D in hours, latitude λ (degrees), solar declination δ (degrees), the offset of the sine of the solar height (SS) and the amplitude of the sine of solar height (CC).

All listed variables (S_c, D, λ, δ, SS and CC) eventually depend on just the number (1-365) and the latitude.

Prepare a spreadsheet using three named cells as input fields (latitude, month, and day within the month) to compute the value of R_A. To determine the day number J corresponding to a month M and a date (Date) within the month, use the following expression:

$$J = round\,(30.4\,M - 31, 0) + Date\;; \qquad (66)$$

for the fifth day of a dekad (Dek = 1, 2, 3) in a month, use

$$J = round\,(30.4\;M - 35 + 10\,Dek\,, 0) \qquad (67)$$

Several preliminary calculations will be required: S_c, δ, SS, CC and D (in that order) before being able to compute R_A. The detail is given below[75]:

The energy radiated by the sun is relatively constant, and amounts to 1370 W m^{-2} at the average distance between the earth and the sun. The value is now well known thanks to satellite-based measures, but since the orbit of the earth is elliptical, the distance actually varies, so that the energy reaching the upper atmosphere on day J (J=1 to 365) is approximately

$$S_c = 1370 \times (1 + 0.033\cos(2p\ \frac{J}{365}) \qquad (68)$$

in W m^{-2}. This function goes through a maximum during the northern hemisphere winter.

The next variable to be computed is the declination of the sun: because of the inclination of the axis of the earth on the ecliptic (the plane that contains the orbit), the northern hemisphere has longer days and receives more direct solar energy during the northern hemisphere summer. The declination is the latitude where the sun is directly overhead at noon. It varies from -23.45° (N winter) to +23.45° (S winter) and defines the equatorial zone. Outside the equatorial zone, the sun stays always S of the zenith (N hemisphere) or N of the zenith (S hemisphere).

The declination δ (in degrees) can be approximated by

$$d = -23.45\cos(2p\ \frac{J + 10}{365}) \qquad (69)$$

δ is in degrees (**but** the arguments of the trigonometric functions are in radians).

[75] Unless otherwise specified, the formulae in this section are from Supit et al., 1994.

Before proceeding, it is necessary to compute the *seasonal offset of the sine of the solar height* (SS) and the *amplitude of the sine of solar height* (CC) . Both are derived directly from declination δ and latitude λ as follows:

$$SS = \sin(\delta) \times \sin(\lambda) \qquad (70a)$$

$$CC = \cos(\delta) \times \cos(\lambda) \qquad (70b)$$

Note that

- when doing the calculations with a computer or with a spreadsheet, it will be necessary to convert the angles in degrees to radians by multiplying then by π/180=0.01745328;
- southern latitudes are counted as negative (λ<0) and northern latitudes are positive (λ>0);
- the calculations are not valid between the polar circles and the poles (-90 < λ < -90+23.45 and 90 > λ > 90-23.45) where day length may exceed 24 hours.

Day length in hours is computed next (using the equation implemented in Gommes and See (1993):

$$D = D_r + 2 \times \frac{24}{\pi} \times \arctan \sqrt{\frac{CC + SS}{CC - SS}} \qquad (71)$$

where D_r is a daylight refraction correction factor. As the sun becomes visible due to refraction of sunlight by the atmosphere before it actually crosses the horizon, the actual day length is slightly longer than the astronomical day length by D_r (about 10 to 15 minutes, or 0.16666... to 0.25 decimal hours).

7.3 Beta distribution model for development rate

Using equation of Xinyou Yin et al. (1995),

$$DR = e^{m} (T - T_{b})^{a} (T_{u} - T)^{b} \qquad (27, 2.3.2.3)$$

draw the DR curve for Tuxpeno maize (Crema IC18) where the following , parameters where found by Xinyou Yi et al: $\mu = -4.876$; $\alpha = 0.504$; $\beta = 0.207$; Tb = 11.0 and Tc = 37.1. Find the optimum temperature and the corresponding maximum rate of development.

Study how the curve varies as a function of α and β (distinguish 4 cases $\alpha<1$, $\beta<1$; $\alpha<1$, $\beta>1$; $\alpha>1$, $\beta<1$; $\alpha>1,\beta>1$); determine the values of T_o and R_o and see how they vary as a function of α and β; subsequently compute Q10 as a function of temperature. Plot and compare. Where does the concept of Q10 apply?

The solutions are given in figures 27 and 28.

Figure 27 : Development rate of Tuxpeno *Crema IC18* maize as a function of temperature, together with the variation of Q10.

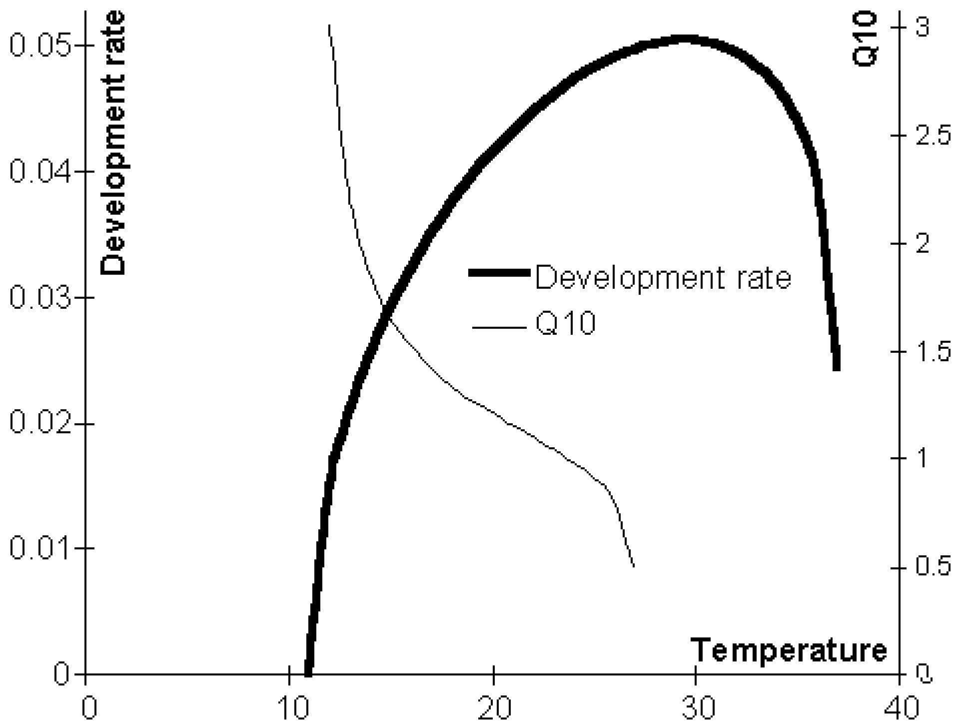
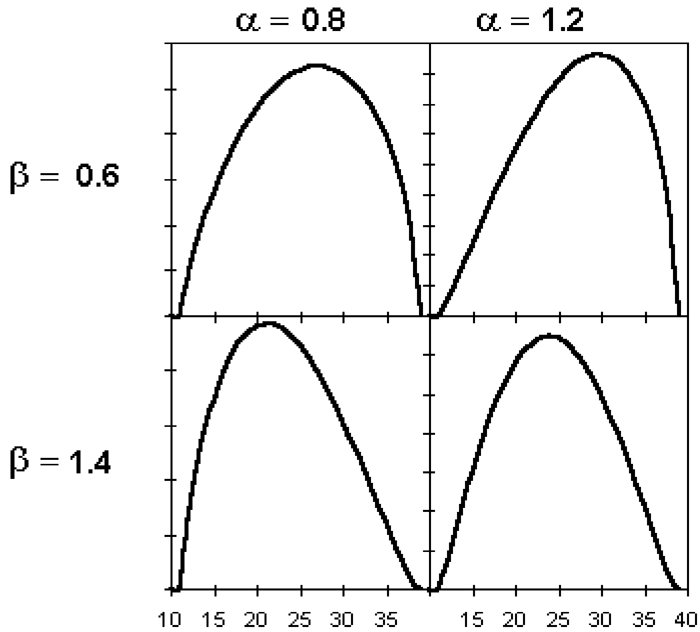


Figure 28 : Variation of the beta model for rate of development as a function of the two shape parameters α and β.



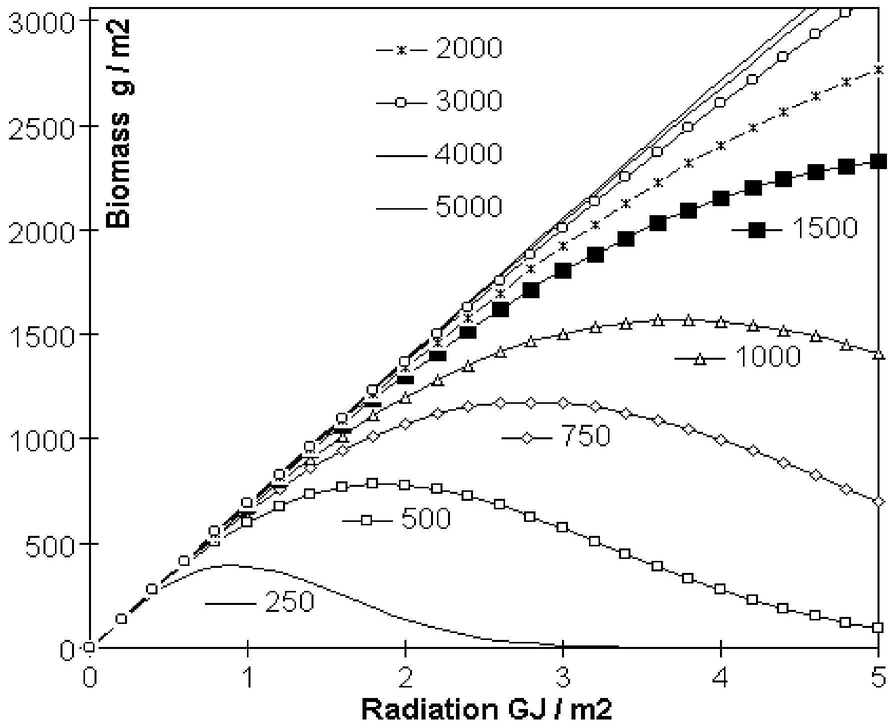
7.4 Determination of net primary production (Chikugo model)

The Chikugo model expresses the net primary production potential as a function of rainfall and net radiation according to the equation:

$$NPP = 6.938 \cdot 10^{-7} H\ e^{\left(-3.6 \cdot 10^{-14}\left(\frac{H}{Prec}\right)^2\right)} \quad (50, 3.1.4)$$

where NPP is in g (DM) m^{-2} $year^{-1}$, H in J m^{-2} $year^{-1}$ and Prec in mm (equivalent to Kg m^{-2}). Plot biomass as a function of net annual radiation from 0 to 5 GJ m^{-2} and rainfall amounts up to 5000 mm.

Figure 29 : Annual potential biomass according to the Chikugo model as a function of annual net radiation and rainfall (mm) varying between 250 and 5000 mm per year

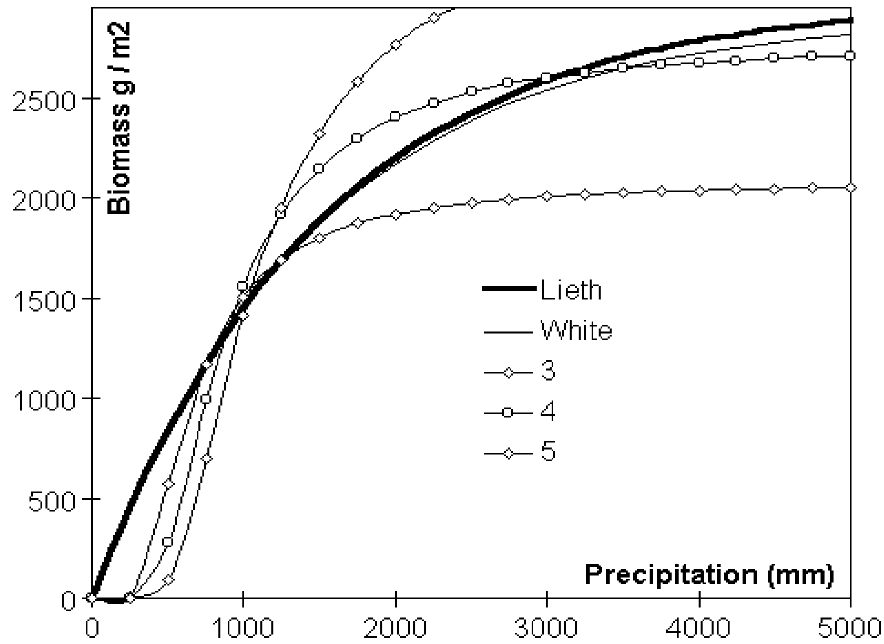


Next compare NPP as a function of rainfall as given by Lieth's Miami model and the curves listed by White et al. (1992) :

$$NPP = 3000\,(1 - e^{-0.000664\ \text{Rainfall}}) \quad (44, 3.1.2)$$

$$NPP = 2909(1 - e^{-0.000688 \cdot \text{Rainfall}}) \quad (47, 3.1.3)$$

Figure 30 : A comparison of potential annual biomass using three empirical models: Lieth's Miami model, the curves derived from White et al. and the Chikugo model for 3 different net radiation values of 3 GJ m^{-2} $year^{-1}$, 4 GJ $year^{-1}$ and 5 GJ m^{-2} $year^{-1}$



Biomass g / m2
Precipitation (mm)
Lieth
White
3
4
5
0
500
1000
1500
2000
2500
0
1000
2000
3000
4000
5000

7.5 Sums of temperatures; determination of cardinal temperatures

Based on the provided weather files for Suwon (Republic of Korea; 32.27 °N, 126.98 °S, 37 m a.s.l.), and the phenology data below for *Ilpoom* Paddy rice , prepare a spreadsheet computing the sums of degree days from planting to transplanting. The spreadsheet will have two named cells for the base temperature T_b and the cut-off temperature T_u which can be used to determine some of the parameters below by trial and error.

