WORKBOOK ON CLIMATE CHANGE IMPACT ASSESSMENT IN AGRICULTURE

BASIC KNOWLEDGE, METHODOLOGIES AND TOOLS

PREPARED BY

Roger E. Rivero Vega

April 2008

IN COLLABORATION WITH THE

CARIBBEAN COMMUNITY CLIMATE CHANGE CENTRE

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Foreword

One component of the Mainstreaming of Adaptation to Climate Change (MACC) regional project executed by the Caribbean Community Climate Change Centre and funded by the Global Environmental Facility (GEF) is supporting the development of an Adaptation strategy for the agriculture sector in Guyana. As part of this process the project supported a vulnerability assessment study of the sector and an assessment of the impacts of climate change on agriculture in Guyana. To facilitate the implementation of the latter process, a workshop was organized in Guyana to train a cadre of national agriculture professionals to familiarize them with the basic knowledge, methodologies and tools required to carry out climate change impact assessments in the agriculture sector. Expertise for the ten-day workshop was provided by staff of the Institute of Meteorology (INSMET) in Cuba. As a result of the success of this activity it was decided to organize a follow up workshop for regional agricultural professionals, so as to further disseminate the use of biophysical models in assessing climate change impacts on agriculture in the Caribbean. This workshop was organized by the Caribbean Community Climate Change Centre (CCCCC) with sponsorship from the Commonwealth Secretariat, the UNDP's regional Caribbean Risk Management Initiative (CRMI), and the Barbados regional office of the Food and Agriculture Organisation (FAO).

This manual presents the range of topics covered during the two-week regional workshop which was held in Guyana and is meant to reinforce the basic skills imparted to participants in the two Guyana workshops. Participants from the Caribbean Institute of Meteorology and Hydrology (CIMH) and the Faculty of Agriculture at the University of the West Indies (St. Augustine) campus were included in the regional workshop. It is anticipated that these two institutions will provide professional support to further training in the region. It is hoped that this manual will be a useful tool for such future endeavours. We also hope that the manual will emerge as one more useful tool for the community of professionals engaged in studies aimed at understanding climate change impacts on agriculture.

We are indebted to Drs Roger Rivero-Vega Sr. and Roger Rivero-Vega Jr. for providing the technical direction for the two workshops and to Dr Roger Rivero Vega Sr. for undertaking the daunting task of writing this manual. We would like to express our gratitude to them and to the management of INSMET for so generously sharing their knowledge with our regional colleagues. We would also like to express our appreciation for the generous support received from the Commonwealth Secretariat, the UNDP's CRMI regional programme and from the FAO sub-regional office in Barbados which has culminated in the production of this manual.

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GENERAL OUTLOOK OF ASSESSMENTS PROCEDURES IN AGRICULTURE

A climate change impact assessment in agriculture usually begins by defining what is usually called a baseline. A baseline consists in a reference climate defined for some previously established past time period, usually 30 years, and a reference socioeconomic baseline for the same period depicting the actual state of the agricultural sector and a whole set of socioeconomic indicators describing the general socioeconomic, technological, and management conditions in which agriculture has been developing during that chosen time period. For well-based reasons a 30-year period is usually chosen to coincide with what World Meteorological Organization (WMO) defines as a normal period, which is 1961 – 90. In some cases two subsequent normal periods such as 1931 – 60 and 1961 – 90 are studied to find if there is some significant difference between the behaviour of mean climate and some extreme phenomena such as was done with meteorological drought in Cuba. That, however, is not usually done in climate change impact assessments because both of them are already in the past.

As climate change began to be evident in climate data trends since around the middle of the seventies, some research groups and organisations have used a different 30-year period such as 1951 – 80 which was recommended by the U. S. Country Study Programme (Benioff et al, 1996). The general agreement for using 1961–90 as a baseline for climate change impact assessments was taken in the nineties but, seeing that we are already past 2000 and getting near to 2010, it would not be surprising if some time in the future a new 30-year period, such as 1971 – 2000 or 1981 – 2010, could be universally adopted for making baselines in the assessment of climate change impacts.

One of the reasons why a 30-year period is chosen is because different climate variables have different time periods for which you can consider that the variable itself has expressed its internal variability, and mean values have stabilized in the sense that another equally long period would have a very similar mean value to the chosen one. A variable such as daily wind speed could reach stable mean values for periods as short as 3–5 years, but highly erratic variables such as monthly precipitation values are supposed to require at least a 30-year time series to reach stable mean values. Indeed, rainfall varies so much in some regions of the planet that it is doubtful that we could find a suitable period in which we could assert that we are obtaining stable mean values for the variable itself.

As a 30-year baseline might be difficult to obtain in developing countries, not only in the case of climate data, but in the case of socioeconomic data also, it could be possible that some research team could not fulfil this requirement. That should not halt the effort of making a climate change impact assessment in the agricultural sector and a shorter time period could be used as a baseline.

Once we have a suitable baseline, then a projected future climate is obtained using specific techniques to be described below. This projected future climate should be envisioned in the frame of an accompanying socioeconomic scenario and it is usually named as a climate change scenario. Once we have both a reference baseline and a projected climate change scenario, very sophisticated impact tools and methodologies are applied to current and projected climate and socioeconomic scenarios. Results obtained with the same impact tools in both situations (actual and projected) are compared, one with the other, to obtain an assessment of the expected climate change impact on basic parameters characterizing the sector as a whole or a part of it. Once the impact of climate change has been assessed, an analysis of possible adaptation measures and strategies is done and its expected results are estimated using the same impact tools that were used to derive the original impacts. This complex intercomparison of results constitutes the basis for the elaboration of recommendations about strategies, policies, and adaptation measures that could be adopted to minimize, eliminate or even revert the negative impacts of climate change in the agricultural sector. We stress here that an adaptation option should never be created from thin air, instead every adaptation option should be derived by making a thorough study of its possible outcomes using the same impact tools used to derive the expected impacts of climate change.

After completion of such intensive research effort by the assessment team, a comprehensive set of adaptation measures and strategies is now available for policy and decision-makers. The actual implementation of those recommendations now becomes a very important issue in societal efforts for minimizing the possible negative impacts of climate change in basic national issues such as food security, income, and the livelihoods of people.

CLIMATE CHANGE SCENARIOS: RECOMMENDED PROCEDURES

Introduction

Every assessment of the plausible impacts of climate variability and change on any sector must be based on an appraisal of what future climate will look like and how its variability will be. But it happens that future climate conditions and variability cannot be forecast in the same sense that the weather for the next five days can be forecast in national meteorological services. The problem of weather forecast can be stated as what will be the state of the atmosphere in a given region, if we know its previous state at a specified date. A forecast is then made by the procedure of applying statistical relationships derived on a dependent sample between the state of the atmosphere at a given date and its state at a latter date or solving the time dependent system of coupled partial differential equations of hydro thermodynamics. In both cases external influences that could exert a given action on the meteorological system during the lapse of time existing between the initial and the final date are not taken into account. It means that tomorrow's weather forecast is made without taking into account the possibility that a nuclear war, a catastrophic explosion of a super volcano, or the falling on Earth of a huge meteorite could occur during that 24-hour period.

Beside this the development of science has been gradually reaching a point in which the deterministic behaviour of atmospheric and weather processes is being questioned in the sense of making doubtful the notion of weather predictability in a mechanistic way, because of the infinity of interactions and feedbacks

that confers atmospheric behaviour a rather chaotic nature. This kind of notion somewhat implies the idea that a certain amount of unpredictability is embedded in the atmospheric system itself, because of its nature and cannot be attributed only to our limited scientific and technological knowledge.
This leads us to the fact that we cannot forecast the state of the climate system during the next one hundred years with any accuracy and leaves us only the possibility of drawing an educated guess of what earth climate will look like at a future date, even if a very educated one. That educated guess is what we will be calling here a climate change scenario to distinguish it very clearly from a climate change forecast.

The need of using climate change scenarios comes from two great sources of uncertainties:

- The inherent unpredictability of the climate system and our actual limited scientific knowledge and technological development
- The fact that a large set of external influences, that can and will be exerted over the climate system in the rather long lapses of time involved in climate change, cannot be envisioned completely or are dependent from human actions that cannot be derived from the laws of physics.

It should be clear to the reader that the climate of the 22nd century, if we cease burning fossil fuels today completely and derive energy only from renewable sources, will differ very much from what climate would be if we continue to burn fossil fuels at the same rate as we are doing now. It happens that we do not really know what human societies will do in the intervening years because actions taken by a supposedly rational individual cannot be derived from the already known laws of nature. Even if everybody is sure that scientific knowledge and technological development will keep growing at an accelerated pace during the 21st century and will contribute substantially in reducing the first source of uncertainty that impedes us from making a climate forecast. The second source of uncertainty related to the course of human actions is not expected to decrease noticeably in the near future.

The usual procedure of creating a climate change scenario begins by making a whole set of reasonable assumptions about the future actions of human society during a certain lapse of time, such as a century. These assumptions give rise to what we usually call a storyline depicting a set of plausible paths of development for man on Earth. For a given storyline there will be a description of the relative use of different kinds of energy sources, population growth, expected income and livelihood of people on this planet. From the point of view of climate change science these storylines allow us to estimate what the emissions of greenhouse gases will be during the lapse of time between an actual and a future date. The expected changes in atmospheric concentrations of greenhouse gases (carbon dioxide, methane, ozone, chlorofluorocarbons and oxides of nitrogen) are then derived from these assumptions using appropriate physiochemical models. The final result of this process is what is usually called a greenhouse gases (GHG) emissions scenario.

Even if at the beginning of the development of climate change sciences such kinds of scenarios were depicted by individual scientists or by a rather small group of them, assuming as an example, that carbon dioxide atmospheric concentrations would increase at a rate of one percent annually. Today such kinds of scenarios are now made by very large groups of experts designated by international agencies. More specialised knowledge and expertise are now available.

When a global climate model is run so as to simulate a large time period (100 – 200 years) assuming as true a given greenhouse gases emission scenario what we get as a result for a future time date is known as a climate change scenario. The making of a scientifically sound climate change scenario is an extremely complex procedure involving much scientific knowledge, manpower, and resources. That procedure is not an objective of this manual, so the reader is referred to the published scientific literature (Benioff et al, 1996; UNEP/IES, 1998; Parry and Carter, 1998) and IPCC Reports. But taking into account that the assessment of impacts derived from climate change in any given sector can hardly be done without understanding how a climate change scenario is development and how even educated guesses are needed to guide our impact assessments' efforts, this subject will now be developed, even if in a somewhat sketchy manner.

Specificity of Climate Change Scenarios for V&A in Agriculture

In most cases climate change scenarios for impact assessments in different sectors (agriculture, water resources, human settlements, coastal ecosystems and others) are made by national meteorological services. Under the prevailing historical concept that climate can be described by a set of monthly values for temperature and precipitation, these available scenarios will not necessarily contain the whole set of variables needed for assessing impacts in the agricultural sector. This happens to be one of the sectors for which much more complex assessment impact tools are available and they usually require a larger set of detailed climate variables than what is normally provided by national meteorological services in developing countries. This problem will be discussed in greater details in subsequent chapters. Because of this, many times the agricultural assessment team has to become part of the climate change scenarios' development effort to guarantee that the necessary information is provided.

THE BUILDING OF CLIMATE CHANGE SCENARIOS

Many procedures are available for building climate change scenarios and not all of them will be discussed here. Only three general procedures will be discussed in some details, that is synthetic (incremental), analogous, and model-based climate change scenarios.

Synthetic Scenarios

A synthetic scenario consists of a (rather arbitrary) set of changes in values for different climate variables. A simple example would be to assume that annual mean temperature is going to increase by 2.5 degrees while annual precipitation is going either to remain unchanged, decrease by 10% or increase by 10%. Here we have three different synthetic scenarios. The first problem here is that these climate change scenarios correspond to an undetermined future date because we have no available knowledge about when these changes would take place. The second and even more important issue is that some of the so created scenarios could be physically impossible and could violate the very well-established laws of physics. A third problem is created by the fact that there is no guide as to what the corresponding variation in global solar radiation or other climate variables (wind speed or air humidity) could be consistent with. There could be an arbitrary change in temperature and precipitation values.

The simplest example of an inconsistent synthetic scenario could be that of assuming that temperature will remain unchanged while precipitation values increase or decrease in an arbitrary manner. As the most evident characteristic fact of climate change consists of a progressive warming of the planet to assume that temperature will remain unchanged in the future would take us out of the realm of climate change as is being used in this book. Notwithstanding this, synthetic scenarios are commonly used in the preliminary stage of impact assessments to test the ability of impact tools to reflect a change in climate and the sensitivity of agricultural systems to a prescribed amount of change to infer vulnerability and intolerable thresholds beyond which the whole agricultural system could collapse. Synthetic scenarios were used in the first stages of the Cuban effort to make its initial climate change impact assessments (INSMET, 1998) and in a somewhat modified form combined with climate model results actually named by us as a semi synthetic scenario they were also used in our first assessment for the agricultural sector (Rivero et al, 2000).

Analogues scenarios

Analogues scenarios rest upon the possibility that in actual climate conditions expected future climate conditions could already exist in a different spatial region of our planet or in (even paleontological) past times. Finding analogues to expected climate conditions in tropical lowlands could be very difficult or practically impossible even if this kind of approach has been used by taking historical events to simulate the expected response of agriculture response to prolonged drought episodes in the United States. The most difficult problem with analogues probably resides in the fact that even if a near match, if found, between an expected future climate state and an actual or past one, atmospheric concentrations of very important gases such as carbon dioxide and ozone would be very different. It happens that both of them produce a direct impact on plant physiological processes besides producing a change in climate, and thus a so-called secondary or indirect impact on agricultural systems.

Model-based scenarios: Global and Regional Climate Models

The science of simulating climate evolution solving the equations of physics has developed very fast, since the initial efforts of Budyko and Sellers based on appropriate solutions to the equations of balance to be described in latter chapters and the pioneering efforts of Charney and other scientists during the first half of the twentieth century. Modern coupled ocean – atmosphere general circulations models can take into account practically all important interactions between oceans, atmosphere, land and ice cover as to give a very plausible image of what climate is and how it could evolve under the external forces produced by man's actions over the different components of the biosphere. All this has been possible not only because of the constant increase in accumulated knowledge, but to the increase in computing power associated with the intense development of computing science. Model-based scenarios are totally coherent and internally consistent with the laws of physics, surpassing in this way the shortcomings of the already discussed synthetic and analogue procedures. Additionally, all values obtained are explicitly associated with a previously specified future date.

But even at this stage of development the most powerful supercomputers cannot economically handle and solve the overwhelming complexity of the system of differential equations involved in an arbitrary spatial and temporal resolution for a continuous period of 100–150 years. That implies that some compromise has to be made, usually involving spatial resolution of results. Most global climate models have spatial resolutions in the range of 3 * 3 degrees latitude. The outputs of a global climate model generally represent averaged values for each grid cell having these dimensions and cannot be interpreted as point values for a specific location on the earth's surface.

Owing to this circumstance the output of a global climate model is usually taken as a change in the corresponding variable that should be applied to all baseline values in the corresponding grid cell. Baseline values can have, in principle, any spatial resolution depending on the density of observing meteorological and climatological stations belonging to and operated by national institutions. This approach to building a climate change scenario has become the recommended procedure by most handbooks and scientific literature in the field.

Because of the coarse resolution inherent in global climate models many physical processes cannot be solved explicitly and must be parameterized losing valuable information in the process. The initial topographical representation of emerged lands can be so crude as to not take into account the existence of small island states in the Atlantic, Indian, and Pacific Oceans. This shortcoming prevents global climate models from adequately reflecting topographical influences and distinguishing between northern and southern shores of even larger islands as Cuba.

To avoid these problems the scientific community has developed a whole set of additional approaches collectively named as downscaling procedures that, in a very simple way, can be divided into statistical and dynamical downscaling. Following the line of thought that we will continue using in this workbook, based on the idea of explaining agricultural assessments on the basis of the description of natural processes, and not on its statistical relationships with components of the climate system, only a brief description of dynamical approaches will be described here. A regional climate model is an area-limited model in which the system of differential equations representing physical processes is solved by numerical procedures. Being limited in area, the computer resources needed for their use can be drastically reduced in comparison with global climate models. This advantage allows modellers to increase spatial resolution and include the explicit solution of processes that in low resolution global climate models have to be parameterized. The main disadvantage of this pathway to downscaling is that regional climate models generally have to be initialized using variables calculated at their boundaries by a global climate model. The most used approach during the last few years in the Caribbean region had been that of using the PRECIS regional climate model embedded in the HadCM3 or ECHAM4 global climate models (Jones et al, 2004).