Part of the spreadsheet is illustrated at figure 31.

Determine the value of T_b that minimises the coefficient of variation of the sum of temperatures between planting and transplanting, and plot the development rate as a function of temperature.

Solution: figures 32 and 33.

Figure 31 : Part of the spreadsheet used to determine sums of temperatures and the cardinal temperatures.

			Base=	7 deg.C					
			Cutoff=	35 deg.C					
	1992	**1993**	**1994**	**1995**	**1996**	**1997**			
SUMS OF TEMPERATURES							**Average**	**Stdev**	**Coeff. V.**
Planting to transp.	291.6	348.8	414.4	332.5	329	420.3	291.6	51.04006	17.5
Transpl. to heading	1337	1394	1563	1431	1490	1453.5	1444.867	78.05443	5.4
Heading to harvest	696.2	635.5	800.9	747.9	822.9	811	752.4	74.29773	9.9
VERIFICATION									
Sum of above	2324.8	2379	2779	2512	2642	2684.8			
Sum 1 Jan - harvest	2431.3	2397	2847	2549	2662	2686.5			
AVERAGE TEMPERATURE									
Transpl. to heading	22.729	22.57	25.94	23.95	25	24.718			
1/D	0.0118	0.011	0.012	0.012	0.012	0.012			

Figure 32 : Empirical determination of base temperature for Ilpoon paddy rice grown at Suwon (Korean Republic) between 1992 and 1997: coefficient of variation of the length of 3 phases as a function of temperature. The curves correspond to planting to transplanting (P → T), transplanting to heading (T → F) and heading to harvest (F → M).

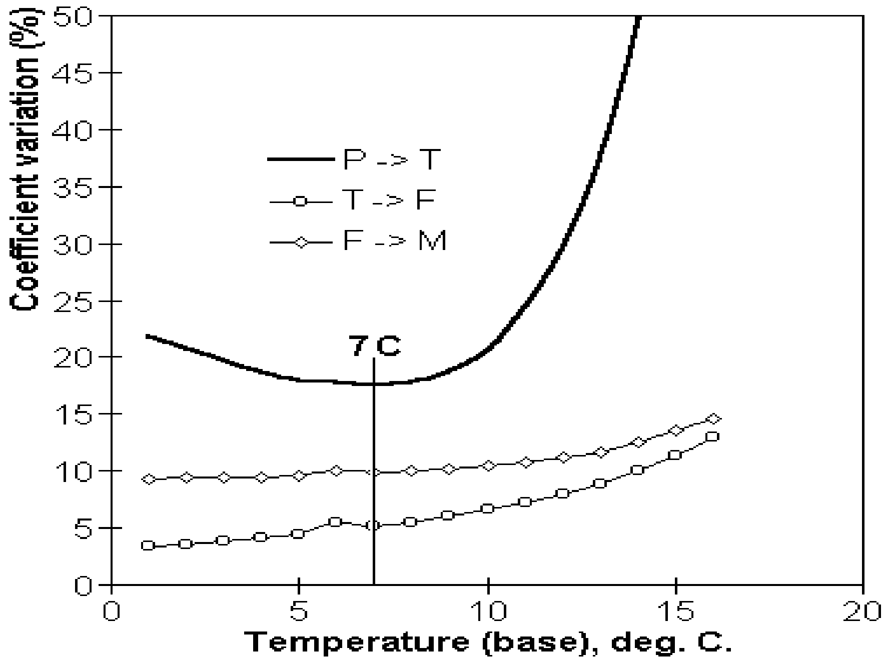
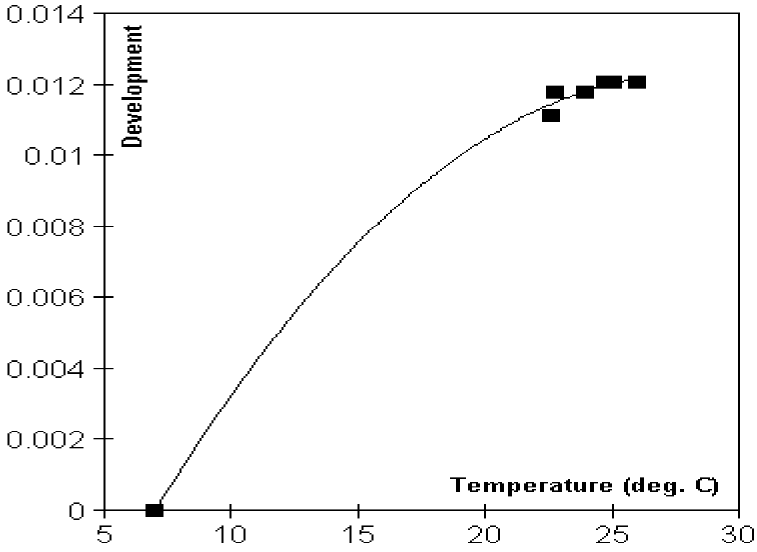


Figure 33 : Rate of development (d^{-1}) of Ilpoon paddy rice grown at Suwon (Korean Republic) between 1992 and 1997 between planting and transplanting. The lowest point (7,0) is not an observed point but corresponds to the base temperature.



The exercise includes the following steps:

- determine the best "statistical" base temperature for the phenophases from planting to transplanting. To do so, compute the sums of temperatures using the named “base” and “cut-off” cells, provisionally set to 8 and 32 °C, respectively. The effective temperature will be given by

$$IF(T < Base, 0, IF(T > Cutoff, Cutoff - Base, T - Base)) \quad (72)$$

- Compute the average sum of temperatures, the standard deviation and the coefficient of determination over the 6 years available, from 1992 to 1997. By modifying T_b it will be observed that the Coefficient of variation goes through a minimum at 7 °C. Note that we call this the “statistical base temperature” because there may also be a physiological base temperature. The plot of the coefficient of variation against the base temperature is shown in Figure 33;
- compute average temperatures over the time from planting to transplanting , and plot the rate of development (DR) against temperature. The rate of development is simply the reciprocal of the length of the phase in days. If the phase is long, DR is low, and vice-versa. Do not forget to include the value of T_b for which DR is nil, by definition. The plot is shown in Figure 33. What are the rates of development and the time from planting to transplanting at 10 °C, 15 °C, 20 °C, 25 °C and 30 °C ? Compute the three corresponding Q_{10}, and discuss the concept;
- based on the plot of DR as a function of temperature, make some guesses about the optimum and cut-off temperatures (T_o and T_u). It is suggested that the optimum is between 25 °C and 30 °C, which puts the cut-off temperature at least to 35 °C;
- using the values just determined for the base and cut-off temperatures (7°C and 35 °C), determine the sums of temperatures for the given phenophases. The value below are found:

Table 7 : Phenology of Ilpoon paddy rice grown at Suwon (Korean Republic) between 1992 and 1997, in day number (1-365).

	1992	**1993**	**1994**	**1995**	**1996**	**1997**
Planting	102	101	101	101	102	101
Transplanting	146	145	145	145	146	145
Heading	231	235	228	230	229	228
Harvesting	276	280	281	284	282	283

Table 8 : Sums of temperatures for Ilpoon paddy rice grown at Suwon (Korean Republic) between 1992 and 1997, assuming as base temperature of 7 °C and a cut-off temperature of 35 °C.

Phase	**Sum of Degree-Days**
Planting to transplanting	292 °C
Transplanting to heading	1445 °C
heading to harvest	752 °C

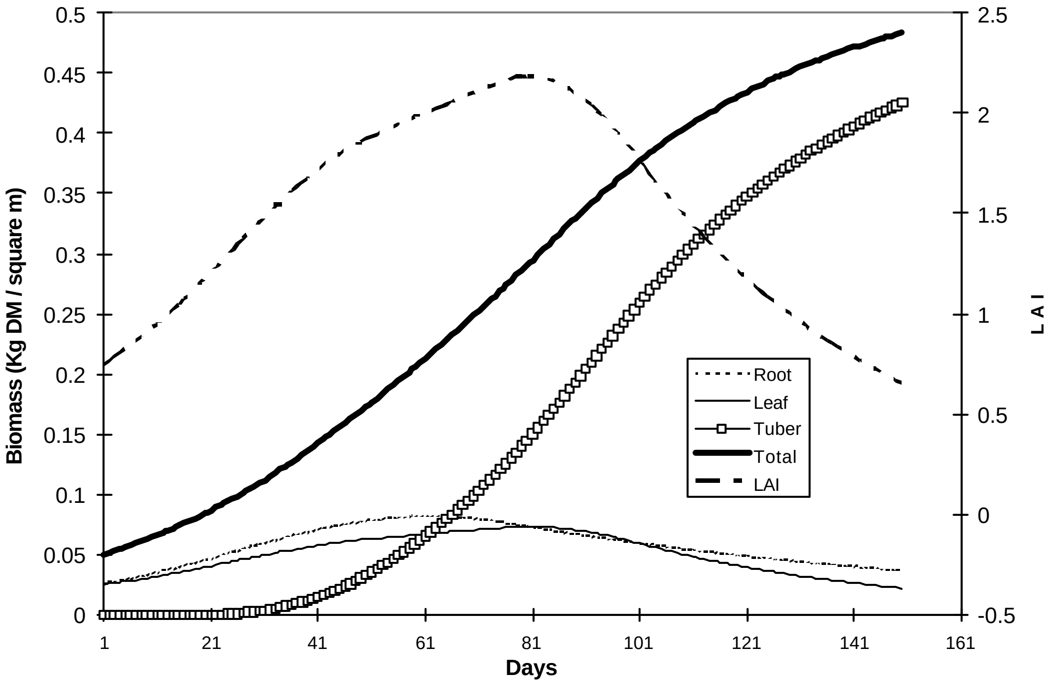
7.6 Simple spreadsheet simulation with partition table

Elementary simulation of a root crop: the crop is assumed to be a tuber crop with the following partitioning table (illustrated under figure 8, 2.3.3).

Table 9 : Biomass partitioning table for a root crop (corresponds to figure 8)

Day	Root	Leaf	Tuber
1	0.5	0.5	0
20	0.5	0.5	0
50	0.25	0.3	0.45
75	0	0.28	0.72
130	0	0	1
150	0	0	1

Figure 34 : Results of a simple root crop simulation using a spreadsheet. Variation of LAI and biomass as a function of time.



The values for the other days of the cycle (assumed to be 150 days) have to be linearly interpolated between the values above using the **Fill** and **Series** options of the spreadsheet. Please pay attention to the fact that only values for two of organs must be interpolated (e.g. roots and leaves); the third has to be computed as 1 - root - leaf (why?).

The model is an extremely simple one : LAI is obtained from the leaf biomass applying a specific leaf area (SLA) factor provided in the table below (table 10).

The specific daily assimilation W_s [Kg (DM) m-2 (leaf)] is assumed to be constant, hence the daily assimilation rate [Kg (DM) m-2 (ground)] is simply the product:

$$\Delta W = W_r \times LAI \qquad (73)$$

In the next step we partition ΔW into roots, leaves and tuber according to the partitioning table, resulting in ΔW_r, ΔW_l and ΔW_t.

On the second and on all subsequent days, the new root and leaf biomass are computed as

$$W_r^d = (W_r^{d-1} + \Delta W_r)\,\frac{100 - R_d}{100} \qquad (74)$$

and

$$W_l^d = (W_l^{d-1} + \Delta W_l)\,\frac{100 - R_l}{100} \qquad (75)$$

$$W_t^d = W_t^{d-1} + \Delta W_t \qquad (76)$$

where W_r^d indicates root biomass on day d, etc. The factors (100-X)/100, where X (R_d and R_l) is a decay factor in percent can be regarded as equivalent to maintenance respiration or conversion efficiency. The factor was introduced to "force" root death. Another technique which is often implemented in models assigns leaves a life expectancy expressed in Degree-Days.

Table 10 : Parameters and variable used for a simple root crop simulation with a spreadsheet

Parameter	Cell name	Value	Unit
Initial biomass	W0	0.05	Kg(DM) m^{-2}(ground)
Specific leaf area	SLA	30	m^2(leaf) kg^{-1}(DM)
Specific daily assimilation	WR	0.003	Kg(DM) m^{-2}(leaf) day^{-1}
Leaf decay rate	Ld	2	percent
Root decay rate	Rd	1	percent
Variable			
Daily assimilation rate	ΔW	-	Kg(DM) m^{-2}(ground)

The layout of the spreadsheet should be (columns):

Table 11 : Spreadsheet layout for simple root crop simulation with a spreadsheet.

Column	**Variable**	**Line 1 (initial conditions)**	**Line 2 and following ones**
A	Day number	1	2
B	Root biomass	W0/2	(B1+K1) x (100-Rd)/100
C	Leaf biomass	W0/2	(C1+L1) x (100-Ld)/100
D	Tuber biomass	0	D1 + M1
E	Total biomass	B1+C1+D1	B2+C2+D2
F	LAI	SLA x C1	SLA x C2
G	ΔW	F1 x WR	F2 x WR
H	Root (part. table)	0.5	0.5
I	Leaves (part. table)	0.5	0.5
J	Tuber (part. table)	0.0	0.0
K	Biomass production (roots) ΔW_r	H1 x G1	H2 x G2
L	Biomass production (leaves) ΔW_l	I 1x G1	I 2x G2
M	Biomass production (tuber) ΔW_t.	J 1x G1	J 2x G2

The results of the simulation are given in figure 34. Seminar participants will vary the values of the model parameters given in table 10 to study their effect on the simulation.

7.7 Simple soil-crop water balance

The purpose of this exercise is to compute a soil water balance for an irrigated maize crop with a cycle of 120 days (emergence at day d=1, harvest at day d=120), the growth of which is given by

$$LAI = \frac{LAI_{\max}}{1 + 220 \times GSF \times e^{-0.1d}} \tag{77}$$

in m^2 (leaf) m^{-2} (ground) where LAI_{max} = 3.3 and GSF (Growth Shape Factor) = 1. The student is invited to experiment with this curve and to determine the significance of the GSF, including negative values!

Whenever sufficient moisture is available, crop transpiration T_0 and evaporation E_0 from soil are proceeding at the potential rate ET_0 which is assumed to be constant at ET_0 = 6 mm d^{-1}.

ET_0 is partitioned into E_0 and T_0, which are given by

$$T_0 = ET_0 \frac{LAI}{LAI_{\max}} \tag{78}$$

$$E_0 = ET_0 \left(1 - \frac{LAI}{LAI_{\max}}\right) \tag{79}$$

The soil is a 1 layer soil with a maximum water holding capacity (WHC) of 150 mm and a depth of 1 m from where evaporation takes place and which is also the depth eventually reached by the roots.

No ET takes place during rain, which is to say that water infiltrates first, and only subsequently is it being depleted by evaporation and transpiration. Moisture from rainfall and irrigation (total: Prec mm) distributes homogeneously over the whole profile. No horizontal nor ascending vertical movements of water take place from below 1 m. Initial soil moisture is 75 mm. All water infiltrates instantaneously. The soil water behaviour is described by

$$\begin{aligned} H_d &= H_{d-1} + Prec \quad && if\ H_d < WHC \\ H_d &= WHC && if\ H_d > WHC \end{aligned} \tag{80}$$

where H_d is the soil moisture of day d.

The farmer irrigates 60 mm every ten days between days 10 and 110 (inclusively), except on days 50 and 60 when her pumps failed.

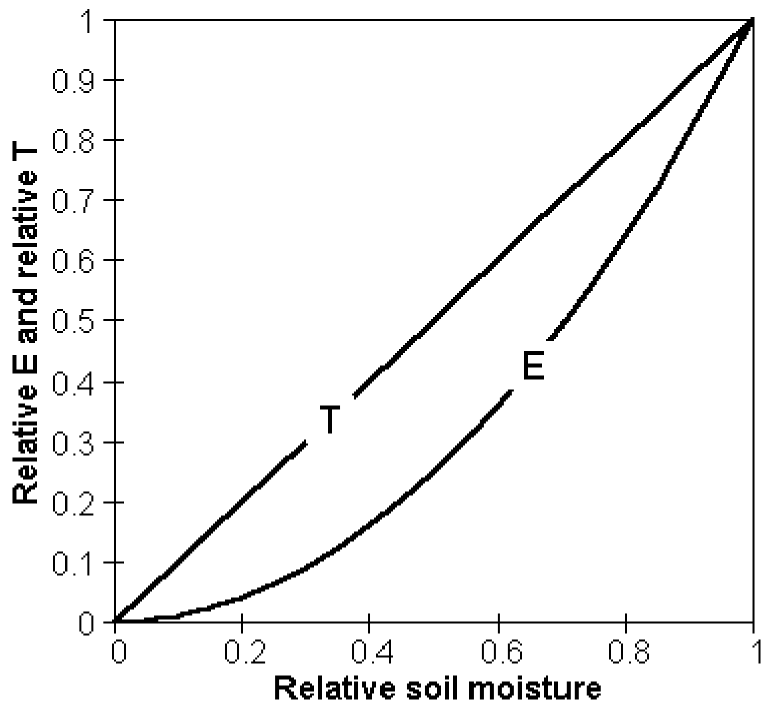
Rain falls on 7 days only as per the table below:

Table 12 : Rainfall amounts (mm) for simple soil water balance simulation with a spreadsheet

Day number	9	10	11	39	66	67	105
Amount (mm)	54	17	60	45	121	47	52

Water stress is introduced in the model by making both actual evaporation (E_a) and transpiration (T_a) dependent on relative soil moisture H_r, as shown in figure 35.

Figure 35 : Dependence of relative evaporation and relative transpiration on relative soil moisture for a simple soil water balance simulation with a spreadsheet.



The corresponding equations are

$$T_a = H_r \times T_0 \text{ and } E_a = H_r^2 \times E_0 \qquad (81)$$

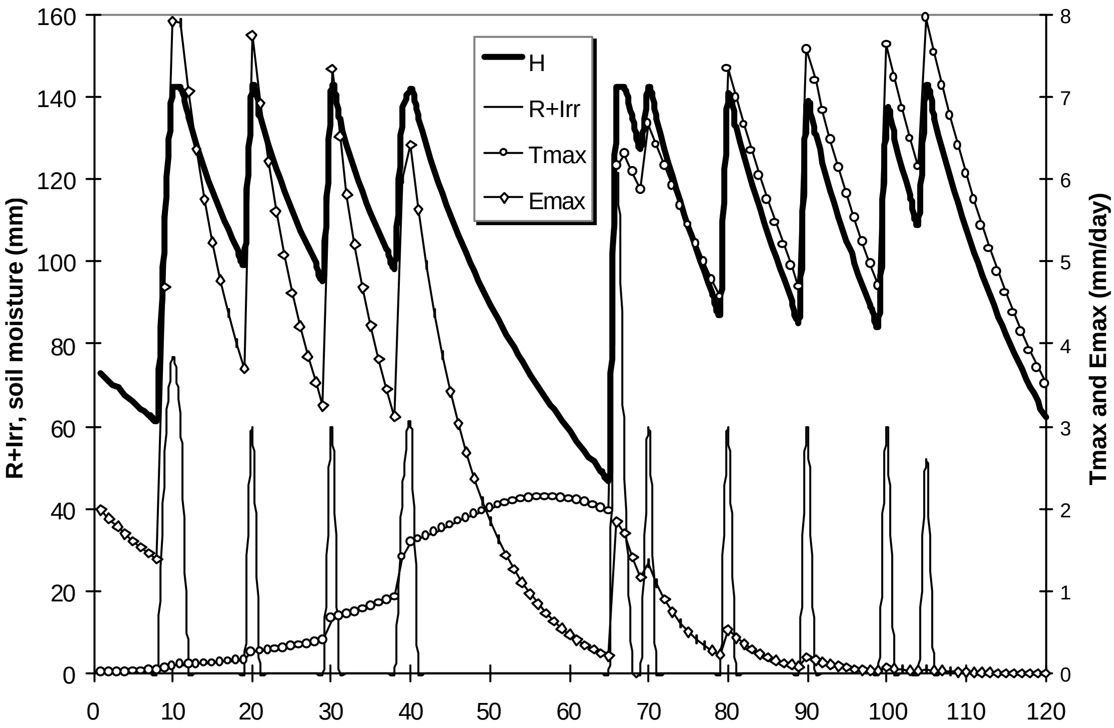
As soil mositure is depleted, both actual T (T_a) and E_a drop to zero, with the consequence that

$$H_d = H_{d-1} - T_{a,d} - E_{a,d} \qquad (82)$$

should never actually drop below 0.

The final steps is the estimation of the daily biomass production (g d^{-1} m^{-2}) and yield (tonnes Ha^{-1}) assuming that the water use efficiency WUE is 500 g of water for each g of dry matter and the harvest index is HI = 0.6.

Figure 36 : Some simulated model variables (soil moisture, water supply as rainfall and irrigation, potential transpiration and potential evaporation).



The following inputs, parameters and variables will be used (tables 13a and 13b). The parameters will be assigned names in the spreadsheet so that they can be used to experiment with their numerical values.

Table 13a : Inputs and parameters and variables used for a simple soil water balance simulation using a spreadsheet.

Input	Value	Unit
Prec	-	mm
Irrigation	-	mm
Parameter		
LAI$_{max}$	3.3	m^2/m^2
WHC	150	mm/m
ETP	6	mm/d
Irrig	60	mm
H$_0$	75	mm initial soil moisture
WUE	500	Kg water/Kg biomass
HI	0.5	dimensionless
GSF	1	dimensionless

Table 14b : Variables used for a simple soil water balance simulation using a spreadsheet. Water amounts in mm (Kg m^{-2}) refer to one day.

Variable	Unit
RI = Precip + Irrigation	mm
LAI	m^2(leaf)m^{-2}(ground)
T_0 Maximum transpiration	mm
E_0 Maximum evaporation	mm
T_a Actual transpiration	mm
E_a Actual evaporation	mm
H_r Relative soil moisture	-
H_d Actual soil moisture	mm
DW_d Biomass growth	Kg (DM) day^{-1}
W_d Accumulated biomass	Kg (DM) m^{-2}
Yield	tons (grain) Ha^{-1}

Although soil moisture H_d is, strictly speaking, only one variable, it will be computed in several steps, which we will identify as $H_d(1)$, $H_d(2)$ and $H_d(3)$.

The final value on a given day is $H_d(3)$ and quite obviously $H_{d-1}(3)$ is the final value of the **previous** day.

The steps are listed below.

1. New soil moisture is soil moisture at the end of the previous day ($Hd_{previous}$) plus water supply RI, i.e. the sum of rainfall and irrigation. If the sum exceeds capacity, it is set to capacity:

$$Hd(1) = IF(Hd_{previous}+RI > WHC, WHC, Hd_{previous}+RI)$$

Note that on day 1 $Hd_{previous}$ is H_0, the initial soil moisture - and one of the parameters -, and $H_{d-1}(3)$ on the second and all subsequent days;

2. Potential and actual values of evaporation and transpiration (E_0, T_0, E_a and T_a) are computed next, and will subsequently be subtracted from Hd(1), leading to Hd(2):

$$Hd(2) = Hd(1) - T_a - E_a$$

3. Since the resulting value of Hd(3) might drop below 0 (although this is unlikely, given the way they tend to 0 when relative soil moisture drops close to 0), we apply the final EXCEL function

$$Hd(3) = IF(Hd(2) < 0, 0, Hd(2))$$

The seminar participants will prepare the layout of the spreadsheet in such way that the parameters are at the top of the spreadsheet proper, leaving enough space right of the parameters to display a graph showing soil moisture (as in figure 38).

The spreadsheet proper will be arranged in the logical order presented in table 14. Note that the table is transposed in comparision with the previous exercise (table 11).

Table 15 : Layout of spreadsheet for simple soil water balance simulation. RI, the sum of rainfall and irrigation is the total water supply. $H_{d-1}(3)$ stands for soil moisture at the end of the previous day. The initial biomass (seed) is assumed to be negligible.

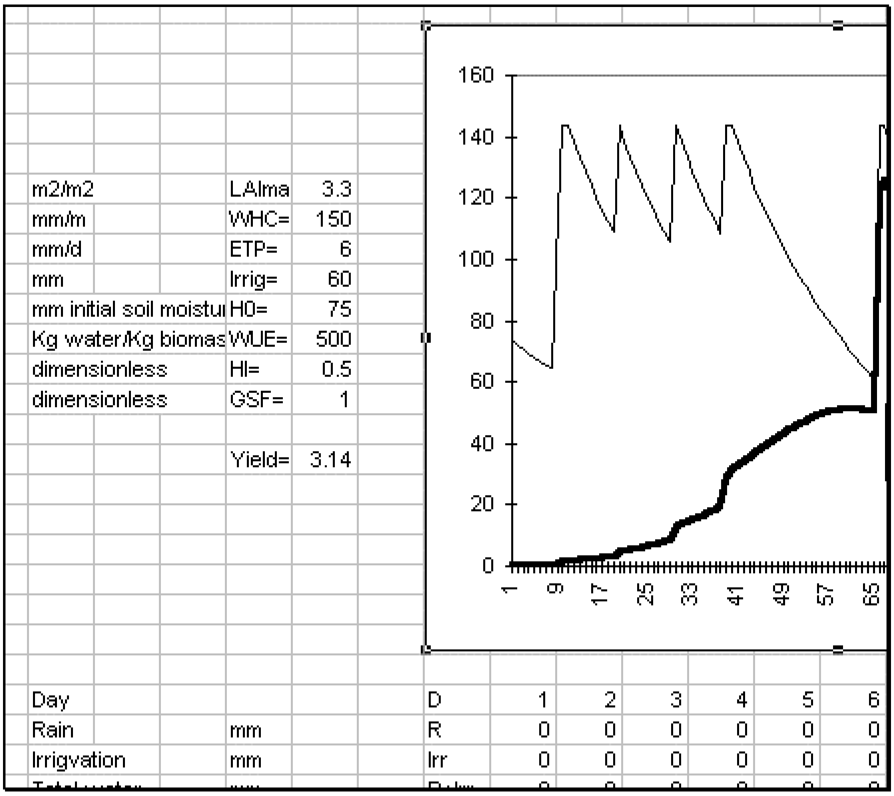
Variable	**Unit**	**First day**	**Day 2 and after**
D number		1	2
Precip. (rain)	mm	0	0
Irrigation	mm	0	0
RI = Precip. + Irrigation	mm	Sum of two previous lines	Sum of two previous lines
LAI	m^2/m^2	$\frac{LAI_{max}}{1+220\,GSF\,e^{-0.1d}}$	$\frac{LAI_{max}}{1+220\,GSF\,e^{-0.1d}}$
T_0	mm/d	ETP x LAI / LAImax	ETP x LAI / LAImax
E_0	mm/d	ETP x (1- LAI / LAImax)	ETP x (1- LAI / LAImax)
$H_d(1)$	mm	IF(H_0+RI>WHC,WHC, H_0+RI)	IF($H_{d-1}(3)$+RI>WHC,WHC, $H_{d-1}(3)$+RI)
H_r	H_r	$H_d(1)$ / WHC	$H_d(1)$ / WHC
T_a	mm/d	$T_0 \times H_r$	$T_0 \times H_r$
E_a	mm/d	$E_0 \times H_r^2$	$E_0 \times H_r^2$
$H_d(2)$	mm	$H_d(1) - T_a - E_a$	$H_d(1) - T_a - E_a$
$H_d(3)$	mm	IF($H_d(2)$<0,0,$H_d(2)$)	IF($H_d(2)$<0,0,$H_d(2)$)
Biomass growth DW_d	g(DM) $d^{-1}m^{-2}$	$\Delta W_d = T_a \times 1000 / WUE$	$\Delta W_d = T_a \times 1000 / WUE$
Accumulated biomass W_d	g/m^2	ΔW_d (previous ↑ cell)	$W_d = W_{d-1} + \Delta W_d$ sum of ← and ↑ cells
Yield	tons/Ha	W_d / 100 x HI	W_d / 100 x HI

The final part of the exercise will be a series of graphs showing the sensitivity of yield to the different parameters (in particular the GSF; do not forget negative values; pay particular attention to the behaviour between -0.05 and 0.05) and a validation of the model using soil moisture considering that the values in table 15 were actually measured.