The output of global and regional climate models can be used directly to generate the necessary climate change scenarios for an assessment of the agricultural sector and this is not an easy task for an assessment team. In fact that was the form in which the first quantitative climate change scenarios were made in Cuba by Rivero and Rivero (1997). Complete outputs from global or regional climate models are not usually available and to obtain them requires collaboration among diverse institutions in different countries. As it is usually recommended that climate change scenarios using different and contrasting global climate models should be used to incorporate the existent uncertainties derived from the fact that different global climate models give different results for some particular regions, especially in relation to precipitation regimes, the magnitude of this effort may be multiplied by a factor greater than three (Hulme, 1996).

The MAGICC/SCENGEN procedure

The MAGICC/SCENGEN system was originally designed so as to make possible for assessment teams in any country, developed or not, to build climate change scenarios using any greenhouse gases emissions scenarios and global climate model. The ability of doing this resides in the fact that the MAGICC/ SCENGEN system contains the one dimensional MAGICC climate model that can be run in an ordinary PC for any greenhouse gases scenario and calculates mean planet warming and sea level rise, additionally to greenhouse gases atmospheric concentrations, for any date from 1990 to 2100. Essentially MAGICC/ SCENGEN is a coupled gas-cycle/climate model (MAGICC) that drives a spatial climate-change scenario generator (SCENGEN). The climate model in MAGICC is an upwelling-diffusion energy-balance model that produces global and hemispheric-mean output (Wigley, 2003). The system contains also the SCENGEN program in which the output files from more than a dozen global climate models are combined (scaled or standardized) by the global temperature rise predicted by MAGICC (Hulme et al, 1995). In this way MAGICC/SCENGEN can be used in minutes to obtain world maps depicting mean 30-year values for monthly, seasonal and annual changes in temperature and precipitation for any grid cell at any future date. The spatial resolution provided by the system is 5 by 5 degrees latitude which is a compromise between the very different original spatial resolutions of the different global climate models available.

Global-mean temperatures from MAGICC are used to drive SCENGEN. SCENGEN uses a version of the pattern scaling method described in Santer et al (1990) to produce spatial patterns of change from an extensive data base of atmosphere/ocean general circulation models. The pattern scaling method is based on the separation of the global-mean and spatial-pattern components of future climate change, and the further separation of the latter into greenhouse gas and aerosol components. Spatial patterns in the data base are ‘normalized’ and expressed as changes per 1^{o}C change in global-mean temperature. These normalized greenhouse gas and aerosol components are appropriately weighted, added, and scaled up to the global-mean temperature defined by MAGICC for a given year, emissions scenario and set of climate model parameters (Wigley, 2003). A workbook for the 2.4 version of the system is easily available (Hulme et al, 2000).

Climate change scenarios built for the First National Communication of the Republic of Cuba to the United Nations Framework Convention for Climate Change (INSMET, 2001) were made using the 2.4 version of MAGICC/SCENGEN using the IS92a greenhouse gases emissions scenario and three contrasting global climate models (Centella et al, 1999). New sets of climate change scenarios have been created for the province of Camagüey, Cuba, using either the 2.4 or the 4.1 version of MAGICC/ SCENGEN (Rivero and Rivero, 2003). These new climate change scenarios were used in the impact assessments on livestock and on the energy sector.

From the point of view of an agricultural sector assessment team the greatest disadvantage of the described procedure consists in different versions of this system providing mainly changes in values of daily mean temperature and precipitation. But it happens that, as we will see in latter chapters, agricultural sector impact models require more input variables to be capable of describing crop responses to climate change. These additional variables include maximum and minimum temperatures, global solar radiation, wind speed, an atmospheric humidity parameter, and even the monthly mean number of rainy days (Rivero et al, 2000; Rivero et al., 1999). Some procedures are available to circumvent this lack of input data, even if rather arbitrary. In the next section we will be discussing what we have come to name as Bultot's climate change scenarios (Wolf and Diepen, 1993).

Bultot's scenarios

Whenever a climate change scenario is needed for providing input data to a climate index-based assessment or to a process-based impact model (crop model) and you do not have all the necessary estimated variables derived from a global climate model. You may always, in principle, estimate the change in the missing variables in a similar way to what is done when you are building a synthetic scenario. In the same way as it was discussed when synthetic scenarios were presented in this chapter, an assessment team will have to be extremely careful ,so that those missing variables are estimated accordingly with additional knowledge or assumptions about how they are expected to evolve with climate change. Assumptions that differ very much from reality could give rise to a combination (Bultot's) scenario that violates the laws of physics. Seen in this way a Bultot's climate change scenario can be seen as a climate model-based scenario combined with a general common sense synthetic scenario. When using the MAGICC/SCENGEN procedure a climate change scenario to be used in the agricultural sector will have to be most of the time, a Bultot's scenario, because even the simplest process-based crop model will not run without global solar radiation input values or without having the necessary data to estimate internally the rate of potential evapotranspiration.

The additional assumptions to be made cannot be specified "a priori", so the assessment team will have to study each individual case on the basis of available knowledge and expertise. Only with the purpose of guiding the thoughts of an assessment team we could list some assumptions that could be made in such cases:

- Global solar radiation and potential evapotranspiration values can be estimated using formulations based only in temperature values. This possibility is discussed in the later chapters.
- As global warming both leads to an increase in evaporation from wet surfaces and in air capacity of holding water in vapour form, it can be assumed that air relative humidity could be considered unchanged or restricted to vary in a narrow interval with climate change. The reader should observe that this assumption implies that all the rest of humidity parameters used to describe water

vapour content of the atmosphere will change noticeably because of the associated increase in temperature.

- Evidence seems to imply that even if rain intensity is expected to increase with climate change, because total water vapour content in a vertical column through the atmosphere (a magnitude known as precipitable water content of the atmosphere) will be growing with time, the actual number of rainy days will have a much lesser variation and at a first guess it could be considered as constant in such a scenario.

Until today all agricultural impact assessments made in Cuba with the MAGICC/SCENGEN system have been based on Bultot's type scenarios. The main reason for that choice came from the fact of that system not providing global solar radiation values from any of the available global climate models.

THE IMPACT METHODOLOGIES AND TOOLS

In a concrete impact assessment effort made in developing countries it could happen that a very complete climate model-based scenario is available and impact methodologies and tools must be chosen to reach the best possible conclusions about the expected impacts of climate change. But it could also happen that complex sophisticated impact methodologies and tools are available, while a complete physically-based climate change scenario is not. Climate change scenarios and impact tools are interrelated in such a way that a complete detailed climate change scenario allows the use of complex tools such as process-based crop models while an incomplete partial scenario gives only the possibility of using impact tools implying the use of so-called climatic and bioclimatic indexes. Both kinds of impact tools have different input data requirements as we shall see in later chapters.

These two kinds of impact tools have in common the fact that both of them are especially suited to the estimation of first order (biophysical) impacts of climate change on crops and terrestrial ecosystems. These will be the main type of impacts that we will be discussing and, with one exception, the only types of tools that are going to be discussed in depth here. Higher order (socioeconomic) impacts can always be estimated, at least in principle, combining basic biophysical impacts with socioeconomic scenarios using higher order (integrated) impact tools.

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CHAPTER 2

BASIC BALANCE EQUATIONS

CHAPTER 2 Basic Balance Equations

1. Introduction
2. The Radiation Balance Equation
3. The Water Balance Equation
4. The Energy Balance Equation
5. The Biomass Balance Equation
6. Climatic Indexes

INTRODUCTION

The basic balance equations reflect the laws of conservation of carbon, water, and energy in the biosphere. All assessment methodologies of the biophysical impacts of climate change on natural and agricultural ecosystems depend on them, even if at times that fact is hardly evident. The radiation, energy, and water balance of the surface are the cornerstones on which physical climatology is built. The reader should be aware that even though we will be dealing with these balance equations in a way best suited for the study of processes at the terrestrial surface, the concepts involved can be extended to encompass the balance of energy and water in the planet – that is, including emerged surfaces, oceans, ice cover, and atmosphere – as a whole. Such an extension of the balances equations forms the basis on which the theory of climate change as a consequence of the continuous increase in the atmospheric concentrations of greenhouse gases is constructed.

In studying the surface energy balance equation we will be able to appreciate that the radiation energy balance could be completely included there. Mainly for pedagogical reasons that is not done in this workbook, even if that is the choice made by some prestigious authors (Wieringa and Lomas, 1991). The calculation of the radiation balance term is complicated and illustrative enough to deserve an independent analysis in this book as was done originally by Sellers (1965).

By circumstance and for historical reasons, classical textbooks as those already mentioned, evade the analysis of the biomass balance equation in their formulations. This could be caused in part by the tremendous amount of effort that has to be devoted to solving this last equation. But even without specifically studying and discussing this equation many authors have to refer constantly to the use of concepts such as transpiration, potential evapotranspiration and albedo of the vegetative cover in addition to the specification of surface roughness, crop coefficients (k_c) and other terms whose spatial and temporal variation can hardly be understood without having a comprehension of the behaviour of natural and agricultural ecosystems. To deal with all these balance equations was the choice elected by the authors of this book in an effort to offer the reader something of the kind of an integrated vision of the methodologies for assessing the impacts of climate change in the agricultural sector.

The individual terms of these balance equations as well as the relationships among them have been used to formulate a whole hierarchy of climatic and bioclimatic indexes. Some of them proportionate indirect information from which net primary productivity of ecosystems and even biodiversity issues can be inferred, while others can be used to obtain direct estimation of those very important assessment parameters.

The balance equations discussed here, or some suitable modification of them, are constantly being solved in every process-based biophysical crop model. Trying to understand what a crop model is doing and how a crop model is doing the apparent miracle of making for us a detailed description of the time evolution of a crop, without knowing and understanding the basic balance equations discussed in this chapter is not really possible.

THE SURFACE RADIATION BALANCE

Extraterrestrial solar radiation

The sun provides about 99.97 percent of the energy required by all physical processes taking place in the earth – atmosphere system (Sellers, 1965). The intensity of solar radiation energy per unit area incident on a spherical surface with centre in the sun and a radius equal to the mean distance to the sun from our planet ($\mathbf{D_m}$) is usually called the solar constant (**S**). For most practical uses this value can be considered as a constant, even if it exhibits rather small variations with time, of the order of 1.5 percent, and it could have slightly different values in geological times.

Usual reported values of the solar constant lie around 1.94 – 2.0 cal/cm ^{2} – min. In more usual systems of unit this is roughly equivalent to,

$$\mathbf{S = 1393.3\ J/m^2 - sec = 1393.3\ watt/m^2}$$

But the amount of solar radiation actually incident on the top of the atmosphere upon a given place on earth will depend on the time of year, the time of day and the latitude at that place. This dependence is a consequence of the earth being spherical, rotating around its axis and following an elliptical orbit while it rotates around the sun.

The actual amount of solar radiation per unit area at the top of the atmosphere falling on a plane parallel to the earth's surface at the corresponding latitude, for a particular time of year and time of day, can be calculated using well known astronomical formulas (**Appendix A**). Its daily amount is usually known as the extraterrestrial solar radiation (R_a).

The daily amount of solar radiation incident on a horizontal surface at the top of the atmosphere, integrated from sunrise to sunset and thus independent of the time of day, can be expressed by (Sellers, 1965),

$$\mathbf{R_a = S\ (1\ 440 / \pi)\ (D_m / D)^2\ (H \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin H)}$$

Where

D - The actual distance to the sun at that day,

δ – Solar declination angle

φ – Latitude of the observation measurement

H – The half–day length

Observe that this formula is correct only if **S** is given in calories/m ^{2} – min. If **S** is given in watt/m ^{2} then the numerical factor 1 440, the number of time minutes in one day, must be changed by multiplying by 60 to obtain the value 86 400. The final value of $\mathbf{R_a}$ will be expressed then in $\mathbf{J/m^2}$. The usual practice is expressing the numerical value in $\mathbf{MJ/m^2}$.

In the equinoxes at the equator we have that $\boldsymbol{\varphi = \delta = 0}$ and **H = 6 hours = 90 degrees**. For this particular case, and assuming that ($\mathbf{D / D_m}$) is very near unity, we would have that,

$$\mathbf{R_a = S\ (86\ 400 / \pi) = 27\ 502\ S = 38.3\ MJ/m^2}$$

Global solar radiation incident on a horizontal area at the ground

Almost 99 percent of extraterrestrial solar radiation is contained in the so-called short wavelengths. In energy units about 9 percent is in the ultraviolet, 45 percent is in the visible and 46 percent in the infrared regions of the spectrum (Sellers, 1965). Entering the atmosphere this radiation is subject to many processes of reflection, absorption and scattering by aerosols, clouds and atmospheric gases before reaching the ground in the form of direct (**Q**) and diffuse (**q**) solar radiation.

Global solar radiation ($\mathbf{R_g}$) reaching the ground and actually measured by special instruments at selected so-called actinometrical meteorological stations, is then defined as,

$$\mathbf{R_g = Q + q}$$

The reader should be aware that, upon reaching the ground, a sizable fraction of global solar radiation is reflected back to the atmosphere and the space beyond depending on the reflectivity (albedo) of the surface.

The short wave radiation balance of the surface can then be expressed as,

$$\mathbf{R_{0\,s} = (1 - a)\ R_g}$$

Where the albedo (**a**) of the surface can have values as low as 0.06 for water surfaces, it lies between 0.15 and 0.25 for crops and natural vegetation and can be as high as 0.95 over fresh snow covers. Only the amount of energy expressed by $\mathbf{R_{0\,s}}$ is actually available for driving processes at the surface, such as photosynthesis, evaporating water and heating the ground.

It can be seen here that climate variability and even climate change could be generated in principle by variations in $\mathbf{R_g}$, caused by fluctuations in solar constant (**S**) or by changes in planetary albedo through altered patterns of tropospheric and stratospheric aerosols, cloud cover and absorption by gases. These kinds of phenomena could be caused also by variations in surface albedo, as in glacial ages, when extensive ice cover of ground and sea areas introduced feedback effects reflecting back to the atmosphere, and space beyond, a large fraction of actually solar radiation reaching the ground. Hazards leading to these types of fluctuations could be related to a huge asteroid falling on Earth, volcanic and super volcanic eruptions and gigantic firestorms caused by limited nuclear war and leading to the so-called nuclear winter (Velikhov, 1995).

Terrestrial radiation

The short-wave balance term $\mathbf{R_{0\,s}}$ is that fraction of sunlight reaching the ground that is actually available for heating the ground and fuelling processes such as photosynthesis and evaporation of water. If our planet had no atmosphere at all, consisting of bare rock as an asteroid or an airless world as Mercury, this balance term would be completely used in heating the ground. If we assume that a chunk of rock such as an asteroid radiates as a blackbody, then its warmed surface would irradiate by the Stefan-Boltzmann law in such a way that,

$$\mathbf{T_r = \sigma\, T^4}$$

Where $\boldsymbol{\sigma} = \mathbf{5.67 * 10^{-8}\ W / m^2 - K^4 = 1.17 * 10^{-7}\ cal / cm^2 - day - K^4}$ is the Stefan-Boltzmann constant and $\mathbf{T_s}$ is the surface temperature of the body. Usually it is assumed that surfaces radiate as grey bodies in the infrared. In this case the emitted radiation by a heated body would be given by the Stefan – Boltzmann law,

$$\mathbf{T_r = \varepsilon\, \sigma\, T_s^4}$$

In this last formula $\boldsymbol{\varepsilon}$ is the infrared emissivity (and absorptivity) of the surface and equal to unity for black bodies.

Under the action of the shortwave balance term the object in question would be heated (We can assume that the body's initial temperature is as low as 0.0 K.) and radiates energy in the infrared sector of the spectrum until the radiated energy results are equal in magnitude to the shortwave balance term and the body itself reaches equilibrium at a given temperature T.