Table 16 : “Observed” soil moistures to validate a simple soil moisture balance using a spreadsheet

Day	9	21	35	51	58	78	112
Soil moisture	119	138	121	81	71	102	93

Figure 37 : Layout of spreadsheet with variables from table 13 used to determine the effect of inputs on simple soil moisture balance.



Critically assess the model and list strong and weak points, as well as areas for improvement.

7.8 Introduction to CropSyst

7.8.1 General operation, input and output files

We will assume that the user wants to run her simulation for BINGO agricultural research station, specialising in peas.

The installation programme provided for both the DOS and the WINDOWS 95 versions does not pose any problem. If running the programme from DOS, insert the CRopSyst path in your AUTOEXEC.BAT file. If running the DOS version from WIN 3.11, create an icon for the programme and set the working directory to the directory where you keep your BINGO files.

The suffixes (extensions of file names) are fixed, but the user has the choice of the file names proper (the prefixes). Note that all files are pure ASCII (text) and they can be easily edited with a text editor. All the variables and parameters are coded using rather transparent names and, with some experience, the user will modify the files directly without using the menus.

- The user first has to define the location at which the crop will be grown (LOC file, i.e. BINGO.LOC. This is done with menu option **Location** where several station specific parameters have to be entered, for instance the geographical co-ordinates, and the prefix used for the weather file. We will use BNG as a prefix as all our weather files are called BNGyyyy.DAT, where yyyy is the year the data belong to. We will come back to the structure of the weather data files below (7.8.2).
- The next step is to define a crop (**Crop menu**). Sample files are provided for most of the crops, but it may be necessary to modify them to suit e user has to adjust the crop variables to the varieties being grown in BINGO, in particular the local BINGOVAR pea. As the crop variables are many and not always straightforward, more details about the crop parameters are listed below (7.8.3). The data will be written to file BINGOPEA.CRP
- Next comes the soil (**Soil menu**). The number of layers, their thickness, hydraulic properties etc. must be defined and stored in the soil file BINGO.SIL.
- Management data are entered in *.MGT files created under the **Management menu**. “Automatic” management can be selected for irrigation, nitrogen fertiliser application and clipping (used for hay, hedges, etc.). A series of specific events like irrigation or tillage can also be planned to take place at one or more dates, either absolute dates (25 May 1998) or relative ones (6 days after planting). Assume that we have created two management files, one with irrigation (BINGOIRR.MGT) and the other under rainfed conditions (BINGODRY.MGT). Note that maximum allowable depletion under automatic irrigation is the value below which soil moisture at the “observation” depth may not fall. Automatic irrigation is triggered every time the water content drops below the maximum allowable depletion value.
- The **Control menu** is where the details of a given simulation are assembled, either as a single year of as a rotation (BINGO.ROT). For each year, the following must be specified: crop, planting date, and management. Soil and

location do obviously not change from year to year. The simulation parameters are saved in BINGODRY.SIM and BINGOIRR.SIM. The SIM files also contain initial conditions of soil mositure and some other variables, plus of the run-time options like the type of water balance (simple or finite difference) and whether or not graphs of soil mositure, biomass etc. should be displayed while the programme runs.

Before running the simulation proper from the **File menu,** it is necessary to indicate which variables should be stored prior to a routine simulation or so that a proper model validation can be carried out. Virtually all significant variables can be selected with **File menu**, **Report format**. For daily outputs, files BINGODRY.WKD and BINGOIRR.WKD will be created. The suffix WKD belongs to an early LOTUS format which can be read by all current spreadsheets.

Finally, the user selects **Run simulation** from the **File menu**.

7.8.2 Weather data files

Weather data files are formatted according to three possible formats according to whether the evapotranspiration potential has to be determined using a simple temperature-based method, Priestley-Taylor or Penman-Monteith. The option can be defined in the **Location menu** and saved in the LOC file. Whenever the data for the requested method are not available, the programme will automatically default to the lower option.

Option 1 : simple ETP, requires daily rainfall , maximum and minimum temperature in ASCII formatted as

Day_number_(1-365) rainfall(mm) Tx(C) Tn(C) space separated, like in

```
1   0    32.1   23.4
2   10.1  34.0  26.2
```

Option 2: ETP according to Priestley-Taylor. Input data as above, plus radiation in MJ m^{-2} day^{-1}.

```
1   0    32.1   23.4 3.2
2   10.1  34.0  26.2 2.6
```

Option 3: ETP according to the Penman-Monteith approach. Inputs as above, plus maximum relative humidity (%), minimum RelHum (%) and windspeed (m/s)

```
1   0    32.1   23.4  3.2 92  82  1.5
2   10.1  34.0  26.2  2.6 95  80  2.1
```

7.8.3 The Crop input parameters

7.8.3.1 RESIDUE PARAMETERS

```
Decomposition time constant                  100 Days
Area to mass ratio of residue cover          5.000 m2/kg
Fraction of straw remaining after harvest    0.700 (0-1)
```

The decomposition time constant is the time required to decompose 63% of the residue biomass under ideal conditions

7.8.3.2 NITROGEN PARAMETERS

```
Nitrogen uptake adjustment                          1.000 (0-2)
Nitrogen availability adjustment                    1.000 (0-2)
Amount of residual nitrogen per soil layer          0.000 kg/Ha
Maximum N concentration during
                           early growth  0.009 kg N / kg
Biomass
Maximum N concentration
                   at maturity           0.027 kg N / kg
Biomass
Minimum N concentration
                   at maturity           0.009 kg N / kg
Biomass
Maximum N content of
                standing stubble         0.007 kg N / kg
Biomass
```

Nitrogen uptake adjustment is an empirical factor to adjust for nitrogen uptake per unit root length. Nitrogen availability adjustment should be left at 1. Amount of residual nitrogen per soil layer is the amount that will not be extracted from the soil layers by the model. If set to 0, all N can be used.

7.8.3.3 HARVEST-INDEX

```
Unstressed index                                    0.50 (0-1)
Sensitivity to water stress:
           during flowering                         0.60 (0-1)
           during filling                           0.30 (0-1)
Translocation factor                                  0.30 (0.0-
0.4)
```

Sensitivity to water stress during flowering and during grain filling: use 0 if stress at those stages is insignificant or can be ignored. Translocation factor is the fraction of above-ground biomass at flowering that can be traslocated to grain.

7.8.3.4 SALT TOLERANCE

```
Osmotic potential for 50% yield                    -200 J/Kg
Response slope                                      3.000
```

7.8.3.5 MORPHOLOGY

```
Maximum rooting depth                              0.80 m
Maximum leaf area index (LAI)                      12.00 m2/m2
Fraction of max. LAI at physiol. maturity          0.80 (0-1)
Specific leaf area SLA                        22.00 m2/kg leaf
Stem/leaf partition                           3.00 (1-10 m2 per
Kg)
Leaf duration (deg-days)                             800 Degree
days
Leaf duration sensitivity to water stress          2.50 (0-3)
Extinction coefficient for solar radiation         0.45 (0-1)
ET crop coefficient at full canopy                   1.10 (0.8-
1.4)
```

Note that LAI and SLA must be consistent with observed yield data and harvest index.

Fraction of maximum LAI at physiological maturity includes senescent and green leaves. SLA applies only to above-ground biomass. Extinction coefficient is defined under 2.2.3 (also see last paragraph of this section). Leaf duration sensitivity to water stress: during water stress, leaf temperature increases, and the life of leaves shortens; the parameter indicates ho sensitive leaves are in this respect.

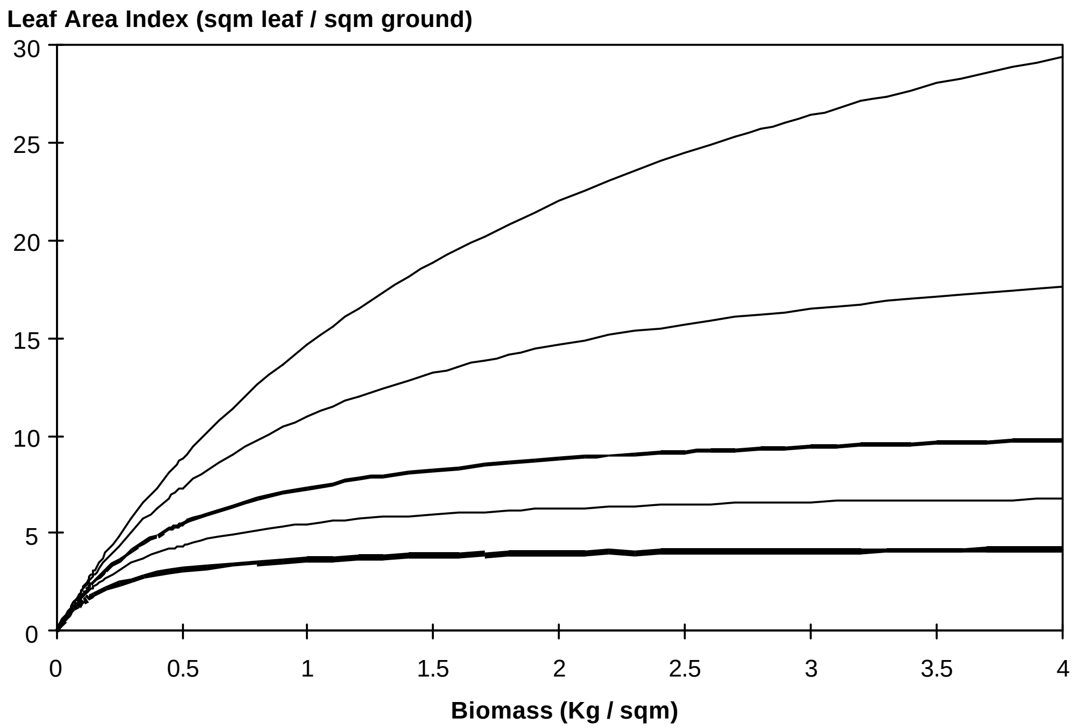
Stem/leaf partition is slightly more difficult. Claudio Stöckle explains it as follows (personal communication): the following equation represents the LAI production as a function of above ground biomass:

$$LAI = SLA * B / (1 + p\,B) \qquad (83)$$

where LAI = Leaf area index (m^2 leaf / m^2 ground), SLA = specific leaf area (m^2 leaf / kg leaf biomass), B = Aboveground biomass (Kg biomass / m^2 ground) and p = stem-leaf partitioning coefficient (m^2 ground / kg biomass).

p has the inverse units of B to that (1 / denominator) is a unitless fraction. When B is very small (near zero), the fraction is essentially one and near all biomass is "leaf biomass". As B increases, the fraction become less and less than 1, implying that less of the total aboveground biomass is leaf biomass. CropSyst uses the derivative of this equation is used to calculate the daily amount of LAI produced as a function of "today's biomass" and currently accumulated biomass.

Figure 38 : LAI as a function of biomass for various stem-leaf partitioning factors varying from 0.5 (top) to 1, 2, 3 and 5 m^2 ground / kg biomass (bottom).



The extinction coefficient is used directly to partition ET into transpiration and soil evaporation. Values vary from 0.35 (vertical leaves, or erectophile) to 0.65 for heliotropic leaves). "We have found that, from theoretical considerations, PAR extinction coefficient is around 40% larger than the coefficient for solar radiation. This concept is used to determine PAR interception" (C. Stöckle).

7.8.3.6 GROWTH PARAMETERS

```
Above ground biomass-transpiration coeff.       5.00 KPa Kg/m3
Light to above ground biomass conversion     3.00 g/MJ
At/Pt ratio limit to leaf area growth        0.95 (0-1)
At/Pt ratio limit to root growth             0.50 (0-1)
Thermal time to cease temperature limitation 0      degC-days
Maximum water uptake                              10.0 mm/day
Critical Leaf water potential (negative!)    -1000  J/kg
Wilting leaf water potential  (negative!)    -1600  J/kg
```

The above ground biomass-transpiration coefficient is the above-ground biomass production per meter of transpiration under given conditions of atmospheric vapour pressure deficit (3.0-9.0 ((Kg/m^2) . KPa)/m). It is a measure of water-use efficiency (WUE, 2.2.4) and varies from 3.5 to 6 in C3 species to 6 to 9 in C4 plants.

Light to above ground biomass conversion (Eff_c) is also C3/C4 dependent. Typical values are 2 to 3 for C3 and 3.5 to 4 for C4 plants. An approximation of light to above-ground conversion can be derived from the observed yield and radiation data (see 3.1.1).

At/Pt (actual to potential transpiration) measures water stress. Below the input value (0.95 in the example) , leaves stop developing, which affects the stem/leaf ratio.

Maximum water uptake is about KCr * PET at the time of full canopy development. Critical leaf water potential is the leaf (and soil!) potential just before stomatal closure due to water deficit. The wilting potential corresponds to the point when plants can no longer extract water from the soil.

7.8.3.7 THERMAL TIME REQUIREMENTS

```
Emergence                                              100  degC-
days
Peak LAI                                               1500 degC-
days
Begin flowering                                        1000 degC-
days
Begin grain filling                                    1200 degC-
days
Physiological maturity                                 1600 degC-
days
Base temperature                                      8.0  degC
Cut-off temperature                                    30.0 degC
Temperature below
    which growth rate is reduced                      18.0 degC
Phenologic sensitivity to water stress                1.00 (0-3)
```

DegC-days are accumulated from planting. Thermal time does not accumulate below the base temperature or above the cut-off temperature. Phenologic sensitivity to water stress indicates how cycle length reacts to water stress (i.e. increased SDD; use 0 is cycle lengthens).

7.8.3.8 PHOTOPERIODIC BEHAVIOUR

There is a critical day length Dif below which long day plants do not flower and above which short day plants do not flower. In addition, there is a day length above which the response of long-day plants is maximum (Dins>Dif in long-day plants) and below which the response of short-day plants is maximum (Dins<Dif in short-day plants). In practice, day-length interacts with thermal time.

```
for insensitivity (Dins)                           0.00   hours
to inhibit flowering (Dif)                         0.00   hours
```

7.8.4 Other input parameters

No special comments are given for the other input parameters. The user should run the **Validation** option under the **Control menu** to ensure the absence of some blatant contradictions in the data.

7.8.5 A real world example

7.8.5.1 Phenology and yields

The following files are provided by Suwon Agricultural Research Station (Korean Republic, 37.27 °N, 126.98 °E, 37 m a.s.l.) for the years 1992 to 1997.

Yield and phenology data are given by tables 17 to 19.

Table 17 : "Ilpoom" paddy phenology and yield at Suwon Agricultural Research Station. The days are expressed as day numbers (1-365) and the yield (Kg/Ha) is rough yield, i.e. grain with glumes. To convert to grain with 14% residual moisture, multiply by 0.8.

	Planting	Trans-planting	Heading	Harvest	Yield
1992	102	146	231	276	6560
1993	101	145	235	280	6940
1994	101	145	228	281	7560
1995	101	145	230	284	6830
1996	102	146	229	282	8090
1997	101	145	228	283	8090

Table 18 : Winter barley phenology and yield at Suwon Agricultural Research Station. The days are day numbers and the yields (Kg/Ha) corresponds to 14% moisture.

	Planting	Heading	Harvest	Yield
1992	279	120	158	4850
1993	278	126	164	5250
1994	278	122	161	5440
1995	278	126	163	6080
1996	278	129	167	6170
1997	278	122	163	4200

Table 19 : Winter wheat phenology and yield at Suwon Agricultural Research Station. The days are day numbers and yield (Kg/Ha) correspond to 14% moisture content.

	Planting	Heading	Harvest	Yield
1992	279	131	169	4550
1993	278	135	173	4530
1994	278	132	171	5130
1995	278	137	172	5920
1996	279	137	176	5860
1997	278	132	173	5390

7.8.5.2 Simulating Paddy

Paddy was chosen for this first exercise as the crop is irrigated. It provides a way to illustrate the automatic irrigation feature of CropSyst. The following input files are provided:

SUWON.LOC

SUW1993.DAT to SUW1997.DAT, with option_2 weather data

PADDY.CRP, with data derived from the information available for SUWON, as well as generic rice ecophysiology from Yoshida (1981). Leaf duration in degree-days varies significantly for early leaves (200 Degree-Days) to mid season (800 Degree-Days) and late season leaves (1500 degree days). A value of 800 was retained.

SUWON.SIL: no local soil information is available. A heavy soil with poor drainage has been selected.

SUWON.MGT : tillage one month before planting, automatic irrigation and automatic nitrogen

SUWON.SIM runs a simulation starting on 1 January 1992 until 31 December 1997 (rotation data in SUWON.ROT, created by SUWON SIM)

SUWON.RPT the report format selected for this test run.

The results, as concerns paddy yields are given in table 20 below.

The students will discuss the differences between estimated grain DM yields and observed ones. Where are the differences largest? Try to understand why by carrying out a sensitivity analysis of estimated DM as a function of main crop parameters (7.8.3.3; 7.8.3.5 to 7.8.3.7).

Table 20 : Estimated and observed Yield of Ilpoom paddy rice at Suwon.

	Estimated	Observed Yield

		Rough Kg / Ha	14% H_2O ton / Ha	Dry matter ton / Ha
1992	3.07	6560	5.25	4.51
1993	5.83	6940	5.52	4.74
1994	4.97	7560	6.05	5.20
1995	5.43	6830	5.46	4.70
1996	4.51	8090	6.47	5.56
1997	5.23	8090	6.47	5.56

Appendix : A quick overview of SI units

As far as possible, this document follows the recommended system of SI units (Système International d'unités in all languages). The SI is a redefinition of the MKS (meter-kilogram-second), and its seven base units are the ampere, candela, kelvin, kilogram, meter, mole and second (Jerrard and McNeill, 1986).

Land area

Acre = 0.40467 hectares. A hectare is a square of 100 m x 100 m (10^4 m^2), equivalent to 2.47 acres. There are 100 Hectares in a square km.

Pressure (tension, suction)

A pressure is a force exerted on an area. The SI unit is the pascal (Pa) which is equivalent to 1 newton per square meter (1 Pa = 1 N m^{-2}), or one joule per cubic meter.

$$pascal = \frac{newton}{m^2} = \frac{newton \times m}{m^3}$$

$$= \frac{joule}{m^3} = \frac{0.001 joule}{kg} \qquad (84)$$

The newton (N) is the force required to accelerate 1 kg by one meter per second per second (1 N = 1 Kg m s^{-2}). Much work on plant water potential still uses the bar which is equivalent to 10^5 N m^{-2} so that 1 bar is 100 J Kg^{-1} ; 1 millibar is 10^2 pascal, or 1 hectopascal (hPa).

On the other hand, a pressure is an energy per volume, as shown above: 1 J kg^{-1} is 1000 Pa or 1 kPa or 100 bar.

Work, energy, power, radiation and evaporation

The joule is the practical unit of work; it is equal to a force of one newton (N) acting over a distance of 1 meter, thus 1 J = 1 N m. Since energy is "stored" work, the units used for energy and work are the same.

The joule has superseded the still ubiquitous calorie, a cgs unit, representing the quantity of heat required to raise one gram of water through one degree Celsius. One calorie is 4.18 Joule and the specific heat of water at 15°C is 4185.5 joule $^{-1}$. .

The watt (W) is the practical SI unit of power. It is the power dissipated when 1 joule is expended in 1 second (W = J/s). 1 J = 2.78 10^{-7} kWh and 1 W = 0.2388 cal s^{-1}.

Radiation (solar, incoming short-wave, outgoing long-wave, net radiation, etc.) is now mostly expressed in J m^{-2} d^{-1}. Alternative expressions are W m^{-2}.

For instance, Stefan's law, which states that the energy emitted by a full radiator is proportional to the fourth power of its absolute temperature:

$$B = s T^4 \qquad (85)$$

where B is in W m^{-2} , the Stefan-Boltzman constant $\sigma = 5.57\ 10^{-8}$ W m^{-2} K^{-4} and the absolute temperature is T (°K).

The solar "constant", i.e. the amount of solar energy which reaches the upper atmosphere is now known to be variable (thanks to the measurements carried out by satellites - ERB (Earth Radiation Budget, 1978), ERBS (Solar Maximum Mission satellite, 1980), NOOA9 in 1984, and NOOA10 in 1986 - and close to 1366 W m^{-2} (which is approximately 2 cal cm^{-2} min^{-1}).

The solar constant amounts to about 400 TJ $hectare^{-1}$ $year^{-1}$ at the equator. Due to a number of factors (rotation of the earth and alternating light and darkness periods, albedo of the earth, absorption in the atmosphere, clouds etc.) only about 50 TJ $hectare^{-1}$ $year^{-1}$ is actually available at plant level.

In crop modelling, energy absorbed or emitted by a surface is often expressed in mm of water, i.e. the amount of energy required to evaporate (condense) 1 mm of water spread over 1 square meter (1 litre of water per square m). L, the latent heat of vaporisation of water[76] is 2.45 10^6 J kg^{-1} . The product of L and E, the rate of water loss from a surface (kg m^{-2} d^{-1}), LE, is thus the evaporative heat loss (J m^{-2} d^{-1}) .

Physiologists in discussing metabolism use the large calorie or Kilocalorie which is in fact 1000 calories. For example, a dish listing its energy content as 128 Kcal or 537 KJ, will release 537000 J when burnt in a bomb calorimeter.

Biomass energy content is usually set at 15 GJ per ton at 20% moisture.

Others

Atmospheric concentrations of CO_2 are often expressed in ppmv, equivalent to parts per million in volume, or millilitres per cubic meter. Since one mole (M g) occupies 22.4 litres under standard conditions

$$1\ ppmv = \frac{M}{22.4}\, mg/m^3 \qquad (86)$$

the current CO_2 concentration of 360 ppmv amounts to 360 x 44 / 22.4 ≈ 700 mg per m^3.

[76] The latent heat varies with temperature. It is 2.46 MJ Kg^{-1} at 10°C and 2.42 MJ Kg^{-1} at 30°C

Multiples

The common multiple-prefixes are well known (milli, kilo, etc.). The list below indicates the larger multiples with their symbols

Table 21 : Multiplier prefixes for scientific units in the SI system.

Exponent	Multiple	Prefix	Symbol	Fraction	Prefix	Symbol
0	10^0 or 1	-	-	10^0 or 1	-	
1	10	deca	da	1/10	deci	d
2	100	hecto	h	1/100	centi	c
3	10^3	kilo	K or k	10^{-3}	milli	m
6	10^6	mega	M	10^{-6}	micro	µ
9	10^9	giga	G	10^{-9}	nano	n
12	10^{12}	tera	T	10^{-12}	pico	p
15	10^{15}	peta	P	10^{-15}	femto	f
18	10^{18}	exa	E	10^{-18}	atto	a

8. Bibliographic references

Abbaspour, K.C., 1994. Bayesian risk methodology for crop insurance decisions. Agric Forest Meteorol. 71:297-314.

Abdellaoui,A., F. Becker, E. Olory-Hechinger, 1986. Use of METEOSAT for mapping thermal inertia and evapotranspiration over a limited region of Mali. J. climate appl. Meteorol., 25(11):1489-1506.

Acock, B., 1994. Model of Photosynthesis Accounting for Leaf Anatomy. Proceedings of 24th Annual Workshop on Crop Simulation. March 15-18, 1994. Raleigh, NC. 18 pp.

Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A.McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote and L.H.Allen, Jr., 1990. Global climate change and US agriculture. Nature, 345:219-224.

Adiku, S.G.K., R.D.Braddock and C.W. Rose, 1996. Modelling the effect of varying soil water on root growth dynamics of annual crops. Plant and Soil, 185(1):125-135.

Adler,R.F. and A.J. Negri. 1988. A satellite infrared technique to estimate tropical convective and stratiform rainfall. J. appl. Meteorol., 27: 30-51.

Aggarwal, P.K., 1995. Uncertainties in crop, soil and weather inputs used in growth models: implications for simulated outputs and their applications. Agricultural Systems, 48(3):361-384.

Allen, L.H., J.T. Baker and K.J. Boote, 1996. The CO_2 fertilization effects: higer carbohydrate production and retention as biomass and seed yield. Pp 65-100 *in*: F. Bazzaz and W. Sombroek (Eds.), 1996. Global climate change and agriculturalproduction. Direct and indirect effects of changing hydrological, pedological and plant physiological processes. FAO and John Wiley & Sons, 345 pp.

Ashenfelter, O., D. Ashmore and R. Lalonde, 1995. Bordeaux Wine vintage quality and the weather. Change, 8(4): 7-14.

Asseng S., C.Richter and G. Wessolek, 1997. Modelling root growth of wheat as the linkage between crop and soil. Plant and Soil, 190(2):267-277.

Bachelet, D., and C.A. Gay, 1993. The impacts of climate change on rice yield: a comparison of four model performances. Ecol. Mod. 65:71-93.

Badini, O., C.O. Stöckle and E.H. Franz, 1997. Application of crop simulation modeling and GIS to agroclimatic assessment in Burkina Faso. Agric. Ecosystems & Environment, 64:233-244.

Baker, R.H.A., 1996. Developing a European pest risk mapping system. Bulletin OEPP, 26(3-4):485- 494.

Bastiaanssen,W.G.M., T. Van der Wal and T.N.M. Visser, 1996. Diagnosis of regional evaporation by remote sensing to support irrigation performance assessment. Irrigation and Drainage Systems, 10: 1-23.

Bazlen, E., J. Schlaghecken and H.J. Wiebe, 1996. Harvest forecasting of cauliflower in the Pfalz. Gemüse München, 32(8): 498-501.

Bégué, A., J.F. Desprat, J. Imbernon and F. Baret. 1991. Radiation use efficiency of pearl millet in the Sahelian zone. Agric. For. Meteorol., 56(1-2):93-110.

Bellon,A., and G.L. Austin, 1986. On the relative accuracy of satellite and raingauge rainfall measurements over middle latitudes during daylight hours. J. climate and appl. Meteorol., 25: 1712-1724.

Ben Mechlia, N., and J.J. Carroll, 1989. Agroclimatic modeling for the simulation of phenology, yield and quality of crop production. Int. J. Biometeorol., 33(1):36-51.

Besselat, B., and P. Cour, 1997. Early harvest forecasting: report and prospects for using a new tool based on atmospheric pollen analysis. Pp. 145-152 *in*: EU/FAO, 1997.

Blaak, G., 1997. Crop forecasting in oil palm. Pp. 243-246 *in*: EU/FAO, 1997.

Bogaert, P., P. Mahau and F. Beckers, 1995. The spatial interpolation of agro-climatic data. Cokriging software and source code. User's manual B. Diskette ver.1.0b. FAO Agrometeorology Working Paper series N. 12, FAO Rome, 60 pp.

Boote, K.J., J.W. Jones and N.B. Pickering, 1996. Potential uses and limitations of crop models. Agronomy Journal, 88(5):704-716.

Booth,T.H., J.A. Stein, H.A. Nix and M.F. Hutchinson, 1989. Mapping regions climatically suitable for particular species: an example using Africa. Forest ecology and management, 28:19-31.

Bouman, B.A.M.,1994. A framework to deal with uncertainty in soil and management parameters in crop yield simulation: a case study for rice. Agricultural Systems, 46(1):1-17.

Bouman, B.A.M, 1995. Crop modelling and remote sensing for yield prediction. Netherlands J. Agric. Sci., 43:143-161.

Bouman, B.A.M., H. Van Keulen and H.H. van Laar, 1995. The “school of de Wit” crop growth simulation models, pp. 83- 89 *in*: Dallemand and Vossen, 1995.

Bouman B.A.M., H. Van Keulen, HH van Laar HH, R. Rabbinge, H. Van Keulen, 1996. The 'School of de Wit' crop growth simulation models: a pedigree and historical overview. Agricultural-Systems, 52(2-3):171-198.