For a case as this we would have that,

$$\mathbf{R_{0\,s} = (1 - a)\, R_g = \varepsilon\, \sigma\, T_s^4}$$

allowing us to estimate actual temperature of the body knowing the short wave radiation balance. For actual blackbodies we have **a = 0** and **ε = 1**. It is then possible to calculate (**Exercise 1**) if we substitute planet Earth by a blackbody of the same size at the same position then we would have that,

$$\mathbf{T_s = 278.997\ K = 5.83\ degrees\ Celsius}$$

If we take into account that the actual value of planetary albedo is very near **a = 0.28**, our planet not being a blackbody, the actual value obtained for planet Earth would then be,

$$\mathbf{T_{s\ Earth} = 257\ K = -\ 16.17\ degrees\ Celsius}$$

At this temperature the maximum radiated energy by our planet surface would be in the region of the spectrum near 11 300 nanometres, corresponding not to the visible wavelengths, but to the far infrared. But it happens that climatology tells us that the mean surface temperature of our planet is very near 288.12 K (15 degrees Celsius). The problem is that our planet has an atmosphere.

Long-wave radiation balance

The far infrared terrestrial radiation emitted by our planet surface would be completely lost to outer space if our planet did not have an atmosphere. Actually, a sizable fraction of terrestrial radiation is absorbed by atmospheric components that can be gases (water vapour, carbon dioxide and other greenhouse gases as methane and chlorofluorocarbons) or aerosols made of water droplets (clouds) and other chemical substances as sulphates. These atmospheric components are then also heated and start radiating as grey bodies following laws analogous to the Stefan –Boltzmann one. As this radiation is emitted by atmospheric components in all directions a sizable part of it is radiated back to the surface as counter radiation.

Designating terrestrial radiation previously described as $\mathbf{I_{up}}$ and counter radiation as $\mathbf{I_{down}}$, we arrive at the long wave radiation balance term as.

$$\mathbf{I_{up} = I\ (a)_{up} + I\ (s)_{up}}$$

$$\mathbf{I\ (a)_{up} = I_{down} + I\ (as)_{up}}$$

$$\mathbf{R_{0\ l} = I_{up} + I_{down}}$$

Where:

$\mathbf{I\ (a)_{up}}$ – Infrared radiation from the earth’s surface absorbed by the atmosphere

$\mathbf{I\ (s)_{up}}$ - Infrared radiation from the earth’s surface lost to outer space

$\mathbf{I_{down}}$ – Infrared radiation from the atmosphere absorbed at the ground (counter radiation)

$\mathbf{I\ (as)_{up}}$ – Infrared radiation from the atmosphere lost to outer space

Reordering terms we arrive at the final expression,

$$\mathbf{I_{up} = I\ (a)_{up} + I\ (s)_{up} = I_{down} + I\ (as)_{up} + I\ (s)_{up}}$$

$$\mathbf{R_{0\ l} = I_{up} - I_{down} = I\ (as)_{up} + I\ (s)_{up}}$$

This last formula constitutes the long wave radiation balance of the surface. This variable is also known as the effective outgoing radiation from the earth's surface.

Any factor altering the counter radiation term in the long wave radiation balance will lead to climate variability and change. That is the basic theory behind climate change. Since the beginning of the Industrial Revolution man's activities related to the burning of fossil fuels as oil, gas and carbon have been increasing the atmospheric concentrations of carbon dioxide. In combination with other agricultural and industrial practices the atmospheric concentrations of methane, nitrous oxides, tropospheric ozone and chlorofluorocarbons have also increased. This effect is compounded with very high rates of deforestation and changes in land use conducive to higher emissions of these so-called greenhouse gases. As the radiation balance term that remains for warming the surface of the planet is continuously increasing (because greenhouse gases atmospheric concentrations are also increasing) this effect leads to the so-called radiative forcing term in the balance equation. More available energy at the surface is conducive to more available energy for the evaporation of water leading to the continuous increase of water vapour in the atmosphere, in fact one of the most effective greenhouse gases, through a very well known positive feedback effect.

The precise calculation of $\mathbf{R_{0\,l}}$ is a very complicated physical-mathematical task that cannot be included in this workbook. As the approximate estimation of the radiation balance terms is crucial for many practical purposes, we will be discussing a simple formulation for this purpose. The reader should be aware that the formulations that follow cannot be directly used to estimating actual global warming caused by climate change.

The effective outgoing radiation term $\mathbf{R_{0\,l}}$ will be calculated here by the so-called Angstrom and Brunt formulas (Sellers, 1965). Even if there are a handful of even more precise formulations for this purpose (Wieringa and Lomas, 2001), this approach has the advantage that the greenhouse effect of water vapour is explicitly stated and that the Angstrom and Brunt formulas have been extensively divulged in FAO reports (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Oldeman and Frere, 1982). The reader should be aware that empirical constants in these formulas may diverge in different textbooks. Brunt's formula follows,

$$\mathbf{R_{0\,l} = (-1)\,\varepsilon\,\sigma\,T^4\,(0.395 - 0.048\,\sqrt{e})}$$

Where $\mathbf{e}$ is the actual water vapour pressure at station level (hPa) and $\mathbf{T}$ must be given in Kelvin. The negative unit is included here because the effective outgoing infrared radiation is usually taken as positive when it is directed towards outer space and then it has the same sign as the reflected short wave term given by $\mathbf{(-1)\,a\,R_g}$.

The surface radiation balance

Combining the formulation discussed we arrive at a final expression for the surface radiation balance ($\mathbf{R_0}$) as given by,

$$\mathbf{R_0 = R_{0\,s} + R_{0\,l}}$$

$$\mathbf{R_0 = (1 - a)\,R_g - \varepsilon\,\sigma\,T^4\,(0.395 - 0.048\,\sqrt{e})}$$

The significance and meaning of the surface radiation balance cannot be overstated. It represents all the available energy to drive processes on the earth's surface, especially those having to do with heating the soil and adjacent atmosphere as well as for melting ice and evaporating water.

According to Budyko, the radiation balance (cal / cm ^{2} – year) can be estimated by the following empirical formula, where $\mathbf{T_m}$ is now the mean annual ordinary screen temperature in degrees Celsius,

$$\mathbf{R_0 = 3\ 650\ T_m}$$

and the potential ability of the atmosphere to evaporate liquid water in millimetres/year (a parameter known as potential evapotranspiration) could be approximated by,

$$\mathbf{E_0 = R_0 / L = 61.864\ T_m}$$

Where $\mathbf{L = 597 - 0.56\ T_m}$ is the latent heat of condensation for water vapour in cal/g.

For a mean annual temperature of 24.0 degrees Celsius at screen height these formulas imply that,

$$\mathbf{R_0} = 86\ 700 \text{ cal/cm}^2 - \text{year}$$

$$\mathbf{E_0} = 1484.7 \text{ mm/year}$$

The surface radiation balance ($\mathbf{R_0}$) has been used, alone or in combination with other balance terms, to build an entire set of so-called climatic and bioclimatic indexes very useful for preliminary assessments of climate change impacts on forests and natural ecosystems.

THE SURFACE ENERGY BALANCE

As we already know what the radiation balance is and how it can be estimated, we are in a position that allows us to examine how this energy is expended in terrestrial processes. According to Sellers (1965) the energy balance equation can be expressed as,

$$\mathbf{R_0 = H + LE + G + \Delta F}$$

Where,

H – Sensible heat energy transferred from (or to) the surface to (from) the adjacent atmosphere

E – Amount of water evaporated from the surface

LE – Latent heat of the evaporated water

G – Vertical energy transfer into the soil

Δ F – Lateral transfer of heat from a column with unit area

In land surfaces this last column may extend from 5 to 30 metres below soil surface while in water surfaces the depth of this column may reach more than 600 metres below sea surface. The last term comprising subsurface heat transport in and out of the column is negligible for land surfaces, simplifying this equation to,

$$\mathbf{R_0 = H + LE + G}$$

Meaning that the available energy (**R_0**) is being used to warm the air (**H**), evaporate water (**LE**) and heat the ground (**G**).

The storage term **G** is seasonally variable because in some months the ground is receiving energy and upper layers of the ground are transferring energy to lower soil layers, while in other months deep soil layers transfer energy to upper layers. If there are no secular changes or trends (climate change) this storage term **G** can be neglected in the annual heat balance of the surface (but not on a monthly basis), leading to the following annual energy balance equation,

$$\mathbf{R_0 = H + LE}$$

The flux of sensible heat (**H**) allows us to define our first climatic index (Bowen's ratio) as,

$$\mathbf{Bo = H / LE}$$

This index has been widely applied in climate studies and recommended by Rivero et al (1998) as a useful parameter for the monitoring of meteorological and agricultural drought.

To estimate the sensible heat flux (**H**) we need to estimate not only the radiation balance term (**R_0**), but also the actual amount of water (**E**) evaporated from the soil – water – ecosystem on the surface. To do this solving, the water balance equation is the most recommended procedure.

THE SURFACE WATER BALANCE

The water balance equation is most complicated and laborious to solve. It also happens that a water balance equation can be as complicated as you wish depending on the problem that needs to be solved and the accuracy that is needed. We will be examining only simple general cases. The complexity of the water balance problem is best appreciated by making a somewhat artificial description of the processes at hand.

Let us assume that a certain amount of precipitation water (**P**) can be measured at the top of a crop field before entering the canopy. Before reaching the soil part of this, water is retained (intercepted) in the canopy where it has two possible futures, being evaporated into thin air or flowing down over leaves and stems and even dripping from the foliage. Only part of the original water reaches soil level. Another part of the initial water falls unimpeded to the top of the soil layer that now is receiving it in various ways.

Reaching soil level this water does not necessarily go into the soil, because it is usually covered by debris and plant residues that allow the water to flow over it for some distance before it reaches true soil to infiltrate, the so-called "tile" effect.

Infiltration of rainwater into soil depends on soil nature and structure (an infinite diversity of soil nature) depending not only on the soil itself, but on its previous history and antecedent conditions (dry or wet). A certain fraction of this water never infiltrates the soil and appears as surface runoff (immediate one) flowing to lower heights or even accumulating in ponds. The fraction of water that really infiltrates deeper soil layers does so according to differential equations (Kalma and Calder, 1994; Sivakumar et al, 1991).

Water that remains in the crop root zone becomes available to vital crop processes, while that amount of water goes beyond that depth and is said to percolate to deep soil and can eventually appear as subsurface runoff, ground water, or aquifer recharge. Some part of it appears later, as it happens with surface runoff, in brooks, streams, and rivers eventually flowing into lakes, artificial reservoirs, and the sea.

Once in the soil or over it, the initial water is now available for evaporation, from soil or water surfaces, and is transpired into the atmosphere again by vegetative cover. This water vapour goes into new clouds and precipitation systems and the process itself is closed – the so-called hydrological cycle.

In looking at the complexity of these processes it is not surprising at all that you cannot find two scientific papers or crop models solving the same set of water balance equations.

The Budyko – Sellers model

In this section we will be concerned with a very simple model, the Budyko – Sellers model, not allowing for interception and having to do with a single term named water surplus (**S**) that contains eventually all that water that does not infiltrate the soil and appears as runoff.

Let us assume an isolated soil layer able to retain against gravity forces a maximum amount of water given by $\mathbf{w}_{max}$ whose initial water content (millimetres) is given by $\mathbf{w}_1$. Our water balance equation, neglecting dew contribution, will then be given by,

$$\mathbf{w}_2 = \mathbf{P} + \mathbf{w}_1 - \mathbf{E} - \mathbf{S}$$

Where,

$\mathbf{w}_2$ – Water remaining in the soil after a certain time period (hours, days, months and years)

P – Total precipitation during specified period

E – Total amount of water evaporated from the soil plus that amount transpired by crop

S – Surplus water not contributing to soil humidity and eventually leading to runoff

As we can easily see only **P** is usually measured in meteorological stations. Even if $\mathbf{w}_1$ is measured many times in specialized agricultural meteorological stations we will see that this initial value can become irrelevant for our purposes in solving the water balance equation. That leaves us with a difficult mathematical problem of having only one equation with three or four unknowns.

In this very simple model soil represents only one use and that is to store liquid water, let us say a sponge. Soil water can vary from **0** to $\mathbf{w}_{max}$, usually in the range 100 – 200 mm. No water is allowed to percolate deeper than the soil depth necessary to contain that amount of water, because there is only one soil layer. The depth of the soil will never enter in the calculations to be made. In crop models the parameter $\mathbf{w}_{max}$ is usually taken as a soil parameter measured in practice with the name of field capacity (**FC**). The value **w = 0** is taken as the limit amount of water that the soil can withhold and still be available to plants through their root system. This amount of water left in the soil, but adhered to soil particles by forces so strong that plants cannot make any use of it, is named the wilting point (**WP**) and is not necessarily zero. In agronomy and crop models the parameter **FAW = FC – WP** is considered the maximum freely available water to plants for that soil. In our simple model **w** is only a representation of soil humidity allowed to vary in the range (**0, FAW**). **FC** and **WP** can be considered as a function of soil texture, meaning the relative amount (%) of sand, silt, and clay particles in soil. The real problem is more complex because **WP** could be different among crops and **FC** could depend on soil compactness and organic matter content. Soil sciences are rather complex by themselves which is the reason why we cannot go any deeper in the analysis of the physical properties of soil, not even trying to discuss its chemical and biological ones. The reader can see better into these subjects in specialized textbooks (Bruce and Clark, 1969) and FAO reports (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Oldeman and Frere, 1982). To find in a clearly stated way the necessary information needed to fully understand the relevant soil properties and processes, we need in crop modelling is not an easy task.

Total (real) evapotranspiration (**E**), a concept slightly different from evaporation because this last one does not specifically refer to the process of plant transpiration, is partitioned in many models by the following formulation,

$$\mathbf{E = E_s + T_p}$$

Where $\mathbf{E_s}$ is water directly evaporated from soil surface and $\mathbf{T_p}$ is the amount of water actually transpired by plants or crop canopies. Given the root system characteristics of plant ecosystems, transpired water comes from deeper layers in the soil and not necessarily from its surface.

The estimation of this term of the water balance equation requires the introduction of a new concept named potential (reference) evapotranspiration ($\mathbf{E_0}$). Theoretically speaking, potential evapotranspiration should be a physical magnitude that depends only on atmospheric variables. The number of approximate expressions trying to find a suitable formulation with this meaning is countless (Sellers, 1965; Riabchikov, 1975; Doorenbos and Pruitt, 1977; Benioff et al, 1996). Its measuring instruments also appear to be countless (Class A water pan, soil evaporimeters and lysimeters). Many practical definitions have been adopted in engineering. The parameter "total evaporated water from a complete cover canopy of Sudan grass (Sorghum sudanensis) of a specified height completely supplied with water" has been used many times as a measure of potential (reference) evapotranspiration. For our present purposes we could assume that $\mathbf{E_0}$ is being determined by the Penman – Monteith approach (Allen et al, 2000). Formulas involved are so complex that they require knowing a whole set of meteorological variables, even some which are not usually measured in standard meteorological stations.

The reader should be aware that, different from the rest of atmospheric gases, water vapour cannot be mixed with dry air in a previously chosen arbitrary proportion. At a given temperature (**T**) dry air can contain a maximum amount of water vapour given by the so-called water vapour saturation pressure that can be calculated by a lot of slightly different formulas, namely Teten's formula given by,

$$\mathbf{e_s(T) = \exp((19.079\,T - 4782.9) / (T - 35.9))} \quad \textbf{with T in Kelvin}$$

$$\mathbf{e_s(T) = 6.11 * 10 \wedge [7.5\,T / (T + 237.6)]} \quad \textbf{with T in degrees Celsius}$$

This fact accounts for, partially at least, the existence of such a concept as potential evapotranspiration. Other reasons justifying its existence reside in the limited rate at which roots can extract water from a soil and at which water in deep soil layers can flow upward to its surface to be evaporated. In this section of our book it will be sufficient to know that the potential evapotranspiration concept has a definite physical meaning and that we will always have some, even if crude, way of estimating its real values.

Actual evapotranspiration (**E**) can be estimated using an appropriate model for the soil drying process, additional to the procedure of estimating **E** as a residue once we estimate or measure **P**, $\mathbf{w_1}$, $\mathbf{w_2}$ and **S**. In our simple two soil drying stages model (Covey and Bloodworth, 1966) it is usually assumed that (Figures 2.1 and 2.2),

$$\mathbf{E = E_0} \qquad \textbf{if } \mathbf{w_m > w_k} \quad \text{- First soil drying stage}$$

$$E = (w_m / w_k) * E_0 \ \text{ if } w_m < w_k \qquad \text{- Second soil drying stage}$$

Where w_m is mean soil water content during a specified time period and $w_k = k\, w_{max}$ is a threshold soil humidity below which real crop evapotranspiration rate (**E**) starts decreasing in relation to potential rate (E_0) . Even if not always true, it is normally assumed that,

$$w_m = (w_1 + w_2) / 2$$

Parameter **k** is generally taken as **0.75**, but readers should be aware that this parameter depends on soil type and specific crops. The model described is a very general one so as to enable us to obtain general conclusions. During the life cycle of a given crop its crop potential evapotranspiration, (E_{0c}), will depend on crop phenological stage and will not be equal to reference potential evapotranspiration, in such a way that $E_{0c} = k_c E_0$ where k_c are the very well known FAO crop coefficients (Doorenbos and Pruitt, 1977; Allen et al, 2000). This fact can be taken into account when changing the model equations in an appropriate way.

As we can calculate E_0 and we have already additional equations for **E**, even if with an implicit dependence of w_m, we have now one balance equation with only two unknowns, **S** and w_2 (or w_m). In this approach, that we have come to call Budyko – Sellers, our system of equations is closed postulating a reasonable expression for **S** which is explicitly dependent on w_m. The postulated expression reads as:

$$S = B * P * (w_m / w_{max})$$

Where **B** is an empirical parameter adjustable to actual climate – soil local interactions. The original expression recommended by Sellers for the United States reads as,

$$B = 0.8 * P / (E_0 + P)$$

Substitution of these expressions in the original balance equation leads to two alternative expressions for w_m,

$$w_m(1) = (P - 2 * w_1 - E_0) / [2 + (B * P / w_{max})]$$

$$w_m(2) = (P - 2 * w_1) / [2 + (B * P / w_{max}) + (E_0 / w_k)]$$

If $w_m(1) > w_k$ then $w_m = w_m(1)$ else $w_m = w_m(2)$.

Once the appropriate expression for w_m has been chosen additional conditions are imposed such as,

If $w_m > (w_1 + w_{max})$ then $w_2 = w_{max}$ and $w_m = (w_1 + w_{max}) / 2$

If $w_m < w_1 / 2$ then $w_2 = 0$ and $w_m = w_1 / 2$

The reader should be warned that these formulas are not foolproof and may give irrational results for some cases leading to negative **S** values, erroneous **E** values and final values of **P**, w_1, w_2, **E** and **S** leading to the left hand side of the balance equation not being equal to the right hand side. The additional necessary corrections have been introduced by this collection of authors and derive from the definition of w_m in the model.

The Thornthwaite – Mather model

This water balance model is superficially treated here only for completeness and because it was in its times widely distributed and referred to. According to its description by Sellers (1965), this formulation starts by deciding if the precipitation (**P**) during the time period considered is lesser or greater than the potential evapotranspiration ($\mathbf{E_0}$).

If $\mathbf{P < E_0}$ then the following decision process follows,

$$\mathbf{S = 0}$$

$$\mathbf{E = P + (E_0 - P) * (w_m / w_{max})}$$

Leading to,

$$\mathbf{w_2 = w_1 - (E_0 - P) * (w_m / w_{max})}$$

The solutions to these formulas can be explicitly stated as,

$$\mathbf{S = 0}$$

$$\mathbf{w_2 = [1 - ((E_0 - P) / 2 * w_{max})] * w_1 / [1 + ((E_0 - P) / 2 * w_{max})]}$$

$$\mathbf{w_m = (w_1 + w_2) / 2}$$

$$\mathbf{E = P + (E_0 - P) * (w_m / w_{max})}$$

But if $\mathbf{P > E_0}$ then the following decision process takes place,

$$\mathbf{E = E_0}$$

$$\mathbf{S + w_2 = P - E_0 + w_1}$$

Where if $\mathbf{P - E_0 + w_1 > w_{max}}$ then,

$$\mathbf{w_2 = w_{max}}$$

$$\mathbf{S = P - E_0 + w_1 - w_{max}}$$

Otherwise if $\mathbf{P - E_0 + w_1 < w_{max}}$ then,

$$\mathbf{w_2 = P - E_0 - w_1}$$

$$\mathbf{S = 0}$$

Sellers criticized this formulation because it only allows a water surplus **S** in some (not in all) cases where $\mathbf{P > E_0}$. This is a particularly harmful and annoying fact in tropical countries where $\mathbf{E_0}$ can attain very high values in the rainy season when precipitation values are higher, but maybe not so high as to lead to **S** values different from zero. This problem can be avoided by introducing additional constraints like establishing a rule such that a certain fraction of precipitation appears as runoff before water has been able to infiltrate the ground. The exact value of this fraction would be dependent on soil type, cover and soil humidity antecedent conditions which lead to highly clumsy and empirical formulations.

Simplification for multiannual water balance equation

The original water balance equation we have been using, given by $\mathbf{w_2 = P + w_1 - E - S}$ is very often simplified when we are characterizing water balance for a multiannual period composed of **M** years (usually taken as 30 years normal as defined by WMO). If we state this equation for every individual year **j** we would obtain that,

$$\mathbf{w_{2\,1} = P_1 + w_{1\,1} - E_1 - S_1}$$

$$\mathbf{w_{2\,2} = P_2 + w_{1\,2} - E_2 - S_2}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\mathbf{w_{2\,j} = P_j + w_{1\,j} - E_j - S_j}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\mathbf{w_{2\,M} = P_M + w_{1\,M} - E_M - S_M}$$

Adding these **M** equations and realizing that $\mathbf{w_{2\,j+1} = w_{1\,j}}$ we obtain the following representative balance equation for **M** years as,

$$\mathbf{w_{2\,1} = SUM\ P_j + w_{1\,M} - SUM\ E_j - SUM\ S_j}$$

As $\mathbf{w_{1\,j}}$, $\mathbf{w_{2\,j}}$ are limited in value to be equal or less than $\mathbf{w_{max}}$, they can be neglected compared to $\mathbf{SUM\ P_j}$ and $\mathbf{SUM\ E_j}$ leading to,

$$\mathbf{SUM\ P_j} = \mathbf{SUM\ E_j} + \mathbf{SUM\ S_j}$$

Dividing by **M** years we arrive then to a representative water balance equation valid for long time periods as,

$\mathbf{P = E + S}$ … water balance equation for multiyear periods

Alternatively, we could consider the small term $\mathbf{[(w_{2\,1} - w_{1\,M}) / M] << w_{max}}$ included as a correction for **S**.

This last form of the water balance equation is the one usually taken for the definition of climatic and bioclimatic indexes.

The atmosphere water balance

Even if we are not dealing with this problem here, the reader should be aware that an atmosphere water balance can also be established. For that case precipitation (**P**) would be an output variable instead of an input one to the surface water balance and the reverse would be true for real evapotranspiration (**E**). The combination of both balance equations close the hydrological cycle and can be used to obtain valuable information and establishing useful relationships among atmosphere processes and meteorological and agricultural droughts (Rivero y Miguel, 1992; Rivero et al, 1999 a and b).

THE BIOMASS BALANCE

Every terrestrial landscape, except perhaps deserts and ice fields, has a vegetative cover that can be partial (semi deserts) or complete (tropical jungles) and can also be natural (Amazonian rainforests) or man made (crop fields as sugar plantations and wheat fields). A whole diversity of plants species live there as primary producers of food for animal populations, including man. In this section we will be referring specifically to crop fields even if the concepts involved are much more general and can be extended to lakes and marine ecosystems.

Under a set of specific environmental conditions such a plant formation has an upper limit beyond which total live dry matter per hectare cannot be increased. This limit is what we will be designating as Potential Biomass Density (**PBD**). The rate at which a given plant formation is increasing its dry matter density per year will be designated as Net Primary Productivity (**NPP**) of that plant formation. Concepts related to the productivity of plants ecosystems are usually discussed in agronomical and ecology textbooks (Odum, 1971; Colinvaux, 1993).

Total fresh weight of plants and plants organs can have as much as 60 – 90 percent water (80 – 82 per cent for potatoes), and this water could be considered as part of the water balance equations. The rest is what we call dry matter, consisting mainly of carbon, nitrogen, phosphorous and other chemical elements combined to form carbohydrates, oils, proteins and other substances. Carbon is the most abundant element in dry matter (about 50 percent of it) and that is why a biomass balance equation can be considered as a carbon balance one (Colinvaux, 1993; Rivero et al, 2004). In all subsequent discussions the reader should be aware that processes concerning biomass production will be extensively discussed in Chapter 5 of this workbook. Only a minimum amount of information necessary to explain climatic and bioclimatic indexes and its relationships with the productivity of natural and agricultural ecosystems will be given here.

Carbon included in dry matter of plants comes from the atmosphere, where it exists in the form of carbon dioxide. Carbon is sequestered from the atmosphere using solar energy available to plants and through a rather complicated – enzyme mediated – physiological process known as photosynthesis. The new carbon atoms obtained in this way are incorporated into previously existing substances in plants leading to the formation of hexoses (sugars). The amount of daily sugar production per unit area is known as gross photosynthesis ($\mathbf{B}_{gj}$).

Once photosynthesis has been completed plants have to use that sugar, together with other nitrogen and mineral compounds entering the plant from the soil diluted in water, to build complex carbohydrates, oils, proteins and other necessary chemical compounds. Those processes require an additional source of energy. That energy is obtained by oxidizing (burning) part of the sugar produced by photosynthesis in a process known as respiration. The remaining amount of produced sugar is known as net photosynthesis or net biomass production ($\mathbf{B}_{nj}$). This leads to the biomass balance equation for day **j** given by,

$$\mathbf{B}_{nj} = \mathbf{B}_{gj} - \mathbf{r}_j$$

The apparent simplicity of this equation hides the fact that calculations of gross photosynthesis and respiration rates are very complicated and require the specification of many physiological processes, genetically and environmentally conditioned, taking place in plants.

The Chikugo Model

As an example of how relevant terms of the biomass balance equations may be calculated we state here what has commonly named as the Chikugo Model (Gommes et al, 2007). According to this model we have that,

$$\mathbf{NPP = 6.938 * 10^{-7} * R_0 * exp\,[-3.6 * 10^{-14} (R_0 / P)^2]}$$

Where (**R_0 / P**) is proportional to the Budyko radiative index of dryness (**B**) that will be defined in the next section. In using this formula one must be aware that **NPP** is expressed in g DM/m ^{2} – year, **R_0** is expressed in J/m ^{2} and **P** in millimetres (kg/m ^{2}).

CLIMATIC AND BIOCLIMATIC INDEXES

Not everybody is aware that global vegetation maps were made before climatic indexes were introduced in scientific works. In fact when pioneering works (as Koppen climate classification) were made the climate classification itself was derived from actual vegetation maps. This denotes that vegetation distribution is markedly conditioned by climate. In a similar way the first World Atlas of Desertification (UNESCO, 1977) was derived from the values of the Budyko radiative index of dryness (aridity) while the second World Atlas of Desertification (UNEP, 1992) was derived from what we will be referring to here as the UNEP aridity index. It would be interesting to show that this latter index is practically the inverse of the first one.

Indexes are generally created by combining in a suitable way some important terms of the four balance equations already discussed. Climate and bioclimatic indexes try to define or characterize climates and landscapes by using a single parameter that can be related to the productivity and other relevant parameters of actual or potential ecosystems present in a given area of our planet. That can be done directly or indirectly. In the first case an index is directly related to **NPP** or **PBD** of ecosystems while in the second one the index is related to some landscape characteristic (aridity or other) from which plant ecosystems can be characterized. Many well known indexes are described in the referenced literature corresponding to this and other chapters of our workbook. Only some of them will be explicitly described below. The reader should be aware that the definition of an index automatically implies a classification of its values, usually tabulated or in graphic form. In some important cases the relationship between the index itself and relevant parameters of ecosystems can be expressed in the form of an algebraic equation. Some tabulated indexes are shown in **Appendix B.**

The Budyko radiative index of dryness (B)

This index is defined by the expression,

$$\mathbf{B = R_0 / (L * P)}$$

Where the radiation balance **R_0** must be expressed in Kcal/cm ^{2} – year and **P** in centimetres/year. This index was related by Budyko to total real evapotranspiration from hydrological basins through the formula,

$$\mathbf{E = P * \{B*[1 - cosh\,(B) + sinh\,(B)] * tanh\,(1 / B)]^{1/2}}$$

This very useful expression was used by Rivero et al (2005) for estimating the impact of climate change on water resources for the province of Camagüey, Cuba.

The UNEP aridity index (K)

$$\mathbf{K = P / E_0}$$

Where **P** and $\mathbf{E_0}$ are now expressed in the same units.

A simple analysis shows that if we take the approximation $\mathbf{E_0 = R_0 / L}$ we arrive at the conclusion that,

$$\mathbf{B = E_0 / P = 1 / K}$$

$$\mathbf{B * K = 1}$$

Both indexes are very closely related to aridity. In fact, the United Nations Convention to Combat Desertification (CCD, 1995) used a classification of climates based on **K** to define dry subhumid climates (**K < 0.65**) and state that only this type of climate (or drier than it) should be considered as prone to the development of desertification processes.

The Riabchikov index (Ria)

The Riabchikov index have been used by Rivero et al (1999 b, 2000 and 2004) to estimate climate change impact on natural ecosystems such as forests. It happens that this index has been directly related with **NPP** of ecosystems. Its definition follows,

$$\mathbf{Ria = W / R_0}$$

Where $\mathbf{R_0}$ must be measured in kcal/cm ^{2} – year and **W** is identified as the so-called productive (soil) moisture in millimetres/year. For all practical purposes this collection of authors have identified this concept with that of annual real (actual) evapotranspiration of the ecosystem in the simplified water balance equation. This means defining this index as,

$$\mathbf{Ria = E / R_0}$$

No special effort was made by Riabchikov to unify measuring units here, so for Camagüey with $\mathbf{R_0}$ = 85 Kcal/cm ^{2} – year and **E** = 900 mm/year has a Riabchikov index of **Ria** = 10.59. In Riabchikov climate classification this corresponds to seasonally wet (monsoonal) forests.

Riabchikov's work went even farther when he defined the hydrobiothermical potential (**HBP**) as,

$$\mathbf{HBP = Ria * (T_{veg} / 36)}$$

Where $\mathbf{T_{veg}}$ is the duration of the growth period in decades (ten days periods).

In graphic form this collection of authors derived a (practically) linear relationship between **NPP** and **HBP**. The adjusted linear relationship can be represented as,

$$\mathbf{NPP = a + b * HBP}$$

In these formulas **NPP** is expressed in tons of dry matter per hectare. This collection of authors adopted the values **a = - 1.4457087** and **b = 2.6838024** for the adjusted formula.

The ecological aridity index (R).

Even if this index has been used before, without specifying a name for it, the ratio between actual (real) and potential evapotranspiration has been called the ecological aridity index by Rivero et al (1996 and 1999 b).

$$\mathbf{R = E / E_0}$$

Authors had defended the criterion that **R** is a better parameter to define climates, especially climates prone to desertification, because the calculation of **E** requires knowledge of the soil and then it takes into account a kind of drought that cannot be ascribed to climate conditions, but to the inability of the soil-crop system to exchange water. The problem causing this kind of drought resides in the soil itself. That is not possible with other usual climatic indexes and such kinds of soils cover large areas in Camagüey.

In fact, our Agricultural Drought Early Warning System (Rivero et al, 1996 and 1999 b) uses the UNEP aridity index **K** as a predictor for the onset of agricultural drought defined by **R**. In a rather different way, index **R** can be directly related to agricultural yields without having to recur to statistical relationships, using the following (modified) relation proposed by Doorenbos and Kassam (1979),

$$\mathbf{[1 - (Actual\ yield / Potential\ yield)] = k_y\ (1 - R)}$$

This problem will be further discussed in Chapter 4 and 5 of this workbook.

Lieth formulas

Lieth (Colinvaux, 1993) introduced two very well known formulas for estimating **NPP** of ecosystems, one when **NPP** (g DM/year) is considered as limited by temperature (**NPPT**) and another when **NPP** is considered as limited by precipitation (**NPPP**). This approach has been called the “Miami Model” by Grieser et al (2006).

$$\mathbf{NPPT = 3000 / [1 + \exp(1.315 - 0.119*T)]}$$

$$\mathbf{NPPP = 3000 * [1 - \exp(- 0.000664 * P)]}$$

$$\mathbf{NPP = minimum\ (NPPT, NPPP)}\ \text{in g DM/year}$$

Other complex indexes and relationships

Using this type of approach many authors have obtained useful relationships between **NPP** and precipitation (Martín et al, 1987), **NPP** and biotemperature (Holdridge Life Zones) in Benioff et al (1996), **NPP** and real evapotranspiration (Colinvaux, 1993) and others. That practically all indexes can be expressed as functions of other similar ones was demonstrated by Rivero et al (1999 b).