Cabelguenne, M., P. Debaeke, J. Puech and N. Bosc, 1997. Real time irrigation management using the EPIC-PHASE model and weather forecasts. Agric. Water Management, 32(3):227-237.

Cane, M.A., Eshel, G., and Buckland, R.W., 1994. Forecasting Zimbabwean maize yields using eastern equatorial Pacific sea-surface temperature. Nature vol. 370, pp. 204-205.

Cao, W. And D.N. Moss, 1997. Modelling phasic development in wheat: a conceptual integration of physiological components. J. Agric. Science, 129(2):163-172.

Chang, J.H., 1974. Climate and Agriculture, an ecological Survey. Aldine Publ. Company, Chicago. 304 pp.

Chapman, S.C., G.L. Hammer and H. Meinke, 1993. A sunflower simulation model: I. Model development. Agronomy Journal, 85(3):725-735.

Chou TienYin, Chen HuiYen, Chou T.Y., Chen H.Y., 1995 . The application of a decision support system for agricultural land management. J. Agric. and Forestry, 44(3):75-89.

Choudhury, B.J., N.U. Ahmed, S.B. Idso, R.J. Reginato and C.S.T Daughtry, 1994. Relations between evaporation coefficients and vegetation indices studied by model simulations. Remote Sensing of Environment, 50(1):1-17

Cleevers, J.G.P.W., and H.J.C. van Leeuwen, 1997. Linking remotely sensed information with crop growth models for yield prediction - a case study for sugarbeet. Pp. 411-424 *in*: EU/FAO, 1997.

Clevers, J.G.P.W., 1989. The application of a weighted infra-red vegetation index for estimating leaf area index by correcting for soil moisture. Remote Sensing of Environment, 29:25-37.

Clevers, J.G.P.W., 1997. A simplified approach for yield prediction of sugar beet based on optical remote sensing data. Remote Sensing of Environment, 61:221-228.

Clevers, J.G.P.W., C. Buker, H.J.C van Leeuwen and B.A.M. Bouman, 1994. A framework for monitoring crop growth by combining directional and spectral remote sensing information. Remote Sensing of Environment, 50:161-170.

Clevers, J.G.P.W. and H.J.C. van Leeuwen, 1996. Combined use of optical and micro wave remote sensing data for crop growth monitoring. Remote Sensing of Environment, 56:42-51.

Corbett,J.D., 1993. Dynamic crop environment classification using interpolated climate surfaces. Proc. Second International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling, Breckinridge, Colorado, USA, 26-30 Sept. 1993. 12 pp.

Cox, P.G., 1990. The cost of harvest delay in cotton. Proc. Int. symposium on climatic risk in crop production: models and management in the semi-arid tropics and subtropics, Brisbane ,Australia , 2-6 july 1990. CSRIO, Brisbane, Australia. Pp 66-67.

CROPCAST, 1994. Commodity forecasting, food for thought. GIS Europe, 3(6):26-28.

D' Antuono, L.F., and F. Rossini, 1995. Risk of frost damage during linseed (Linum usitatissimum L.) emergence: regional scale assessment in central Italy. Rivista di Agronomia, 29(4):550-556.

Dallemand, J.F., and P. Vossen (Eds), 1995. Agrometeorological models, theory and applications in the MARS project. Proceedings of the workshop for central and eastern Europe on agrometeorological models, theory and applications in the MARS project. Ispra, Italy, 21-25 Nov. 1994. Office for official publications of the EC, EUR 16008, Luxembourg. 246 pp.

de Jager, J.M., and A. Singels, 1990. Economic quantification of climatic risk in maize production using a crop model. Proc. Int. symposium on climatic risk in crop production: models and management in the semi-arid tropics and subtropics, Brisbane ,Australia , 2-6 july 1990. CSRIO, Brisbane, Australia. Pp 68-69.

de Wit, C.T., J. Goudriaan, H.H. van Laar, F.W.T. Penning de Vries, R. Rabbinge, H. van Keulen, W. Louwerse, L. Sibma and C. de Jonge, 1978. Simulation of assimilation, respiration and transpiration of crops. Pudoc, Wageningen, 141 pp.

Decker, W.L., 1997. Risk analysis in biometeorological applications. J. Int. Soc. Biometeorol., 40(1): 24-25.

DeJong, T.M., Y.L. Grossman, S.F. Vosburg, L.S. Pace LS, R. Habib and P. Blaise, 1996. Peach: a user friendly peach tree growth and yield simulation model for research and education. Proc. 4th internat. symposium on computer modelling in fruit research and orchard management, R. Habib (ed.), Avignon, France, 4 8 September 1995. Acta Horticulturae, 416:199-206..

Desclée, E., 1991. Rôle et influence de l'action réciproque des stades phénologiques majeurs et du climat sur la qualité du millésime en Gironde. Mémoire pour l'obtention du diplôme d'Ingenieur industriel en agriculture, Ath, Belgium. 55+45 pp.

Desjardins, R.L., P. Rochette, E Pattey and D. Stewart, 1997. Assessing crop conditions and estimating crop growth from CO2 flux measurements. Pp. 153-164 *in*: EU/FAO, 1997.

Dingkuhn, M., 1995. Climatic determinants of irrigated rice performance in the Sahel - III. Characterizing environments by simulating crop phenology. Agricultural Systems, 48(4):435-456.

Distefano, J.J., A.R. Stubberud and I.J. Williams, 1967. Feedback and control systems. Schaum’s outline series, McGraw-Hill, 371 pp.

Doraiswamy, P.C., and P.W. Cook, 1995. Spring wheat yield assessment using NOAA-AVHRR data. Canadian Journal of Remote Sensing, 21:43-51.

Due,G., M. Morris, S. Pattison and B. G. Coombe, 1993. Modelling grapevine phenology against weather considerations based on a large data set. Agric. forest meteorol., 65(1-2): 91-106.

Dugdale,G., V.D McDougall and J.R Milford, 1991. Rainfall estimates in the Sahel from cold cloud statistics: acuracy and limitations of operational systems. Proceedings of the

International workshop on the Soil water balance in the Sudano-sahelian zone, Niamey, Niger, 18 - 23 february 1991. IAHS publicaton no. 199, pp. 65-74.

Easterling, W.E., N.J. Rosenberg, M.S. McKenney, C.A. Jones, P.T. Dyke and J.R. Williams, 1992. Preparing the erosion productivity impact calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO2. Agric. Forest Meteorol. 59(1-2):17-34.

FAO, 1995. Standardisation and Harmonisation of databases and software for agro-climatic applications. Proc. of an expert meeting held in FAO, Rome, 28 Nov. - 3 Dec. 1993. FAO Agrometeorology series working paper N. 13, 313 pages.

FAO/EU, 1997. Crop yield forecasting methods. Proceedings of a seminar organised from 24 to 27 October 1994 in Villefranche-sur-Mer by the EU (DG VI, JRC Ispra and Eurostat) and FAO. Office for Official Publications of the European Communities, 438 pages.

Fouss, J.L. and G.H. Willis, 1994. Integrated Water-fertilizer-Pest Management for Environmentally Sound Crop Production. Environmentally sound agriculture: Proceedings of the Second Conference, 20-22 April 1994, Orlando, Florida, pp 53-61.

Fredrick, F., and R. Lemeur, 1997. Chlorophyll fluorescence as a tool for rapid assessments of leaf CO_2 assimilation rates: its aplication in plant growth modeling of greenhouse crops. Pp. 461-474 *in*: EU/FAO, 1997.

Frère, M. And G. Popov, 1979. Agrometeorological crop monitoring and forecasting. FAO Plant production and Protection Paper N. 17, FAO, Rome. 64 pp.

Göbel, W., 1995. Adding stochasticity to GIS : stochastic regional models. Pp 225-242 *in* : FAO, 1995.

Gommes, R., 1983. Pocket computers in agrometeorology. FAO Plant production and protection paper N. 45, FAO, Rome, 140 pages.

Gommes, R., 1985. The potential of inexpensive portable computers in agrometeorology. WMO Bulletin, 34(1):17-22.

Gommes, R., 1995. A note on FAO Early Warning Software[77]. In: FAO, 1995: 111-126.

Gommes, R., 1996. Crops, weather and satellites: interfacing in the jungle. Proc. of COST 77 workshop on The Use of Remote Sensing Techniques in Agricultural Meteorology Practice. Budapest, 19-20 Sept. 1995. Pp. 89-96 of EUR 16924 EN, EU Directorate-General Science, research and Development, Luxembourg: Office for Official Publications of the European Communities, 289 pages.

Gommes, R., 1998a. Provisional list of variables used for crop modelling purposes by the Space Applications Institute/MARS, pp. 323-326, in: D. Rijks, J.M. terres and P. Vossen (Eds), 1998.

Gommes, R., 1998b. Agrometeorological Crop Yield Forecasting. Proc. Int. Symp. “Agricultural Ststistics 2000”, Washington, February 1998. In press.

Gommes, R., and Th. Nègre, 1990. The role of agrometeorology in the field of natural disasters . Proc. of IV Congreso Interamericano y II Colombiano de Meteorologia, Bogota, Colombia, 17-21 September 1990: SoColMet, Bogota. An expanded version was published as “The role of agrometeorology in the alleviation of natural disasters” in *FAO Agrometeorology Series Working Papers* N. 2, 22 pp.

Gommes, R., and L. See, 1993. FAOMET, Agrometeorological Crop Forecasting Tools (manual of computer program) . FAO Agrometeorology Series Working Papers N. 8 : 59 pages + 1 diskette.

[77] An updated version (December 1996) with the newer software was included in the proceedings of a training workshop organised by the Fondation Universitaire Luxembourgeoise in Arlon (Belgium) in September 1996.

Gommes, R., and P. Hoefsloot, 1998. Gaps in maps, estimation of missing data in agricultural statistics maps. Proc. of the the COST (EU Committee on Science and Technology) meeting in Volterra (Italy, Sep. 1997) on the Spatial Interpolation of Climatic and Meteorological Data. In press.

Gommes, R., F.L. Snijders and J.Q. Rijks, 1998. The FAO crop forecasting philosophy in national food security warning systems pp. 123-130, in: D. Rijks, J.M. terres and P. Vossen (Eds), 1998.

Guillot, B., 1995. Satellite et précipitations. Constraintes techniques et physiques, analyse de quelques méthodes, problèmes de recherche et de validation. Satellite and precipitations. Technical and physical restrictions, analysis of some methods, research and validation problems. Veille Climatique Satellitaire, ORSTOM, 55:27-58.

Hashmi,M.A., L.A. Garcia and D.G. Fontane, 1995. Spatial estimation of regional crop evapotranspiration. Transaction ASAE, 38(5):1345-1351.

Haskett, J.D., Y.A. Pachepsky and B. Acock,. 1997. Increase of CO2 and climate change effects on Iowa soybean yield, simulated using GLYCIM. Agronomy Journal, 89(2):167-176.

Haxeltine, A., and I.C. Prentice, 1996a. BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability and competition among plant functional types. Global Biogeochemical Cycles. 10: 693-709.

Haxeltine, A., I. C. Prentice and I. D. Cresswell, 1996b. A coupled carbon and water flux model to predict vegetation structure. Journal of Vegetation Science, 7: 651-666.

Herman, A., V.B. Kumar. P.A. Arkin and J.V. Kousky, 1997. Objectively determined 10-day African rainfal estimates for famine early warning systems. Int. J. Remote Sensing, 18(10):2147-2159.

Hess, T., 1996. A microcomputer scheduling program for supplementary irrigation. Computers and Electronics in Agriculture, 15(3)233-243.

Hijmans R.J., I.M. Guiking-Lens, C.A. van Diepen, 1994. WOFOST 6.0: User's guide for the WOFOST 6.0 crop growth simulation model. Wageningen, DLO Winand Staring Centre, Technical Document 12. 1994-146 pp.-48 figs.- 78 ref. ISSN 0928-0944

Hillel, D., 1971. Soil and water, physical principles. Academic Press, New-York, 288 pages.

Hoefsloot, P. 1996. IGT manual, Ver. 1.10. Working paper series N. 5. SADC/FAO, GCPS/RAF/296/NET, Harare, 53 pp. Programme and manual are retrievable from FTP://FTP.FAO.ORG/SDRN/IGT.

Holzmann, A., and P. Niemann, 1988. Prediction of Viola arvensis infestations based on parameters of population dynamics.Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz, Sonderheft 11, pp. 91-96.

Hoogenboom, G., J.W. Jones, L.A. Hunt, P.K. Thornton and G.Y. Tsuji, 1994 . An integrated decision support system for crop model applications. American Society of Agricultural Engineers paper No. 943025, 23 pp.

Hough, M., 1998. The incorporation of radar with raingauge observations. Pp 247-254 in: D. Rijks, J.M. terres and P. Vossen (Eds), 1998.

Hough, M.N., R. Gommes, T. Keane and D. Rijks, 1998. Input weather data, pp. 31-55, in: D. Rijks, J.M. terres and P. Vossen (Eds), 1998.

Hudson, G., and H. Wackernagel, 1994. Mapping temperature using kriging with external drift: theory and an example from Scotland. Internat. J. Climatology, 14:77-91.

Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). Remote Sensing of Environment, 25:295-309.

Hutchinson, M.F., 1991. The application of thin plate smoothing splines to continent-wide data assimilation. *In* : J.D. Jasper (ed), Data assimilation systems, BMRC research report N. 27, Bureau of meteorology, Melbourne, pp. 104-113

Hutchinson, M.F., 1994. Stochastic space-time weather models from ground-based data. Agric. Forest Meteorol., 73:237-264.

Hutchinson, M.F., and J.D. Corbett, 1995. Spatial interpolation of climate data using thin plate smoothing splines. Pp 211-224 *in* : FAO, 1995.

Jackson, R.D., S.B. Idso, R.J. Reginato and P.J. Pinter, 1981. Canopy temperature as a crop stress indicator. Water Resources Res., 17:1133-1138.

Jayet, P.A., and J. Mathurin, 1997. Wine market regulation and bargaining within the European Union. Bulletin l'OIV (France), 70:(795-796):419-444..

Jerrard, H.G., and D.B. McNeill, 1986. A dictionary of scientifc units, including dimensionless numbers and scales. Chapman and Hall, London and New York. 222 pp.

Jones, C.A., and J.R. Kiniry. 1986. CERES-Maize: A simulation model of maize growth and development.Texas A&M University Press, College Station, Texas.

Jones, C.A., W.L. Bland, J.T. Ritchie and J.R. Williams, 1991 . Simulation of root growth. Agronomy, 31:91- 123.

Jones, P.G., P.K. Thornton and P. Hill, 1997. Agro-meteorological models: crop growth and stress indices. Pp. 53-65 *in*: EU/FAO, 1997.

Jordan, J.A. (Jr.) and L.J. Shieh, 1981. Information science technology and agricultural management. Pp 166-178 in A. Weiss (ed) , 1981.

Kamel, A., K. Schroeder, J. Sticklen, A. Rafea, A. Salah, U. Schulthess, R. Ward and J. Ritchie, 1995. Integrated wheat crop management based on generic task knowledge-based systems and CERES numerical simulation. AI Applications, 9(1):17-28.

Karim, Z., S.G. Hussain, M. Ahmed M and L. Erda, 1996. Assessing impacts of climatic variations on foodgrain production in Bangladesh. Water, Air, and Soil Pollution, 92(1-2): 53-62.

Keane, T., 1998. Analysis of Dublin Airport radar rainfall amounts, pp. 255-258 *in* : D. Rijks, J.M. Terres and P. Vossen (Eds), 1998.

Kiniry, J.R., J.R. Williams. P.W. Gassman and P. Debaeke, 1992. A general, process-oriented model for two competing plant species. Transactions of the ASAE., 35(3):801-810.

Klein, G.H., 1997. Tools for detection of hidden dynamics in seasonal development during phenologically opaque periods. Internat. J. Biometeorol., 40(3):123-127.

Kleinhenz, B., and V.Gutsche, 1996. Validation and utilization of the forecasting models SIMCERC and SIMPHYT in plant protection advice. Statens Planteavlsforsog report No. 15, pp. 49-58, Denmark.

Kogan, F., 1997. Global drought watch from space. Bul. Am. Met. Soc., 78(4):621-636.

Kogan, F.N., 1995. Droughts in the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. Bul. Am. Met. Soc., 76(5):655-668.

Körner, Ch., 1995. Towards a better experimental basis for upscaling plant responses to elevated CO_2 and climate warming. Plant, Cell and Envir., 18:1001-1010.

Kramer, P.J., 1983. Water relations of plants. Academic Press, New-York, 489 pages.

Kropff, M.J., C.J.T. Spitters, B.J. Schneiders, W. Joenje and W. de Groot W, 1992. An eco-physiological model for interspecific competition, applied to the influence of Chenopodium album L. on sugarbeet. Weed Research Oxford, 32(6):451-463.

Kumar, L. and J.L Monteith. 1981. Remote sensing of crop growth, In: M. Smith, Ed., Plants and daylight spectrum. Academic press, London. pp. 133-144.

Kustas, W.P., and J.M. Norman, 1996. Use of remote sensing for evapotranspiration monitoring over land surfaces. Hydrological sciences, 41(4): 495-516.

Laguette, S., 1995. Combined use of NOAA-AVHRR indices and agrometeorological models for yield forecasting, pp. 197-208 *in*: Dallemand and Vossen, 1995.

Laguette, S., 1997. Utilisation des données NOAA-AVHRR pour le suivi du blé à l'échelle de l'Europe. Thèse présentée pour l'obtention du grade de docteur de l'ENGREF le 28 1997, Ecole Nationale du Génie Rural, des Eaux et des Forêts, Montpellier. 167 pp.

Laguette, S., A. Vidal and P. Vossen,1998. Using NOAA_AVHRR data to forecast yields at the European scale, pp. 131-146 *in*: D. Rijks, J.M. terres and P. Vossen (Eds), 1998.

Landau,S., and and V. Barnett, 1996. A comparison of methods for climate data interpolation, in the context of yield predictions from winter wheat simulation models. Aspects of Applied Biology, 46:13-22.

Lauciani, E., and A. Ponticiello, 1993. Photosynthetically active radiation (PAR): empirical determination and literature survey. FAO, Rome. Agrometeorology Series Working paper N.7, 85 pp.

Laughlin, G.P., M.F. Hutchinson and B.G. Mackey, 1993. An intuitive approach to analysing small point-source spatial data sets. Internat. J. geographical information systems, 7(1):21-38.

Le Toan, T., H. Laur, E. Mougin and A Lopes,1989. Multitemporal and dual polarisation observatons of agricultural vegetation covers by X-band SAR images. IEEE transactions on geoscience and remote sensing, November 1989, 27(6):709-718.

Li, Zhanqing, H.W. Barker and L. Moreau, 1995. The variable effect of clouds on atmospheric absorption of solar radiation. Nature, 376: 486-490.

Lieth, H. 1972. Modelling the primary productivity of the world. Nature and Resources, UNESCO, VIII, 2:5-10.

Lieth, H. 1973. Primary production: terrestrial ecosystems, Human Ecology, 1(4)303-332.

Lieth, H. 1975. Modelling the primary productivity of the world, Primary productivity of the biosphere, Springer-Verlag, Berlin. pp. 237-263.

Lourens,U.W., C.M. van Sandwyk, J.M. de Jager and J. Van den Berg, 1995. Accuracy of an empirical model for estimating daily irradiance in South Africa from METEOSAT imagery. Agric. Forest Meteorol., 74: 75-86.

Lyamchai, C.J., T.J. Gillespie and D.M. Brown, 1997. Estimating maize yield in northern Tanzania by adapting SIMCOY, a temperate-zone simulation model. Agric. Forest Meteorol., 85(1-2):75-86.: 1 2, 75 86, 26 ref.

MacKerron, D.K.L., 1992. Agrometeorological aspects of forecasting yields of potato within the E.C.. *EUR 13909 EN, Official Publ. EC*, Luxembourg, pp. 247.

Mahmood, R., 1997. Impacts of air temperature variations on the boro rice phenology in Bangladesh: implications for irrigation requirements. Agric. For. Meteorol., 84(3-4):233-247.

Maidment, D.R., 1992. Handbook of hydrology. McGraw Hill. Pages numbered by chapters.

Maracchi, G., and M.V.K. Sivakumar, 1995. Coordeination and harmonization of databases and software for agroclimatic applications : discussion document. Pp. 11-38 *in* : FAO, 1995.

Marcus, K.G. and L.J. Heitkemper, 1997. Commodity market planning worldwide. Pp. 45-49 *in*: EU/FAO, 1997.

Matthews, R.B., M.J. Kropff, T. Horie and D. Bachelet, 1997. Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. Agric. Systems, 54(3):399-425.

McCoy, E.L., 1991. A bioenergetic model of plant root growth in soil. Agric. Systems, 37(1):1-23.

Meinke, H. and G.L. Hammer. 1997. Forecasting regional crop production using SOI phases: an example for the Australian peanut industry. Australian J. Agric. Research, 48(6):789-793.

Mitchell, G., R.H. Griggs, V. Benson, J. Williams, B. Vanicek and D. Dumesnil, 1995. EPIC User's guide, Texas Agricultural research center (Blackand Research Center), USDA-ARS (Grassland, Soil and water Research Laboratory), USDA (Natural Rsource Conservation Service), Temple, Texas, USA. About 200 pp (depending on font).

Monteith, J.L., 1965. Evaporation and environment, in: G.E. Fogg (Ed.) The state and movement of water in living organisms. Cambridge University Press, London.

Moore, P.M., and R.V. Osgood. 1987. Evaluation of a model for predicting sucrose yields following hurricane damage to sugar-cane in Hawai. Agric. For. Meteorol., 40(2):191-197.

Myers, D.E., 1994. Statistical methods for interpolating spatial data. J. Appl. Science & Computations, 1(2):283-318

Nemani,R., L. Pierce, S. Running and S. Goward, 1993. Developing satellite-derived estimates of surface moisture status. J. Appl. Meteorol. 32: 548-557.

Nieuwenhuis, G.J.A, T. Van der Wal, C.A. Mücher and A., 1998. Integrated use of high and low resolution satellite data and crop growth models, pp. 147-159 *in* : D. Rijks, J.M. Terres and P. Vossen (Eds), 1998.

Nieuwenhuis,G.J.A., A.J.W. de Wit, T. van der Wal, C.A. Mücher, and H.J.C. van Leeuwen, 1996. Integrated use of high and low resolution satellite data and crop growth models. DLO N. 127, 130 pp.

Nilsson, H.E., 1997. Remote sensing for assessment of disease impact. Pp. 123-142 in FAO/EU, 1997.

Nokes, S.E., F.M. Landa and J.D. Hanson, 1996. Evaluation of the crop growth component of the root zone water quality model for corn in Ohio. Transactions of the ASAE., 39(3):1177-1184.

Pachepsky, L.B., and B. Acock. 1994. Model of photosynthesis accounting for leaf anatomy. Proceedings of 24th Annual Workshop on Crop Simulation. March 15-18, 1994. Raleigh, NC. 18 pp.

Pages, L., and S. Pellerin, 1996. Study of differences between vertical root maps observed in a maize crop and simulated maps obtained using a model for the three-dimensional architecture of the root system. Plant and Soil, 182(2):329-337.

Pala, M., C.O. Stöckle and H.C. Harris.1996 Simulation of durum wheat (Triticum turgidum ssp. Durum) growth under different water and nitrogen regimes in a Mediterranean environment using CropSyst. Agricultural Systems, 51:147-163.

Palm, R., 1997a. Les modèles de prévision statistique: cas du modèle Eurostat-Agromet. Pp. 85-108 *in*: Tychon, B., and V. Tonnard, 1997. Estimation de la production agricole à une échelle régionale. Official Publications of the EU, EUR 17663, Luxembourg. 202 pp.

Palm, R., 1997b. Agrometeorological models: regression and trend analysis. Pp. 67-76 *in*: EU/FAO, 1997.

Palm, R., and P. Dagnelie, 1993. Tendance générale et effets du climat dans la prevision des rendements agricoles des différents pays des C.E. Official Publications of the EU, EUR 15106, Luxembourg. 132 pp.

Pannkuk, C.D., C.O. Stöckle and R.I. Papendick, 1998. Evaluating CropSyst simulations of wheat mangement in a wheat-fallow region of the US Pacific northwest. Agricultural systems, 57(1). In press.

Pawer, M., 1993. Statistical validation of ecological models. Ecological modelling, 68:33-50.

Penman, H.L., 1948. Natural Evaporation from Open, Bare Soil and Grass. Proc. Royal Soc. (London) A193:120-145.

Penning de Vries, F., M. Jansen and K. Metselaar, 1995. CAMASE guidelines for modelling. CAMASE__NEWS (Newsletter of Agro-ecosystems Modelling) extra edition, November

1995. Downloaded from the CAMASE home page at Wageningen Agricultural University (http://www.bib.wau.nl:80/camase/).

Petty,G.W., and W.F. Krajewski, 1996. Satellite estimation of precipitation over land. Hydrological sciences, 41(4): 433-451.

Pfirman, E., and J. Hogue, 1998. WINDISP_3. Programme and manual are retrievable from FTP://FTP.FAO.ORG/SDRN/WINDISP3.

Phillips,D.L., J. Dolph and D. Marks, 1992. A comparison of geostatistical procedures for spatial analysis of precipitation in mountainous terrain. Agric. forest meteorol., 58(1-2): 119-142.

Pilet, P.A., 1967. L'énergie végétale. Que Sais-je?, PUF, Paris. 126 pp.

Piper, E.L., K.J. Boote, J.W. Jones, S.S. Grimm, 1996. Comparison of two phenology models for predicting flowering and maturity date of soybean. Crop Science, 36(6):1606-1614.

Plentinger, M.C. and F.W.T Penning de Vries, 1995. CAMASE register of agro-ecosystem models, version 1. AB-DLO, Wageningen, Netherlands.179 pp.

Priestley, C.H.B. and R.J. Taylor. 1972. On the Assessment of Surface Heat Flux and Evaporation Using Large Scale Parameters. Monthly Weather Review. 100:81-92.

Rickman, R.W., and B. Klepper, 1991. Environmentally driven cereal crop growth models. Ann. Rev. Phytopathol., 29:361-380.

Rijks, D., 1997. Feedback between yield forecast and farm operations - a matter of weight? Pp. 41-44 *in*: EU/FAO, 1997.

Rijks, D., J.M. terres and P. Vossen (Eds), 1998. Agrometeorological applications for regional crop monitoring and production assessment, Official Publications of the EU, EUR 17735, Luxembourg. 516 pp.

Riou, C., 1994. The effect of climate on grape ripening: application to the zoning of sugar content in the European Community. Le déterminisme climatique de la maturation du raisin: application au zonage de la teneur en sucre dans la communaute europeenne. Official Publications of the EU, EUR 15863 FR/EN, Luxembourg. 322 pp. + 4 maps

Robertson, G.W., 1968. A biometeorological timescale for a cereal crop involving day and night temperature and photoperiod. Int. J. Biometeorol., 12:191-223.

Rosema, A., R.A. Roebeling and D.A. Kashasha, 1998b. Using METEOSAT for water budget monitoring and crop early warning, pp. 161-175, in: D. Rijks, J.M. Terres and P. Vossen (Eds), 1998.

Rosema, A., R.A. Roebeling, A. Van Dijk, G.J.A. Nieuwenhuis, J. Huyghen, D.A. Kashasha, 1998a. ACMP agromet and crop monitoring project in the SADC region. Netherlands Remote Sensing Board (BCRS) Report 96-13, Delft, 108 pp.

Russel, E.W., 1977. Soil conditions and plant growth. English Language Book Society and Longman, London, 849 pp.

Russel, G., and R.I. Muetzelfeldt, 1998. Development of a crop knowledge base for Europe. Pp. 207-224, in: D. Rijks, J.M. terres and P. Vossen (Eds), 1998.

Russell, G., R.I. Muetzelfeldt and K. Taylor, 1998. Crop Knowledge base system. Official Publications of the EU, EUR 17697, Luxembourg. Pages numbered by chapter.