None of these formulations takes into account the carbon dioxide fertilization effect. To make a correction to these formulas for future climates, the following formula, used in different versions of the CENTURY model (Parton et al., 1992) may be used,

$$\mathbf{NPP\ future\ climate = [1 + \beta \ln (C_f / C_r)] * NPP\ reference\ climate}$$

Where $\mathbf{C_r}$. $\mathbf{C_f}$ are the atmospheric carbon dioxide concentrations in the reference and future climate. We have here an adjustable parameter $\boldsymbol{\beta}$ which lies in the range 0.0 – 0.7 and behaves in such a manner that lower values correspond to almost pure **C_4** ecosystems (sugarcane fields) and higher ones correspond to almost pure **C_3** ecosystems (seasonal tropical forests).

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APPENDIX A

Astronomical expressions needed for the calculation of daily extraterrestrial solar radiation.

We start this derivation by stating that,

$$\cos Z = A_n / A_k$$

where,

Z – zenith angle of the sun relative to the vertical axis

A_k – an element of area parallel to the earth's surface at the top of the atmosphere

A_n – the projection of A_k on a plane normal to the sun's rays at the top of the atmosphere

From the very definition of the solar constant (**S**) we can then conclude that,

$$S\,(D_m / D)^2 A_n = Q_n A_k$$

$$Q_k = S\,(D_m / D)^2 \cos Z$$

Where,

Q_n, Q_k – instantaneous flux of solar radiation through areas Q_n and Q_k

In all these formulations the flux of solar radiation must be considered as solar radiation energy units per unit time and area (such as cal/cm ^{2} – min or MJ/m ^{2} – sec). Flux can also be expressed in power units per unit area (watt/m ^{2}).

Applying spherical trigonometry to positional astronomical problems it can be concluded that,

$$\cos Z = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos h$$

Where,

φ – Latitude

δ – Solar declination angle

h – Solar hour angle

Then the (daily) integral of Q_n may be computed as,

$$R_a = \text{INTEGRAL (From} - H \text{ to } H) \ Q_n \, dt$$

$$R_a = S\,(D_m / D)^2 \ \text{INTEGRAL (From} - H \text{ to } H) \ (\sin \varphi \sin \delta + \cos \varphi \cos \delta \cos h) \, dt$$

Substituting **dt** by (**dh / ω**) where **ω** is the angular velocity of the Earth (**2 π rad / day**) we get,

$$R_a = S\,(D_m / D)^2 \ \text{INTEGRAL (From} - H \text{ to } H) \ (\sin \varphi \sin \delta + \cos \varphi \cos \delta \cos h) * (dh / \omega)$$

$$\mathbf{R_a = (1440 / \pi)\ S\ (D_m / D)^2\ (H \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos H)}$$

Where **S** and $\mathbf{R_a}$ are expressed in cal/cm ^{2} – min and **H** is the half – day length. If **S** is expressed in J/m ^{2} - sec and $\mathbf{R_a}$ in J/m ^{2} – day then the formula must be used as,

$$\mathbf{R_a = (86\,400 / \pi)\ S\ (D_m / D)^2\ (H \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos H)}$$

All the previous discussion would be useless if the reader lacks the necessary expressions for calculating the whole set of necessary angles and unknowns. This can be done using the following approximate expressions:

$$\mathbf{(D_m / D)^2 = 1 + 0.033 \cos (360\, n / 365.24)}$$

$$\mathbf{\delta = 23.45 \sin [360*(284 + n) / 365]} \quad \text{in degrees}$$

$$\mathbf{H = arc \cos (- \tan \varphi \tan \delta)}$$

n – Julian day from 1 to 365

APPENDIX B

Some tabulated classifications of usual climatic indexes.

Indexes and classifications are usually defined for annual periods. Some indexes do not merit a classification scheme.

UNEP ARIDITY INDEX (K)

It merits classification.
Definition

$$\mathbf{K = P / E_0}$$

Classification:

- $\mathbf{K} < 0.05$ Hyper arid
- $0.05 <= \mathbf{K} < 0.20$ Arid
- $0.20 <= \mathbf{K} < 0.50$ Semiarid
- $0.50 <= \mathbf{K} < 0.65$ Dry subhumid
- $0.65 <= \mathbf{K} < 0.85$ Subhumid
- $0.85 <= \mathbf{K} < 1.15$ Humid
- $\mathbf{K} > 1.15$ Hyper humid

Values less than (0.65) correspond to Drylands that, according to the United Nations Convention to Combat Desertification (CCD), may suffer desertification processes.

BUDYKO RADIATIVE ARIDITY INDEX (B)

It merits classification.
Definition

$$\mathbf{B = 10\ R_0 / 0.59\ P}$$

with $\mathbf{R_0}$ in kilocalories / cm2 – year (generally less than 100)
$\mathbf{P}$ in mm / year

Classification:

- $\mathbf{B} < 1$ Wet forest
- $1 <= \mathbf{B} < 2$ Dry forest / wet savannah
- $2 <= \mathbf{B} < 7$ Very dry forest / dry savannah
- $7 <= \mathbf{B} < 10$ Semi desert
- $\mathbf{B} > 10$ Desert

From **B** = 2 to larger values, these are collectively named as arid lands.

ECOLOGICAL ARIDITY INDEX (R)

It is practically analogous to Riabchikov index. It is mostly used in Cuba in Agricultural Drought Early Warning System. Its numerical value can be used directly to estimate annual/perennial (**NPP**) net primary productivity (forests, sugarcane and pastures) using the formulas of Doorenbos and Kassam (1988) given by:

{1 – (**Real NPP / Potential NPP**)} = (**Calibration Coefficient)** (1 – **R**)

Definition:

$\mathbf{R = E / E_0}$

Classification:

R < 0.5 Dry
0.5 < = **R** < 0.85 Sub humid
0.85 < = **R** < 1.15 Humid
R > = 1.15 Hyper humid

RIABCHIKOV'S INDEX (**Ria**)

It merits classification.
Definition

$\mathbf{Ria = E / R_0}$ with $\mathbf{R_0}$ in kcal / cm2 – year and **E** in millimetres

Classification:

Ria < 2 Extra arid
2 < = **Ria** < 4 Arid
4 < = **Ria** < 7 Semiarid
7 < = **Ria** < 10 Semi humid
10 < = **Ria** < 13 Humid
13 < = **Ria** < 20 Extra humid

Riabchikov hydrobiothermical potential merits no classification because its values are directly used for the estimation of **NPP** in models and Cuban tools.

FIGURES FOR CHAPTER TWO

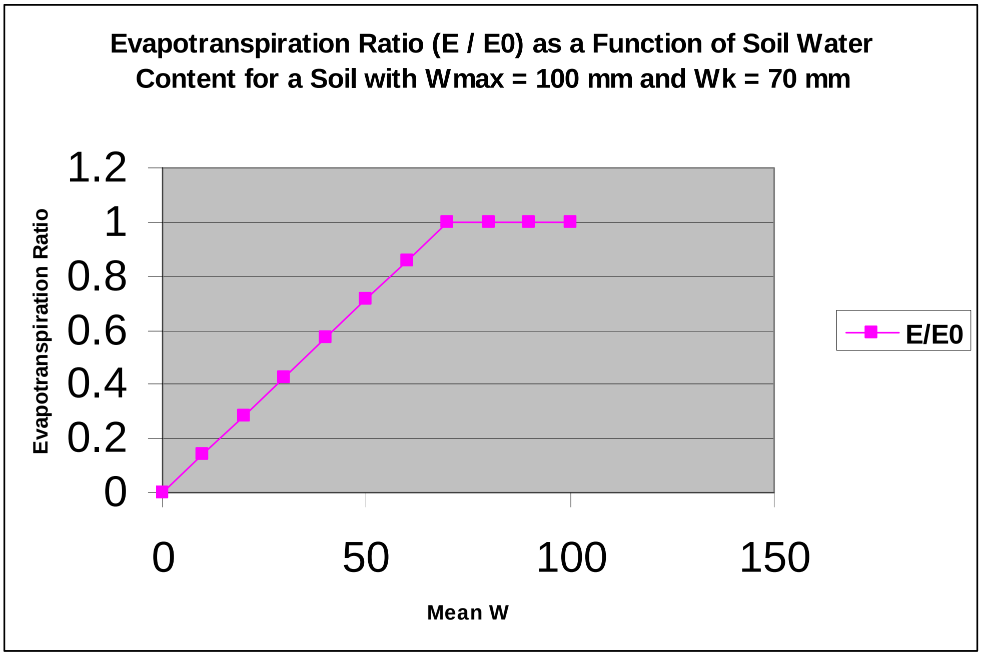

Figure 2.1: Evapotranspiration Ratio (**E** / **E** $_0$) showing the first and second drying stage of soil (in reverse order of increasing **w** $_m$) for a particular set of values of **w** $_{max}$, **w** $_k$ and **E** $_0$.

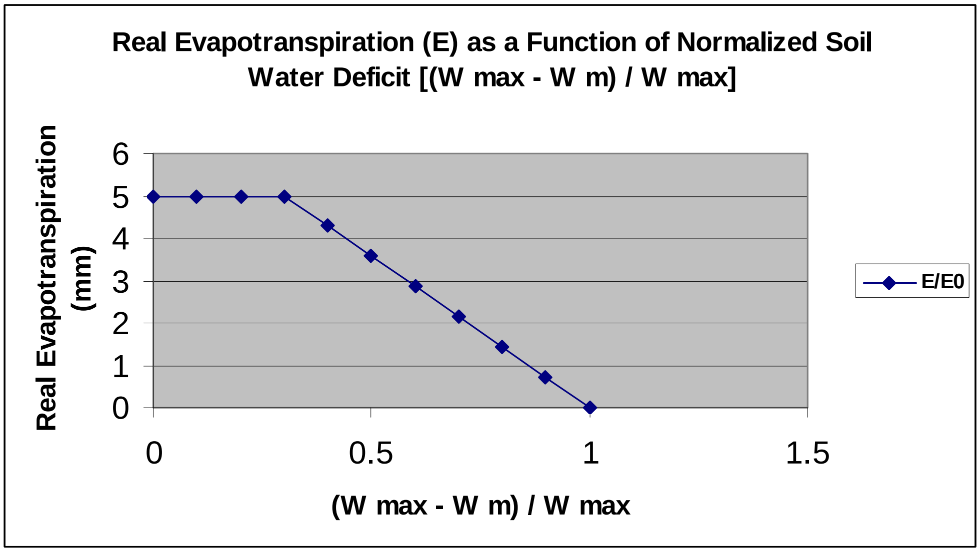

Figure 2.2: Real evapotranspiration (**E**) as a function of normalized soil water deficit for a particular set of values of **w** $_{max}$, **w** $_k$ and **E** $_0$. The first and second drying stage of soil is clearly shown here.

CHAPTER 3

CLIMATE INPUT DATA

CHAPTER 3 Climate Input Data

1. Introduction. Climate data requirements as depending on assessment procedure
    - Weather Generators
2. Climatic Indexes
3. Process-Based Models
4. Some useful considerations

INTRODUCTION

The volume and diversity of necessary input data for climate change impact assessments and adaptation in the agriculture sector is huge and probably greater than in any of the rest of the usual sectors assessed in these kinds of studies. Input data necessary in the case of agriculture is varied and includes climate, soil, crop types and usual management options plus economic information about input levels, national and global markets, costs, technology and livelihood conditions of farmers.

In the framework designed for this workbook only climatic and meteorological data needs will be discussed in this chapter. One of the reasons for this is that no available methodology for assessing impacts on agriculture derived from climate change can be used without this kind of input information and because climate change is precisely the driving force of the impact we are trying to determine. Any methodology or model that does not admit explicit climate data input would be of no use to our purpose. Such models do exist, for example, for estimating final yield of rice using biometric information obtained at field level.

As was agreed in the recent UNFCCC expert meeting on methods and tools and on data and observations, under the Nairobi work programme on impacts, vulnerability, and adaptation to climate change, Mexico City, 4 -7 March 2008 (ENB, 2008) methods and tools to be used in an assessment of the agriculture sector will depend on the objectives and goals that are intended to be achieved. Once those methods and tools have been chosen, an implicit relationship with climatic data needs is established.

In this workbook the only methodologies and tools discussed are those related to the use of climatic indexes and process-based crop models. In the following sections the reader will see that even after narrowing the spectra of discussed tools, there is still a relatively wide set of choices implying simpler or more complex climate data needs. As to a general view of available tools and methodologies the reader is referred to the valuable (even if incomplete) recompilation done by Smith (2004).

There seems to be a current trend making experts to rush after the “best available tool or model”, even if they are not prepared to understand the science behind the “best tool” and lacking the necessary input datasets (including not only climate). In this sense authors recommend experts to use tools that they really understand and for which they have the necessary input datasets. In plain words we recommend that you use what you have.

In our particular case we must be aware that we will need not only past and actual measured climate data, but future inferred climate data generated by global or regional circulation models. This may lead us to the alienating circumstance of having enough climate datasets for using a specific tool in actual climate without being able to do so in future climate scenarios or vice versa. One way of dealing with the first of these problems is discussed under the name of Bultot's scenarios in Chapter 1 while a possible choice to skip the reverse would be the use of weather generators, as follows.

Weather Generators

Stochastic weather generators have been around us since the early sixties and are mainly used to generate long time series of weather (climate) data in order to assess the probability of extreme events and agricultural risks. But possibly they were first used in hydrological applications. Even if these models are site specific they can also be used to simulate weather in unobserved sites using for their calibration input, cell, grid data obtained from interpolation among values predicted by larger scale climate models.

Weather generators are used many times to help solve the problem of insufficient climatic data inputs for running crop models, but the reader should be aware that they have many other useful applications in downscaling procedures and other applied fields (Wilby and Wigley, 2000). These stochastic weather generators are able to simulate monthly or daily time series of some or all of the following parameters: global solar radiation, precipitation, maximum and minimum temperatures. But weather generators cannot work out of thin air and generally need themselves as input some time series of actual measured data for short periods, where the word 'short 'should be interpreted as 5 – 10 years data. This initial climatic input data is necessary for the weather generator to determine basic statistical parameters to be used in generating new time series for the required variables.

Weather generators (statistical methods, such as first or multiple orders Markov's chains) theory will not be discussed in this book and the reader should go to the available literature. A very useful comparison study between WGEN and LARS-WG can be found in Semenov and Jamieson (2000). Many characteristics, advantages, and drawbacks of weather generators can be found there.

CLIMATE INDEXES

Climate indexes are generally derived from combining parameters from the surface balance equations (radiation, water and energy) discussed in Chapter 2 and are usually designed for the purpose of classifying climates and landscapes using one complex climate index only (Sellers, 1965). Even Koeppen's original climate classification, preceded only by the hypothesis that life forms of plants were set by temperature and moisture, made by the founder of ecology, Alphonse de Candolle, can be described as a set of climate indexes built to relate vegetation zones with climatic constraints (Colinvaux, 1993). The concept and usefulness of climate indexes is widened when those indexes are used to estimate a certain type of condition affecting food production (in many different ways including soil degradation) or are directly related to Net Primary Productivity of Ecosystems (Riabchikov, 1976).

In a wider sense some climatic parameters not usually operationally measured, as potential and real evapotranspiration, might be considered as climatic indexes, because there are a rather large set of empirical and theoretical relationships between these parameters and primary productivity as will be discussed in Chapters 5 and 6. It will be also evident that a subset of climate input data in some methodologies and tools is needed only for the tool to be able to estimate potential and real evapotranspiration and water balance terms by itself. The original builders of those tools, generally used as computer software programs, were aware that most users would not be able to estimate these parameters externally and give them as input climatic data to the program.

If we try discussing necessary climate input data needed to estimate such things as daily potential evapotranspiration then input needs for the calculation of climatic indexes would be rather exacting. That was not the original approach of the scientists that developed them. That is why when a concrete index needs potential evapotranspiration, it usually means an estimation made by very simple methods based mainly on temperature and not on the Penman – Monteith approach (Allen et al, 2000).

Most of usual climatic indexes are calculated using annual values and sometimes also monthly or growing season values. To be able to use them we usually require the following minimum climatic input datasets.