Russell, J.S., and M.K. Wegener, 1990. Risk analysis of irrigated sugarcane using responses generated by the AUSCANE model. Proc. Int. symposium on climatic risk in crop production: models and management in the semi-arid tropics and subtropics, Brisbane ,Australia , 2-6 july 1990. CSRIO, Brisbane, Australia. Pp. 88-89.

Rustagi, N.K., 1988. Crop insurance in India: an analysis. Publishing Corp., India. xvi + 143 pp.

Sakamoto, C., 1995. Manual of agrometeorological tools in SADC Early Warning Systems. SADC/FAO Regional Early Warning Systems for Food Security, GCPS/RAF/270/DEN. Pages numbered by chapter.

Sakamoto, C.M, N.D. Strommen and S.K. LeDuc, 1977 Synoptic vs. Cooperative climate data as inputs for wheat estimates. In: Proc. 13th Conf. Agric. For. Meteorology., Am. Meteorol. Soc. Purdue University. Indiana. Quoted by Sakamoto and LeDuc, 1981.

Sakamoto, C., and S. LeDuc, 1981. Sense and non-sense: statistical crop growth and yield models. Pp. 185-200 in A. Weiss (Ed), 1981.

Savin, R., A.J. Hall and E.H. Satorre, 1994. Testing the root growth subroutine of the CERES-Wheat model for two cultivars of different cycle length. Field Crops Res., 38(3):125-133.

Seghi, L., S. Orlandin and B. Gozzini, 1996. Survey of simulation models of plant diseases. FMA, CeSIA, IATA-CNR, Florence, Italy, 127 pp.

Seguin, B., 1992. Utilisation combinée de données satellitaires et de modèles agrométéorologiques. Pp 199-206 in: Proc. Of the Conf. on the application of remote sensing to agricultural statistics. 26-27 Nov. 1991, Villa Carlotta, Belgirate, Italy. Office for Official publications of the EC, EUR 14262, Luxembourg. 380 pp.

Seino, H., and Z. Uchijima, 1992. Gobal distribution of Net Primary Productivity of terrestrial vegetation. J. Agr. Met., 48(1): 39-48.

Selirio, I.S., and D.M. Brown, 1997. An overview of modelling forage yield and quality for crop insurance purposes in Canada. Pp. 247-254 *in*: EU/FAO, 1997.

Sharpley, A. N. and Williams, J. R. 1990. EPIC - Erosion Productivity Impact Calculator: Vol. I. Model Documentation. USDA Technical Bulletin No. 1768. 235 pp.

Shisanya, C.A. and H. Thuneman, 1993. The use of dynamic crop production simulation model in quantifying agricultural resources: an example from Machakos district, Kenya. J. Eastern African Research and Development, 23:176-191.

Smith, M., 1992. Cropwat, a computer programme for irrigation planning and management. FAO, Rome, Irrigation and Drainage Paper N. 46. 126 pp.

Snijders, F.L., 1991. Rainfall monitoring based on Meteosat data - a comparison of techniques applied to the western Sahel. Int. J. Remotes Sensing, 12(6):1331-1348.

Snijders, F.L., 1995. ARTEMIS and the outside world. File formats and naming conventions. In: FAO, 1995: 139-146.

Stein,A., G. Kocks, J.C. Zadoks and H.D. Frinking, 1994. A geostatistical analysis of the spatio-temporal development of Downy Mildew Epidemics in cabbage. American Phytopathological Society, 84(10):1227-1238.

Stewart, J.I., 1988. Response farming in rainfed agriculture. Wharf foundation press, Davis,California,USA. x + 103 pp.

Stöckle, C.O. 1996. GIS and simulation technologies for assessing cropping systems management in dery environments. Am. J. Alternative Agric., 11(2-3):115-120.

Stöckle, C. O. , S. Martin and G. S. Campbell. 1994. CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. Agricultural Systems ,46:335-359.

Stöckle, C. O. and R. L. Nelson. 1994. Cropsyst User’s manual (Version 1.0). Biological Systems Engineering Dept., Washington State University, Pullman, USA.

Stöckle, C. O. , M. Cabelguenne, and P. Debaeke. 1996. Validation of CropSyst for water management in southwestern France using submodels of different levels of complexity. European J. Agron., 7:89-98.

Stöckle, C. O. and P. Debaeke. 1997. Modeling crop N requirement: A critical analysis. European J. Agron., 7:161-169.

Stott, Z., 1996. Predicting sugar beet yields using satellite data. SPOT Magazine, 26:14-16.

Strauss, R., H. Bleiholder, T. van den Boom, L. Buhr, H. Hack, M. Hess, R. Klose, U. Meyer and E. Weber, 1994. Einheitliche Codierung der phänologischen Entwicklungstadien mono- un dikotyler Pflanzen. BBA-BSA-IVA, Basel, Switzerland. 26 pp with several plates.

Supit, I., A.A. Hooijer, C.A. van Diepen (Eds), 1994. System description of the wofost 6.0 crop simulation model implemented in CGMS. Vol. 1, Theory and algorthms. Office for official publications of the EC, Agriculture Series, EUR15956EN, Luxembourg, 144 pp.

Supit, I., 1997a. Predicting national yields using acrop simulation and trend model. Agric. For. Meteorol., 88:199-214.

Supit, I., 1997b. National wheat production volume forecasting with models including influences of market prices and inputs such as plant protection and fertilisers. Application to the European Community. Pp. 109-144 *in*: B. Tychon and V. Tonnard, (Eds.), Estimation de la production agricole à une échelle régionale. Office for official publications of the EU, Luxembourg, EUR 17663, 199 pp.

Supit, I., and R. Van Kappel, 1998. A simple method to estimate global radiation . Solar Energy, in press.

Swanson, E.R., and J.C. Nyankori, 1979. Influence of weather and technology on corn and soybean trends. Agric. Meteorol., 20:327-342.

Tabor,J.A., A.W. Warrick, D.A. Pennington and D.E Myers, 1984. Spatial variability of nitrate in irrigated cotton: I.petioles. J. Soil Science Soc. of America, 48(3):602-607.

Tabor,J.A., A.W. Warrick, D.E. Myers and D.A. Pennington, 1985. Spatial variability of nitrate in irrigated cotton: II.soil nitrate and correlated variables. J. Soil Science Society of America, 49(2):390-394.

Tada, M., and Y. Morooka, 1995. Supply and demand analysis for rice in Peninsular Malaysia - with special reference to direct seeding in the Muda area. JIRCAS Journal, 2(2):1-11.

Takezawa, K., and Y. Tamura, 1991. Use of smoothing splines to estimate rates of development. Agric. forest meteorol., 57(1-3):129-145.

Takle, E., 1995. Use of physically based meteorological models for enhancing agroclimatic databases. Pp. 291-294 *in* : FAO, 1995.

Thomson, S.J., and B.B. Ross, 1996. Model-based irrigation management using a dynamic parameter adjustment method. Computers and Electronics in Agriculture, 14(4):269-290.

Thornton, P.K., H.W.G. Booltink and J.J. Stoorvogel, 1997. A computer program for geostatistical and spatial analysis of crop model outputs. Agronomy J., 89(4):620-627.

Toure, A., D.J. Major, and C.W. Lindwall, 1995 . Sensitivity of four wheat simulation models to climate change. Canadian J. Plant Sci., 75(1):69-74.

Tsai, Y.J., J.W. Jones, and J.W. Mishoe, 1987. Optimizing multiple cropping systems: a systems approach.Transactions of the ASAE, 30(6):1554-1561.

Uchijima, Z. and Seino, H., 1985. Agroclimatic evaluation of net primary productivity. J. Agr. Met., 40(4): 343-352.

Unganai, L., and F. Kogan, 1998. Drought monitoring and corn yield estimation in southern Africa from AVHRR data. Remote Sens. Envir., 63:219-232.

USDA, 1967. Irrigation Water Requirements, Technical Release N. 21, Soil Conservation Service Engineering Division, 83 pp.

USDA, 1972. National Engineering Handbook, Hydrology section, chapters 4-10. USDA-SRC, Washington.

van Diepen, C.A., J. Wol, H. van Keulen, C. Rappoldt, 1989. WOFOST: a simulation model of crop production. Soil Use and Management, 5(1):16-24.

Van Heemst, H.D.J., 1986. Physiology principles, in: van Keulen and Wolf (1986), 13-26.

van Keulen, H., and H.H. van Laar, 1986. The relation between water use and crop production, in: van Keulen and Wolf (1986), 117-129.

van Keulen, H., and J. Wolf (eds), 1986. Modelling of agricultural production: weather, soils and crops. Simulation monographs, Pudoc, Wageningen, 478 pp.

van Kraalingen D.W.G., 1991. The FSE system for crop simulation. Simulation reports CABO-TT 23, CABO-DLO, WAU-TPE Wageningen, 77 pp.

van Leeuwen, H.J.C. and J.P.G.W Clevers, 1994. Synergy between optical and microwave remote sensing for crop growth monitoring. Proc. sixth international symposium physical measurements and signatures in remote sensing, Val d'Isère, France, pp 1175-182.

Vanclooster, M., P. Viaene, J. Diels and J. Feyen. 1995. A deterministic evaluation analysis applied to an integrated soil-crop model. Ecological Modelling, 81(1-3), 183-195.

Vossen, P., 1990. Comparative statistical validation of two ten-day water use models and three reduction hypotheses for yield assesment in Botswana. Agric. For. Meteorol. 51:177-195.

Vossen, P., and D. Rijks (Eds.), 1995. Early crop yield assessment of the EU countries: the system implemented by the Joint Research Centre. Office for Official Publications of the EU, Luxembourg, EUR 16318EN, 182 pp.

Wagner, W., J. Noll, M. Borgeaud, H. Rott, 1999. Monitoring soil moisture over the Canadian Prairies with the ERS Scatterometer, IEEE Trans. Geosci. Remote Sensing, in press (January 1999 issue).

Wagner, W., G. Lemoine, M. Borgeaud, H. Rott, 1999. A study of vegetation cover effects on ERS Scatterometer Data, IEEE Trans. Geosci. Remote Sensing, in press.

Wald,L., 1996. Some comments on the use of satellite data for assessing solar radiation parameters, annex to Potentials of images from geostationary satellite for the assessment of solar energy parameters. In Proceedings of the Workshop 'satellites for solar resource information', held in Washington, D.C., 10-11 April 1996. Edited by R. Perez and E. Maxwell, National Renewable Energy Laboratory, Boulder, CO., USA, 23 p.24-38.

Walker, G.K., 1989. Model for operational forecasting of western Canada wheat yield. Agric. Forest Meteorol., 44(3-4), 339-351.

Weisensel, W.P., G.C. van Kooten, R.A. Schonry, 1991. Relative riskiness of fixed vs. flexible crop rotations in the dryland cropping region of Western Canada. Agribusiness (New York), 7(6):551-562.

Weiss, A. (Ed), 1981. Computer techniques and meteorological data apllied to problems of agriculture and forestry: A workshop. Proc. Of workshop held at Anaheim, California, 30-31 March 1981.NSF ATM-8020422 grant. AMS, ASAE and ASA. 384 pp.

Whisler, F.D., and J.A. Landivar, 1988. A sensitivity test of COMAX/GOSSYM to some soil physical properties.Proceedings, Beltwide Cotton Production Research Conferences, 3-8 Jan. 1988, New Orleans, Louisiana, USA. Memphis, Tennessee, USA, National Cotton Council of America. 85 pp.

White, I.D., D.N. Mottershead and S.J. Harrison, 1992. Environmental Systems, an introduction text. Chapman & Hall, London, 616 pp.

White, I.D., D.N. Mottershead and SJ Harrison, 1992. Environmental Systems, an introduction text. Chapman & Hall, London, 616 pp

Williams, J. R. and H.D.Berndt. 1977. Determining the Universal Soil Loss Equation's Length - Slope Factor for Watersheds. Soil Erosion: Prediction and Control, Soil Conservation Society Journal, p. 217-225.

Williams, J. R., P.T. Dyke, W.W. Fuchs, V.W. Benson, O.W. Rice, and E.D. Taylor, 1990. EPIC - Erosion Productivity Impact Calculator. Vol. II. User Manual. A. N. Sharpley and J. R. Williams, Editors. USDA Technical Bulletin No 1768. 127 pp.

Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel, 1989. The EPIC Crop Growth Model. Trans. ASAE 32(2):497-511.

WMO/CTA, 1992. La radio rurale et la diffusion des informations agrométéorlogiques. Compte-rendu d'un atelier tenu sur invitation du Gouvernement du Mali, Bamako, 18-22 mai

Wolf, J. 1993. Effects of climate change on wheat production potential in the European Community. Eur. J. Agronomy. 2(4):281-292.

Wolf, J. And C.A. van Diepen, 1994. Effects of climate change on silage production potential in the European Community. Agric. For. Meteorol. 71(1-2):33-60.

Wolf, J., and C.A. van Diepen, 1995. Effects of climate change on grain maize yield potential in the European Community. Climatic Change, 29(3): 299-331.

Wolfe, D.W., and J.D. Erikson, 1993. Carbon dioxide effects on plants: uncertainties and implications for modelling crop response to climate change. Pp 153-178 *in*: Kaiser and Drennen, 1993. Agricultural Dimensions of Global Climate change. St. Lucie Press, Delray Beach, Florida. 311 pp.

Wu, Y., C.M. Sakamoto, and D.M. Botner. 1989. On the application of CERES-Maize model to the North-China Plain. Agric. Forest Meteorol., 49:9-22.

Xiniou Yin, M.J. Kropff, G. McLaren and R.M. Visperas, 1995. A nonlinear model for crop development as a function of temperature. Agric. For. Meteorol., 77:1-16.

Yoshida, S., 1981. Fundamentals of rice crop science. IRRI, Los Baños, Laguna, Philippines. 269 pp

Zentner, R.P., F.B. Dyck, K.R. Handford, C.A. Campbell and F. Selles, 1993. Economics of flex-cropping in southwestern Saskatchewan. Can. J. Plant Sci., 73:749-767.