Monthly or annual time series of:

- **Mean Maximum temperature**
- **Mean Minimum temperature**
- **Total Precipitation**

The estimation of the following parameters has already been discussed in Chapter 2:

- **Mean temperature from mean maximum and minimum temperatures**
- **Radiation balance from mean temperatures**
- **Potential evapotranspiration from mean temperatures**
- **Real evapotranspiration and runoff from the water balance equation**

In fact, mean monthly values of temperature and precipitation comprise all the climate data that can be obtained for future climate change scenarios using the MAGIC/SCENGEN system (Wigley, 2003).

PROCESS-BASED MODELS

In discussing crop process-based models, climatic data needs will be a common set, even if different models have different climatic input parameters.

This set follows:

- **Global solar radiation values or variables from which those values can be derived.**
- **Mean temperature or mean maximum and minimum temperatures**
- **Variables from which the model can derive potential evapotranspiration values and water balance terms**.

According to these common needs every model needs particular –model dependent – climate data inputs. Some of those particular sets are now described:

FAO AEZM model (potential yields):

- **Mean monthly values of global solar radiation or sunshine hours**
- **Mean monthly values of maximum and minimum temperature**

FAO AEZM model (water limited yields):

- **Daily values of global solar radiation or sunshine hours**

- **Mean daily values of maximum and minimum temperature**
- **Daily precipitation values**
- **Daily potential evapotranspiration values or a parameter set from which it can be derived using Priestley – Taylor, modified Penman or Penman –Monteith procedures, global solar radiation, maximum and minimum temperatures, an atmospheric humidity variable (Any of them would do because the necessary one can always be derived from other equivalent parameter.) and wind speed.**

WOFOST 4.1 dynamical crop model:

- **Mean monthly values of global solar radiation or sunshine hours**
- **Mean monthly values of maximum and minimum temperature**
- **Mean monthly values of atmospheric vapour pressure (or equivalent parameter)**
- **Total monthly precipitation values**
- **Number of monthly rainy days**
- **Mean monthly wind speed**

For executing some program options the model would require a daily precipitation time series also (Diepen et al 1988). For calculating potential yields the model will not require realistic precipitation, number of rainy days, atmospheric vapour pressures, and wind speeds, because these parameters are only needed for the calculation of potential evapotranspiration and crop transpiration (by modified Penman approach) and water balance terms needed in the calculation of water balance and water limited yields.

WOFOST 7.1.2 dynamical crop models

In this model of the WOFOST family there are two options available related to the climate input dataset. One of them is the same already presented for the WOFOST 4.1 version. But a new possibility, known as the CABO format, now exists. In this new option all climatic input data are daily time series for the following variables:

- **Daily global solar radiation**
- **Daily maximum temperature**
- **Daily minimum temperature**
- **Daily mean atmospheric vapour pressure (or equivalent humidity parameter)**
- **Daily precipitation**
- **Mean daily wind speed**

The reader may see that the number of rainy days is now unnecessary (It can be derived from the daily dataset.) and a weather generator is not involved.

The DSSAT family of dynamical crop models

The most complete climate input dataset for the DSSAT family of models (Tsuji et al, 1994) should include:

- **Daily global solar radiation**
- **Daily maximum temperature**
- **Daily minimum temperature**
- **Daily precipitation**
- **Daily dew point temperature**

- **Daily wind run**
- **Photosynthetically active radiation (PAR) if measured**

But any member of the DSSAT family is able to run with a **minimum climatic dataset** given by:

- **Daily global solar radiation**
- **Daily maximum temperature**
- **Daily minimum temperature**
- **Daily precipitation**

A member of this family can do that if we choose to calculate potential evapotranspiration by the Priestley – Taylor scheme (Priestley and Taylor, 1972). This scheme is not as precise as the modified Penman or Penman – Monteith, but it does not calculate explicitly the advective term of potential evapotranspiration. By not doing so the scheme avoids the need to use an atmospheric humidity parameter and wind speed.

The DSSAT system comes with an incorporated weather stochastic generator (WGEN).

The CENTURY family of models

The CENTURY family of models (Parton et al, 1992) is designed to simulate slow processes related to the dynamic of organic matter, carbon, nitrogen, phosphorus and sulphur in soils subject to different regimes of exploitation. Its climate input needs are rather simple and generally available, consisting in:

- **Total monthly precipitation values**
- **Mean monthly values of maximum and minimum temperature**

CENTURY model has an internal (stochastic) weather generator that may be adjusted for generating the necessary extended time series if the user has a ten-year real measured or climate change scenario built data set.

The CropSyst family of models

This family of models has slightly different climatic input data needs according to the method chosen for the model calculation of potential evapotranspiration (Stőckle and Nelson, 1994). The maximum set should contain:

- **Daily values of global solar radiation**
- **Daily maximum temperature**
- **Daily minimum temperature**
- **Daily precipitation**
- **Daily maximum relative humidity**
- **Daily minimum relative humidity**
- **Daily mean wind speed**

But this family of models is so flexible that the model can be run only with daily precipitation, maximum and minimum temperatures as climatic inputs. The CropSyst family or CS-Suite comes with an aggregated weather generator known as CLIMGEN.

SOME USEFUL CONSIDERATIONS

The problem of obtaining complete point datasets for running a specific crop model in developing countries is a universal problem. It is still more evident when it comes to the need of disposing of the necessary climate data in large, scarcely populated land areas or geographical regions, especially in large extensions of actual tropical forests and mountainous landscapes. This fact was stressed by Rivero (2008), especially with relation to global solar radiation data. This problem also exists in developed countries in relation to crop genetic parameters used in crop models.

For cases like that the use of gridded world climate data provided by systems such as MAGICC/SCENGEN or FAO databases should be considered as a possible choice. National Meteorological Services should put into practice national programs to correct these deficiencies and others related to the quality, homogeneity and completeness of national climate datasets.
But any assessment team will see clearly that such programs require considerable effort and funding. Those programs also will require a considerable amount of time for being able to supply the impact community with a sufficiently dense and long period dataset for our assessments needs.

A compromise should then be achieved between available data and methodologies used in an impact assessment. The nature and complexity of these methodologies will have to be tailored to the availability of real climate data for the region or country in question.

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CHAPTER 4

BASIC CONCEPTS OF PLANT PHYSIOLOGY

CHAPTER 4 Basic Concepts of Plant Physiology

INTRODUCTION AND PRELIMINARY DEFINITIONS

The building of a crop model requires the integration of pieces of knowledge belonging to many different fields in a way that one or other specialist would like to improve an actual model, refining some of its parts to the most precise knowledge belonging to his particular discipline. We are advising here not to do that at this stage, because a crop model must be not only scientifically sound, but also practically usable in many diverse socioeconomic contexts. If we understood by daily mean temperatures the mean of 24 hourly measurements, that particular crop model could not be used anywhere except in countries with a long standing history of advanced meteorological services. The same is true of solar radiation data that is not directly measured in most developing countries anywhere. This last fact is compounded with the fact that very useful systems as MAGICC / SCENGEN don't provide solar radiation data as output.

In all our analysis here we will be assuming that,

$$T_{daily\ mean} = (T_{max} + T_{min}) / 2$$

$T_{photo} = 0.75\ T_{max} + 0.25\ T_{min}$ This expression mathematically defines phototemperature.

$T_{nicto} = 0.25\ T_{max} + 0.75\ T_{min}$ This expression mathematically defines nictotemperature.

And that global solar radiation ($\mathbf{R}_{\mathbf{g\ j}}$) for day **j** can be estimated from sunshine hours data ($\mathbf{n}_{\mathbf{j}}$), extraterrestrial solar radiation ($\mathbf{R}_{\mathbf{a\ j}}$) and day length ($\mathbf{N}_{\mathbf{j}}$), using an appropriate approximation as given in FAO publications by,

$$\mathbf{R_{g\,j} = R_{a\,j}\,(0.25 + 0.75\,(n_j / N_j))}$$

The mathematical calculation of these parameters is described in appendices. A useful software tool is also provided with the training.

Questions discussed in this chapter constitute the central blocks with which crop models are built, because they belong to the internal crop mechanisms that condition plant responses to environmental conditions. This statement is particularly true in relation to the development, growth, and yield formation in crop plants. Broadly speaking these subjects could be described as contained in the field of plant physiology even if that is not usually done in popular textbooks. Such books lack an integrated approach which reaches the state of a complete modelling of a plant's life cycle as a function of genetics and environmental conditions. Some of the necessary knowledge is usually included in ecology textbooks, to the state that some modelling has been done under the denomination of theoretical ecology. Taking into account the fact that a crop model requires knowledge from soil science, physical climatology, agrometeorology and hydrology many models have been created and published in the context of agronomical sciences.

From these analyses it seems that crop models are built borrowing knowledge from many different disciplines and integrating it into something new not completely pertaining specifically to any of them. If it were not for the integrated approach contained in a crop model, lacking in many multidisciplinary and transdisciplinary working groups, we would be tempted to regard crop models as multidisciplinary tools. Even if the number of highly specialized experts necessary to build and use them effectively could be too high and maybe unattainable, especially for developing countries, we would have to take into account the necessary leadership required to obtain a proper tool with the participation of many specialists who can hardly understand each other.

That is why we rather consider them as nexialist tools. Working under a nexialist paradigm, a specialist tends to forget where a particular piece of knowledge came from. It does not really matter.

PLANT PHENOLOGY AS CONDITIONED BY CLIMATE

Growth and Development

Almost continuously during its life, plants and their different organs increase in number, size and mass. This quantitative process is named growth and will be discussed in more details later in this same chapter. Plants also during their life go through genetically programmed changes in nature or aspect. These changes are qualitative ones and a demonstration that the accumulation of quantitative changes leads to qualitative ones. Different stages of this evolving process are called phenological stages or phases (emergence, flowering, fruiting and maturity) and are similar to human ones from childbirth to death (childhood, puberty, adulthood and old age). The process itself is named development. Further discussion of growth, development, and phenological phases is available in Wieringa and Lomas (2001). Phenological stages are very important in models, because the influence of meteorological and environmental conditions on plant behaviour is different for each stage.

We could say that phenology is an object of study for both agricultural meteorology and agronomy. During plant life a succession of different phenological stages are produced. Each stage has a measurable time duration during which no noticeable changes in nature are observed, but between two subsequent phenological stages there is a much shorter period in which plant aspect changes rather suddenly during a brief time period, and enters into a new, more evolved, phenological stage. These changes are named phenological or phase changes. Plant growth occurs mainly continuously during the somewhat long phenological stages, while phase changes occur mainly in short periods during which most of the available energy is dedicated to the processes involved in the change itself.

Phenological stages are systematically monitored on agricultural fields by agronomists and agrometeorological observers. The monitoring of these stages is supervised and controlled by agricultural institutions such as Plant Protection Departments and by National Meteorological Services.

Phenological stages are not exclusive to plants because they also occur in animals, from insects to human beings. It is also true that they are not the same for all known plants although they are very similar among plants of the same family, for example cereals. But they can be very different between plants from different families. In this way the stages of corn are very different from that of a tuber such as cassava.

The different phenological stages of all major crops have been defined and stipulated by the World Meteorological Organization (WMO), trying to guarantee understanding and information exchange among different research groups and National Meteorological Services (NMS). Notwithstanding this, some NMS still have their own national definition and stipulation of phenological stages for crops. Additionally, modelling research institutions tend to specify particular stages not necessarily recognized in NMS following WMO agreements.

Some very much used crop models use a simplification in the number of phenological stages. That is the case of the WOFOST model (Diepen et al, 1988), in which only two stages are recognized. In this particular case they are the vegetative stage (going from plant emergence to flowering or anthesis), and the generative stage (going from flowering to maturity). This is not a problem at all given that these stages are universally recognized and reported by NMS.

That is not the case for some models included in different versions of the Decision Support System for Agrotechnological Transfer (DSSAT). At least for some crops these models recognize different, usually more, phenological stages than those usually monitored by NMS. This can be a problem if you try to make detailed calibrations and validation of the results obtained, leading to the necessity of executing especially designed field experiments for that purpose.

It is necessary here to stress that the use of this terminology is not univocal and universal. A biologist could state that some specific phase has begun or ended in one particular individual (plant or mosquito), but when one agrometeorologist states that a given crop has flowered he could be saying that 50% of the crop plants in a given field has already flowered. It happens that a crop field could have ten thousand plants per hectare and that is why the agrometeorological observer cannot observe all of them one by one. He would be using representative samples instead.

If we look at the duration of different phases in a given crop we could see at once that not one value, but an interval instead, is specified for each stage (**Table 4.1**). That comes from the fact that development is partially controlled by genetics and partly by environmental conditions, so a dispersion of values obtained according, not only to the species as such, but to different genotypes of the same species (varieties or cultivars) which could be living in very different environmental conditions.

The basic concepts of phenology, growth and development lead to great depths when the concepts of photoperiodicity, day length, thermo periodicity, photo (daytime) and nicto (night-time) temperatures become necessary. We will not dwell into these matters now but will have to do so later when discussing particular models or crops. Basic textbooks on Plant Physiology (Bonner and Galston, 1952; Devlin, 1975;

Went, 1957), Ecology and Theoretical Ecology (Clarke, 1954; Odum, 1971; WMO, 1990; Colinvaux, 1993), Biogeography (Cox and Moore, 1993) and Agricultural Meteorology (Wieringa and Lomas, 2001; Baldy and Stigter, 1997) treat all these concepts from different points of view.

The importance of knowing the actual phenological phase of the crop will be seen clearly in later chapters concerning the WOFOST model and also in this one, introducing the concepts of a biological clock, one specific index of development and the meaning of the so-called dry matter partitioning functions. Modelling approaches used in this and other models belonging to the well-known Wageningen School were thoroughly discussed by some of its members in WMO (1990).

Biological clocks and development index

Plants seem to have a biological clock that tells them when to go through a phenological change of stage, from vegetative stage to flowering. This clock is mainly driven by the accumulation of temperature values (temperature sum) and day length (photoperiodicity). A plant may have a thermal or a photo thermal clock. In the following discussion photoperiod will be defined as the number of hours that the sun is above the horizon and will depend only on latitude and calendar day (Baldy and Stigter, 1997).

We say that a given plant species is photoperiodic or exhibits photoperiodicity when a given phase change does not occur until day length satisfies some specific criteria. The most important phase change that exhibits such behaviour is flowering. Some plants will not flower until day length satisfies some minimum value (short day plants) or some maximum one (long day plants). More clearly stated, photoperiodic plants will remain in its vegetative phase and will not go into the generative one until some day length criteria is satisfied. We could take short day as meaning a day length shorter than 12 hours and long day as meaning a day length larger than 12 hours, but that would be incorrect. According to Devlin (1975) the concept of photoperiodicity escapes a precise definition.

Plant species can be classified as short day, long day, and neutral plants according to phenological responses to the duration of day length as follows:

- Short day plants will not flower until day length reaches values inferior to a specific value. In the case of soybean (*Glycine soja*, *var. Biloxi*) this happens to be a rather high value, as high as 16 hours 30 minutes. If day length reaches values as large as 17 hours during its life cycle this soybean variety will not flower.
- Long day length plants will not flower until day length exceeds a certain value. That is the case of spinach (*Spinacea oleracea Lin.*) because this plant will flower only if day length exceeds 13 hours during its life cycle.
- Neutral plants as tomato and maize will flower irrespective of day length.

It can be observed that the critical value for exemplified short day plant is much higher than the one specified for short day plant. That illustrates the complexity of the involved concept and one of the reasons why many authors prefer to use the duration of the night (dark) period. Another reason is that it can be shown that the interruption of the dark period by sudden artificial flashes of light can modify the behaviour of a plant. Particularly, this method has been used in sugar cane fields in Australia to avoid flowering. The process of flowering is not sudden and does not occur immediately after the day length criterion is satisfied. A certain time lag is present between the fulfilling of the day length criteria and the flowering process. In the following paragraphs we will be discussing only thermal clocks.

In the biophysical dynamical model WOFOST 4.1 (Diepen et al, 1988) phenological stage is given by the value of variable **DVS** (DeVelopment Stage). This term is a development index based on the concept of active temperature sum that will be discussed shortly.

If **A** represents the active temperature sum needed for flowering (anthesis) and **B** is the active temperature sum (counting from flowering) necessary for maturity, then,

$$\mathbf{DVS = Temperature\ sum / A} \quad \text{before flowering,}$$

$$\mathbf{DVS = 1 + (Temperature\ sum / B)} \quad \text{after flowering,}$$

Then **DVS** = 1 when flowering and **DVS = 2** at maturity.

The complexity of the concepts we are discussing is further illustrated by the fact that **A** and **B** are genetically and environmentally conditioned. This means that these parameters could be different for the same plant in different climates. This phenomenon leads to the necessity of model calibration when one of these simulation tools is used in assessments. Finding a prescribed, universal set of the so-called genetic coefficients is a matter of current research and we cannot assert here even that such a set exists.

Active temperatures are those daily mean temperatures higher than a certain threshold ($\mathbf{T_0}$) usually called biological zero. The existence of a biological zero implies the assumption of the existence of a minimum daily mean temperature at which all vital process in plants cease functioning, halting growth and development. This particular threshold can be as low as **0.0** Celsius in wheat and as high as **15.0** Celsius in banana.

Usually, but not always, active temperatures are calculated as,

$$\mathbf{T\ active = T\ day - T_0} \text{ if } \mathbf{T\ day > T_0}$$

$$\mathbf{T\ active = 0} \qquad \text{if } \mathbf{T\ day < T_0}$$

until it reaches some specified value **A**. When that occurs all plants are assumed to have flowered. At that time **DVS** is taken as **1.0** and a new temperature sum is initiated until the second part of the original definition is fulfilled and **DVS** reaches the numerical value of **2.0**. The crop has matured in the field.

There are other ways of defining **DVS** that does not require reinitiating the active temperature sum after flowering. Only that the discussed one can be used to explicitly take into account different rates of development between the vegetative and generative phases.

DEGREE DAYS

The problem of phase changes and development rate being determined by such a thing as an active temperature sum has been widely discussed in scientific literature. Reputed agrometeorologists (physicists) as Vitkevich refused to use the implied concept arguing that an active temperature sum is physically devoid of sense. Other reputed specialists in the field such as McMaster and Wilhem (1997) have demonstrated that in many occasions different authors use at least two different ways to specify active temperatures, and that many of them do not even say what way they used. The concept is rather elusive and this will be made clearer in the following analysis.

Let us assume that the duration in days of some phenological phase is denoted by **n**, the biological zero by $\mathbf{T_0}$ and mean daily temperature during the stage by $\mathbf{T_m}$**.** Then we have the following mathematical definition for the Sum of active temperatures ($\mathbf{T_a}$) during the stage:

$$\textbf{Sum of active temperatures} = \textbf{Sum } T_{ai} = (T_m - T_0) * n$$

As we are talking of **n** days it is clear that a measuring unit of time (day) is implied in this formula. This circumstance leads to the rather interesting fact that the sum of active temperature itself is not a temperature at all, since it is measured in degree – day. The same can be said of **A** and **B**.

We can observe that by dividing by **n** in the last formula we could obtain something as a rate. Something similar can be done in the expression for **DVS** also, leading to a definition of development rate and allowing the assignment of maximum or minimum development rates to the vegetative and generative phases. This procedure would impede the occurrence of unreasonable values for the duration in days of a given phase in the case of exceptionally high or low temperatures for a given crop. The reader should be aware that concepts discussed are rather commonly referred to in scientific literature as Growing Degree Days (**GDD**).

GROWTH HABIT OF CROPS

Growth habit of a crop is a rather loosely defined term because it is applied to morphological aspects (erect, decumbent or semi-decumbent), characteristics of flowering (time duration of the flowering period in the fields) and other aspects of the crop behaviour. Determinate and indeterminate flowering growth habit is exhibited by pea in which flowering can last from two to four weeks depending on the variety growth habit being one or the other. Growth habit as used for soybeans can be seen in **Table 4.2**. A rather practical and amusing description of the growth habit of tomatoes follows:

Determinate:

Determinate tomato varieties feature smaller, compact plants that fit easily into tomato cages. A few varieties need staking, but most do not. The advantages of determinate tomatoes include early production and a plant habit that fits well in containers or small garden spaces. The big disadvantage with determinate varieties lies in the fact that they tend to bear all their fruit over a short production period and then the plant stops growing and dies.

Indeterminate:

The majority of tomato varieties fall into this classification. The vines are large and they sprawl. They are best staked or otherwise contained. The advantage of indeterminate tomatoes, and it is a big advantage, is that the vines continue to grow and produce fruit over a long period, often until killed by frost.

Semi-determinate:

These plants have a larger habit, with better foliage coverage than determinate, but without the sprawling characteristics of indeterminate plants. They live and produce for a longer period than determinate, but usually not quite as long as indeterminate types.

In this Chapter we will be discussing growth habits of plants in the sense expressed by phrases such as “then the plant stops growing and dies” and “continues to grow and produce fruit over a long period, often until killed by frost”. Indeterminate plants in tropical regions usually would not be killed by frost, but they will be killed by drought, high temperatures, plagues and diseases. Different types of growth habit will be recognized here as follows.

A given plant such as maize emerges, grows leaves, stems and roots, flowers, gives fruit and matures, drying all previously created organs, and dies leaving only the product (seed) that guarantees the continuation of the species. Plants like that are said to have a determinate growth habit. The vegetative phase ceases at some moment around the flowering stage, after that all available energy and substances are dedicated to form the final fruits and seeds even at the cost of relocating substances (especially those containing nitrogen) and nutrients already existent in previously formed organs such as stems and leaves. Semi-determinate growth habits are also observed.

Plants such as cowpea or potato and perennial trees go through a similar process many times in their life without necessarily drying and dying, unless external environmental factors become intolerable. They continue making new leaves and budding even when flowering and fruiting. Plants like this are said to have indeterminate growth habit. In these kinds of plants flowering and fruiting consume only a rather small fraction of available energy, so we could say that the vegetative and generative stages coexist during part of the life cycle of the plants.

Different growth habits of crops imply rather different logistic functions, so they are treated differently in modelling. Growth habit is a very important feature in relation to agricultural practices, it is genetically conditioned and so it is an inheritable trait. A single particular species such as soybean (*Glycine maximum L.*) may have determinate and indeterminate varieties or cultivars, including hybrids. The scientific problem of determining the way in which growth habit is gene-controlled and how to obtain varieties with a predetermined growth habit is the subject of current research.

THE GROWTH CURVE

The growth curve concept is widely used and applied in many different subjects of biological sciences. It can be applied as well to the behaviour of a population (number of individuals) of bacteria in a suitable environment as to the growth in stem length of sugar cane plants. This diversity of uses leads to considerable differences in the form of these curves and of the underlying phenomena that cause one particular growth behaviour as expressed in a growth curve. This curve is reported as the logistic curve in practically all sources of information in the Web.

In the context of this chapter we will be speaking of growth curves always in the sense of biomass behaviour with time in terms of an individual plant or crop field. The description is easier to do if we concentrate on a plant with determinate growth habit such as corn. To better illustrate the concept we will be using a kind of language that will sound animist. This circumstance will not convey an animist philosophical conception and will be used because this way of talking seems the simplest way of explaining the underlying phenomena and it is a common way of talking among farmers and common people independently of any particular training.

Let us take a seed. In the formation of this particular seed its parent plant stored into it a survival kit consisting in carbohydrates, oils, proteins, enzymes and genetic information that will allow this seed to grow and develop to produce a new adult individual that will, in turn, produce new similar seeds. That is why a seed can be modelled as a storage organ of plants. In this way the particular species involved has been securing its survival during hundreds of thousands and even millions of years. When this seed is planted in a suitable soil under adequate environmental conditions, such as temperature and soil humidity, the development stage of germination begins in the seed itself. Development is accompanied by growth and what is required is energy.

That energy is derived from oxidative processes of substances in the survival kit and the activation of catalytic (enzymatic) reactions. It also requires water and oxygen already present in the soil. Such processes are usually described as respiratory. Using energy obtained in respiration and substances already present in the seed, the original embryo grows one (initially) tiny root system into the ground to guarantee its supply of more water and chemical nutrients (nitrogen, phosphorus, potassium and microelements) present in it. Simultaneously, it develops an incipient stem with tiny initial leaves in the soil surface direction in order to guarantee an additional source of energy that is different from what it has been using in the germination process. It also develops a supply of the most common chemical element in plants, which is carbon coming from atmospheric carbon dioxide.

It may be surprising, as it was to scientists when this fact was discovered in the past, to become aware that more than 95 % of the dry matter of plants (discounting water) comes from the atmosphere and not from mineral substances in the soil. Carbon is as much a nutrient to plants as nitrogen, phosphorus and potassium. This fact has given birth to the concept of carbon dioxide fertilisation effect on plants.

Once initial stem and leaves emerge above ground a new physiological mechanism starts to work in the green organs of the plant. It is called photosynthesis. That mechanism is a complex one that makes use of available sunlight to produce sugars (gross photosynthesis). Those chemical compounds are transported to every organ of the plant to be transformed in new and more complex compounds (as proteins) containing not only carbon, but mineral substances that were absorbed from the soil, and dissolved in water through the root system. These additional chemical processes require an additional source of energy and occur in those organs themselves. This energy comes from respiration consisting in oxidative processes of the initial sugars made available by photosynthesis. The balance of sugar mass produced by gross photosynthesis minus the sugar mass used as fuel for obtaining energy through the respiratory processes is named net photosynthesis. Net photosynthesis is the amount of new chemical compounds available to the plant for building new tissues and structures. That is new biomass available for growing.

Energy derived from respiratory processes is used not only for building new tissues, but also for keeping previously built biomass alive and functioning. That is why respiratory losses are usually decomposed in growth and maintenance respiration. Maintenance respiration will be nearly proportional to the already existent biomass and will increase with plant age as it grows. That fact could establish a limit to the actual (live) biomass of plants, if a stage is reached in which gross photosynthesis cannot provide sufficient energy to compensate for respiratory losses.

At emergence the plant is in the vegetative stage of development, so all products of photosynthesis are allocated to roots, stems and leaves, but none to storage organs because they do not exist as yet. This allocation process is controlled by the dry matter partitioning functions that specify how much is going to be given to each kind of plant organs. Part of the allocated sugars is consumed to produce new tissues (growth respiration) and part is consumed in keeping alive and functioning previous created biomass (maintenance respiration).

In the first stages of development there is little previously created biomass and maintenance respiration is rather low. This favours growth of plant organs. In these stages plants strive to build an aboveground structure with stems and branches able to sustain a large set of green leaves. Through an adequate leaves structure and number, the plant is trying to guarantee that all available photosynthetic solar radiation falling on the particular patch of ground where it is present may be intercepted by a photosynthetic plant organ. The source of energy necessary for processes still to come will come from that initial effort. Simultaneously, plant is also developing an adequate root structure, so to guarantee the needed supply of soil water and nutrients. Crop (live) biomass starts to increase faster and faster reaching a maximum at some date about the middle of its life cycle.

This striving to build a complete and powerful leaf structure able to use all the available solar energy gave rise to the concept of leaf area index (LAI), which is total leaf area per square meter of ground. At emergence LAI is a very small fraction of unit, but it starts to rise very fast with time and, at its peak, very near to the inflection point of the logistic (sigmoid) function, it will attain values near 4 – 6 square meters of leaf area per square meter of ground in agricultural agroecosystems. In natural ecosystems, with many different species living together such as tropical forests LAI can reach values as high as 10 - 12. With so high values of LAI no global solar radiation reaches the ground. The LAI concept is a crucial one in agriculture and crop modelling. The values of LAI will appear in numerous approaches related to the diffusion of solar radiation and its absorption by crop canopies that consist of many different strata of leaves subject to many different intensities of Photosynthetically Active Radiation (PAR).

The PAR concept comes from the fact that not all the shortwave (visible) radiation coming from the sun can be used as energy source for photosynthesis. In fact plants are green because leaves reflect visible light with wavelengths and frequencies in that part of solar spectrum which cannot be used in photosynthetic reactions. For simple calculations PAR is taken as one half of total solar radiation reaching the upper part of the canopy cover.

Then other factors get into the picture. First of all maintenance respiration has also been increasing as living crop biomass increases. Second, a different phenological stage comes into being as a consequence of genetical control and adequate environmental conditions (such as temperature sums and day length). With the transit to flowering and generative stage the partitioning of dry matter to roots, stems, and leaves may drop to zero after the flowering stage. All available substances are directed to the formation of storage organs such as fruits and seeds. As a consequence, no more leaves are produced and stems cease to increase in length and diameter. Gross photosynthetic rates can increase no more and, in fact, they start to decrease because of leaves already getting older and less efficient with the oldest ones finishing their useful life, drying and falling to the ground. This phenomenon is known as senescence.

The rate of biomass increase starts diminishing and is reduced to zero when, eventually, gross photosynthesis and maintenance respiration losses equilibrate each other. A dried corn plant stands in the field, but its seeds are there alive, still using respiration to keep living during a long period of time, and with their survival kit which will allow them to start a new generation of maize plants.

Theoretical logistic (sigmoid) functions applied to this case are exposed and analyzed in **Figures 4.1** (sigmoid) and **4.2** (rate of biomass increase). Experimental curves do not usually achieve such perfect smoothness as the theoretical ones.

PHOTOSYNTHETIC PATHWAYS

Photosynthesis is a very complex physiological and physicochemical process in green plants. It is so complex that it will not be described here in detail even if it will be repetitively referred to in subsequent discussions. From the point of view of physiology photosynthesis requires specialized structures, organs, cells and structures in cells of plants such as leaves, tissues, stomas and chloroplasts. From the point of view of physical chemistry, photosynthesis requires the presence of special pigments such as chlorophyll and also a set of specialized enzymes. Being an enzymatic process it is possible to study and describe its behaviour using the so-called Michaelis –Menten curves.

A superficial description of the process is necessary here. Green leaves possess specialized organs known as stomata. These stomata may be opened and shut according to genetic traits and environmental conditions. When stomata are shut the inner tissues and vital fluids of the plant are practically isolated from the external atmosphere. But when they are opened the internal tissues and fluids can be in contact with external air containing carbon dioxide. Using its physiological structures and enzymatic processes, the plant is able to capture carbon dioxide from the air using solar radiation energy and release oxygen but losing, at the same time, some of its internal water content in a process known as transpiration.

The initial capture of the atmospheric carbon is subsequently followed by a chain of chemical reactions leading to the formation of sugars we discussed when talking about gross photosynthesis. The balanced equation for initial and final products of photosynthesis may be given as,

$$\mathbf{6\ CO_2 + 6\ H_2O} \text{ leading to } \mathbf{(C\ H_2\ O)_6 + 6\ O_2}$$

We take note here that this balanced equation is practically the reverse of the equation describing respiratory processes, that is,

$$\mathbf{(C\ H_2\ O)_6 + 6\ O_2} \text{ leading to } \mathbf{6\ C\ O_2 + 6\ H_2\ O}$$

We should take note of the fact that the first reaction and its rate of change require an external energy source (PAR) and a particular set of enzymes, substrate, and environmental conditions, while the second one requires no external energy source and a different set of enzymes, substrate, and environmental conditions. The reason for introducing this subject here is that, from the very beginning, the reader should be aware that there are two different ways in which the photosynthesis process can be realized. These two different ways require different morphological structures and sets of enzymes in leaves, leading to different responses of the photosynthesis process to environmental conditions and climate change. Differences in photosynthetic pathways allow classifying plants into two different classes, commonly known as C_3 and C_4 plants. Most of the crops useful to man are C_3 plants, but some of them are C4 ones such as maize, millet, sorghum, sugarcane and tropical pastures.

If the carbon atom coming from atmospheric carbon dioxide is first captured to form a molecule containing a chain of three carbon atoms that plant is a C_3 plant, but if that carbon atom is first captured to form a molecule containing a chain of four carbon atoms that plant is a C_4 one. Subsequent biochemical reactions leading to the synthesis of hexoses (sugars containing a chain of six carbon atoms as glucose) in C_3 plants follow a path known as the Calvin –Benson cycle while those with C_4 photosynthetic pathway follow the Hatch – Slack one (Colinvaux, 1993). Detailed descriptions of the biochemical sequence of reactions involved in these pathways are found in plant physiology, agronomical, and biochemistry textbooks.

Plants belonging to different classes will have different responses to changes in temperature, sunlight intensity, soil, water, humidity, and atmospheric carbon dioxide concentrations. That is, different responses to climate change.

POTENTIAL AND LIMITED BY WATER AND NUTRIENT YIELDS

SOLVING THE BIOMASS BALANCE EQUATION: The Wageningen / FAO Approach for Potential Yields.

Solar radiation energy is used by plants only to break down water in the initial photosynthesis process that leads to the formation of sugars, a process known as **gross photosynthesis** or **gross biomass production**. The necessary energy for further growth processes comes from sugar (biomass) oxidation processes named collectively as respiration. Respiration leading to new growth is named **growth respiration** while that leading to the maintenance of structures already built is named **maintenance respiration.** The difference between gross photosynthesis and total respiration is called **net photosynthesis**, **net biomass production** or **net primary productivity** (**NPP**) of plants.

The biomass balance equation is then given by:

$$\mathbf{B_n = B_g - r}$$

B_n – daily increment in (dry) net biomass per unit area
B_g – daily production of (dry) gross biomass (sugars)
r **--** daily respiration rate

The daily rates of gross biomass production of plant species with C_3 and C_4 photosynthetic pathways differ due to their different dependence on temperature and solar radiation. This fact justifies a species classification, sometimes known as FAO classification, and allows the modelling of growth and development (**Table 4.3**).

Gross photosynthesis dependence on solar radiation

Gross photosynthesis response curves of single leaves to **PAR**, at optimal temperature and actual CO_2 atmospheric concentrations (around 330 ppm in 1961-90), are shown in (**Figure 4.2**).

These curves can be described by expressions of the type given by,

$$\mathbf{B_g = a\ P_m\ I\ /\ (P_m + a\ I)}$$

a is an empirical parameter. If **I** grows indefinitely then **P_m** may be dropped in the denominator compared to **a I** and **B_g** tends to **P_m** in the plateau. This mathematical expression is known as a Michaelis – Menten one and is known to describe a full set of enzymatic biochemical reactions.

It may be observed that photosynthesis rate of C_3 species tend to level off reaching a plateau at rather low light intensities, while C_4 species keep increasing its photosynthesis rate even at the higher available values of PAR. This phenomenon is sometimes referred to as light saturation. In biological sciences this fact is equivalent to saying that some other factor is limiting that rate in C_3 plants. We will see now what that factor is because these kinds of plants are starving as a consequence of a relatively low atmospheric carbon dioxide concentration. The Calvin cycle has a low efficiency if carbon dioxide concentration is low. On the other hand C_4 plants are so efficient at capturing CO_2 that its efficiency cannot be raised by increasing carbon dioxide concentrations, they will always be able to take advantage of higher levels of PAR.

Gross photosynthesis dependence on atmospheric CO_2 concentration

It can be described for C_3 species by,

$$\mathbf{B_g = a\ b\ c\ I\ /\ (b\ c + a\ I)}$$

c is now the atmospheric concentration of CO_2, while **a**, **b** are empirical coefficients. When **I** increases then **B_g** tends to **a**, and then

$$\mathbf{B_g\ maximum = P_m = b\ c}$$

C_4 species dependence on atmospheric carbon dioxide concentrations will be almost nonexistent and **P_m** practically will not depend on CO_2 concentrations. A theoretical example of this effect for C_3 plants (**Fig. 4.4**) shows the so-called CO_2 fertilisation effect.

P_m response to temperature

Response curves of $\mathbf{P_m}$ to temperature are bell-shaped with a maximum at optimal temperature which value depends on species type (**Fig. 4.5**). Optimal temperature at which $\mathbf{P_m}$ reaches its maximum is also different among different species groups (Oldeman and Frere, 1982; WMO, 1994). In this way an additional classifying criterion is introduced leading to cold climate C_3 and C_4 crops and warm climate C_3 and C_4 crops.

Maximum value of $\mathbf{P_m}$ decreases at both sides of its value at optimal temperature. An approximate formula for C_3 cold climate species can be written as

$$Pm = -0.1051 \cdot T^2 + 3.8795 \cdot T - 13.769$$

Base temperature (biological zero) is also different among groups.

Respiration Rates

Respiration rates may be derived from the following formula (Oldeman and Frere, 1982), the first term representing growth respiration and the second term representing maintenance respiration.

$$\mathbf{r = k\ B_{gi} + C_T\ B_i}$$

$\mathbf{B_{gi}}$ is biomass increment on day **i** while $\mathbf{B_i}$ is total accumulated biomass until that same day.

Experience showed that **k = 0.28** independent of type of plant and temperatures. But coefficient $\mathbf{C_T}$ is dependent on plant protein content and temperature.

$$\mathbf{C_T = C_{30}\ (0.044 + 0.0019\ T_m + 0.001\ T_m^2)}$$

Where,

$\mathbf{C_{30} = 0.0283}$ for leguminous

$\mathbf{C_{30} = 0.0108}$ for non – leguminous species

$\mathbf{T_m}$ – Daily mean temperature

There are other ways to take into account respiratory losses. In some models such as FAO Agroecological Zones Model (Doorenbos and Kassam, 1979), respiration losses are expressed through a coefficient in a multiplicative model with different values for warm and cold climates (0.5 – 0.6).

But other models such as Wofost 4.1 (Diepen et al, 1988; WMO, 1990) divides total respiration losses in that leading to the formation of new dry matter biomass in plant organs (growth respiration) and that which is necessary to keep alive already formed dry matter biomass (maintenance respiration).

The term $\mathbf{Q_{10}}$ is introduced for the calculation of maintenance respiratory losses. Loosely speaking parameter $\mathbf{Q_{10}}$ is the relative increase in maintenance respiration rates when temperature increases in 10.0

degrees Celsius from a base value of 20 – 25 degrees Celsius. Values of $\mathbf{Q_{10}}$ are very nearly equal to 2.0 in such a way that respiratory losses double when temperature is increased by 10.0 Celsius degrees.

In Wofost 4.1 the following expressions are used to adjust relative maintenance respiration rates at all temperatures, with TEFF describing the temperature effect on maintenance respiration.

$$\mathbf{Z = (T - 25.0) / 10}$$

$$\mathbf{TEFF = (Q_{10})^{Z}}$$

Growth respiration losses are taken into account by specifying conversion efficiencies of sugars produced by gross photosynthesis to new produced dry matter. These conversion efficiencies are different according to the structural material being formed in the process. Root and tuber crops possess the highest conversion efficiencies (around 0.75) while protein and oil – rich seed crops have the lowest ones (0. 65 – 0.50). This fact reflects the circumstance that forming carbohydrates is a rather easy process with a conversion efficiency of 83%, while the formation of lipids and proteins require a lot of work and energy leading to conversion efficiencies in the range 30 – 40%.

Photosynthesis of crop canopies

In preceding paragraphs we have been discussing the photosynthesis of individual leaves and its response to environmental factors without taking into account that actual plants and crop canopies contain many leaves living in different microenvironments. In the canopy cover there are leaves living under full sunlight as well as shaded ones living in partial shade or almost complete darkness.

To obtain a representative value of canopy photosynthesis some way of integrating the individual contribution of different leaves strata must be found. To do so we will need to know actual intercepted solar radiation by the canopy. The most commonly used expression to calculate this parameter is given as a function of **LAI**,

$$\mathbf{I_z = I_0 (1 - exp (- k * LAI))}$$

Where $\mathbf{I_z}$ is the actual intercepted radiation, $\mathbf{I_0}$ is actual incident radiation at the top of the canopy and exponent **k** is the so-called extinction coefficient. In scientific literature one must be aware that some values of k are reported in reference to solar radiation and not necessarily with respect to **PAR**. A similar function of **LAI** will be used in later chapters to represent the contribution of water transpiration of plants to total evapotranspiration.

To obtain daily values for actual canopy photosynthesis a numerical integrating process must be done using different levels within the canopy and different times during the day.

Dry matter partitioning factors

To be able to build a plant or crop model these formulations must be completed by mathematical expressions describing the partitioning of newly formed dry matter among different plant organs. These factors have been called logistics functions by some authors (Polevoy, 1988). Dry matter partitioning functions depend on species and cultivars (genetic traits), phenological stage and environmental factors.

For typographic reasons, in this section total dry matter biomass per unit area on day j will be represented by the symbol $\mathbf{M}_j$. This biomass will be equal to the sum of dry matter biomass of roots ($\mathbf{M}^r{}_j$), stems ($\mathbf{M}^s{}_j$), leaves ($\mathbf{M}^l{}_j$) and storage organs ($\mathbf{M}^{so}{}_j$):

$$\mathbf{M}_j = \mathbf{M}^r{}_j + \mathbf{M}^s{}_j + \mathbf{M}^l{}_j + \mathbf{M}^{so}{}_j$$

Then the daily increase of dry matter per unit area can be written in finite form as

$$\mathbf{\Delta M}_j = \mathbf{M}_{j+1} - \mathbf{M}_j = (\mathbf{F}\,(\mathbf{t}))_j * \mathbf{\Delta t}$$

The partitioning of daily new dry matter to different plant organs is described by general functions such as (Ross, 1967; Polevoy, 1988)

$$\mathbf{M}^r{}_{j+1} = \mathbf{M}^r{}_j + (\boldsymbol{\beta}^r{}_j\, \mathbf{\Delta M}^r{}_j / \mathbf{\Delta t} - \mathbf{v}^r{}_j\, \mathbf{M}^r{}_j)\ \mathbf{\Delta t}$$

$$\mathbf{M}^s{}_{j+1} = \mathbf{M}^s{}_j + (\boldsymbol{\beta}^s{}_j\, \mathbf{\Delta M}^s{}_j / \mathbf{\Delta t} - \mathbf{v}^s{}_j\, \mathbf{M}^s{}_j)\ \mathbf{\Delta t}$$

$$\mathbf{M}^l{}_{j+1} = \mathbf{M}^l{}_j + (\boldsymbol{\beta}^l{}_j\, \mathbf{\Delta M}^l{}_j / \mathbf{\Delta t} - \mathbf{v}^l{}_j\, \mathbf{M}^l{}_j)\ \mathbf{\Delta t}$$

$$\mathbf{M}^{so}{}_{j+1} = \mathbf{M}^{so}{}_j + (\boldsymbol{\beta}^{so}{}_j\, \mathbf{\Delta M}^{so}{}_j / \mathbf{\Delta t} + \boldsymbol{\Sigma}_j\, (\mathbf{v}^r{}_j\, \mathbf{M}^r{}_j + \mathbf{v}^s{}_j\, \mathbf{M}^s{}_j + \mathbf{v}^l{}_j\, \mathbf{M}^l{}_j)\ \mathbf{\Delta t}$$

Where $\mathbf{M}^r$, $\mathbf{M}^s$, $\mathbf{M}^l$ and $\mathbf{M}^{so}$ are actual dry matter biomass of roots, stems, leaves and storage organs on day **j** and **j +1**.

Variables $\boldsymbol{\beta}_j$ describe the distribution of new products created on leaves and green parts, while variables $\mathbf{v}_j$ describe the redistribution of already existing products between one organ and another. These last functions are better defined in species with determinate growth habit. From some moment onward these plants mobilize assimilated substances from one part of the plant to its flowers and storage organs.

Functions $\boldsymbol{\beta}_j$ and $\mathbf{v}_j$ fulfil the following conditions,

$\mathbf{v}_j <= 0$ for all plant organs

$\boldsymbol{\beta}_j >= 0$ for all plant organs

$$\boldsymbol{\beta}^r{}_j + \boldsymbol{\beta}^s{}_j + \boldsymbol{\beta}^l{}_j + \boldsymbol{\beta}^{so}{}_j = \mathbf{1}$$

If $(\mathbf{\Delta M}^l{}_j / \mathbf{\Delta t}) >= 0$ changes in Leaf Area Index (LAI) may be calculated from,

$$\mathbf{LAI}_{j+1} = \mathbf{LAI}_j + (\mathbf{\Delta M}^l{}_j / \mathbf{\Delta t})\ (\mathbf{1} / \mathbf{Z}^l)$$

Where $\mathbf{Z}^l$ is leaf surface density (grams/cm^2).

For foliage already growing old and dying, **LAI** can be described by,

$$\mathbf{LAI_{j+1} = LAI_j + (\Delta M^l_j / \Delta t)\ (1 / Z^l K_s)}$$

$\mathbf{K_s}$ is a parameter describing critical decrease of live leaf biomass leading to its dying. It is usually related to leaf lifetime as dependent of temperature and other environmental parameters.

Values of functions $\boldsymbol{\beta_j}$ and $\mathbf{v_j}$ depend on phenological stage and are genetically conditioned. In general functions $\mathbf{v_j}$ are null before flowering and $\boldsymbol{\beta^{so}_j}$ is identically null before the beginning of the corresponding phenological stage.

The introduction of functions $\boldsymbol{\beta^r}$, $\boldsymbol{\beta^s}$, $\boldsymbol{\beta^l}$, $\boldsymbol{\beta^{so}}$ and $\mathbf{v^r}$, $\mathbf{v^s}$, $\mathbf{v^l}$ give a complex aspect to this set of equations.

Even if at first sight these new functions could be expressed as functions of time, including that the time step could be different from one day, some models chose to express these variables as functions of biological time using the development index **DVS**. Additionally, models as Wofost 4.1 distinguish aboveground dry matter production from underground. With this distinction the actual imposed condition is,

$$\boldsymbol{\beta^s_j + \beta^l_j + \beta^{so}_j = 1}$$

An example of the actual partitioning functions used for maize in the CROP41.dat file can be seen as function of **DVS** in **Table 4.4** and **Figure 4.6**. This last one is shown to stress the fact that these are not discrete functions because they are, internally, linearly interpolated between contiguous values given in that table.

Harvest Index

In some models, especially in stationary simple ones, the detailed partitioning of dry matter among plant organs is not studied. These kinds of models are very much focused in the problem of estimating yields for practical purposes and to guide agronomists in land evaluation studies. As they need much less amount of knowledge, nature and quantity of data to obtain initial estimates of the expected potential yields of crops, they can be applied to almost any crop without the investment of large resources and research efforts.

Loosely speaking a Harvest Index (**HI**) can be defined as the ratio between final storage organ dry matter content and total biomass dry matter of the crop (excluding roots that are not storage organs). Using the same terminology already seen in the previous section, a Harvest Index can be calculated as,

$$\mathbf{HI = M^{so} / (M^{so} + M^{s} + M^{l})}$$

Readers should be aware that in many crops (tubers and roots) the storage organ is a tuber or a root and not a fruit or aggregate of seeds. Some confusion could arise if we take into account that the final product we are interested in is a set of leaves (lettuce and other horticultural plants) or a stem as in sugarcane when even sucrose content could be chosen as final product of interest. A redefinition of harvest index could be necessary in cases such as these. Common typical harvest indexes are shown in **Table 4.5** and have been published in many FAO reports. It is to be noted that these values of **HI** are potential values obtained in irrigated crops grown in an adequate climate.

In rainfed conditions with a very adverse climate, from the point of view of general climate conditions, a given crop could remain in the vegetative stage forever or to produce very low values of the final product of interest, so as to lead to harvest indexes as low as zero.

SOLVING THE BIOMASS BALANCE EQUATION: The Radiation Use Efficiency (RUE) Approach for **Potential Yields**

An alternative pathway for solving the biomass balance equation is through the use of the so-called Radiation Use Efficiency (**RUE**) or photosynthetic efficiency (**E**). Such an approach has been used by Spitters (1987) and in the widely known model CropSyst (Stockle and Nelson, 1994). Models of the widely known CERES family (Yang et al, 2004) included in earlier versions of DSSAT system, in example DSSAT v3.0, also used a RUE approach.

According to Spitters the daily increase in total dry matter crop biomass for day **j** can be expressed as,

$$\mathbf{\Delta W_j = RUE * (1 - a_{ph}) * f_{int\,j} * PAR_j}$$

Where **RUE** is the crop (photosynthetic) radiation use efficiency, in kilograms of dry matter per megajoule (kg DM / MJ), determined for a crop well supplied with water and nutrients. The parameter $\mathbf{a_{ph}}$ is the photosynthetic albedo of crop canopy cover. As already seen before, the fraction of actual photosynthetic radiation intercepted by crop is given by,

$$\mathbf{f_{int\,j} = 1 - exp\,(- k * LAI_j)}$$

Final crop yield ($\mathbf{W_{so}}$) can be obtained from final accumulated biomass (**W**) using a general Harvest Index (**HI**) and formula,

$$\mathbf{W_{so} = HI * W}$$

Or through the use of a daily dry matter partitioning function to storage organs ($\mathbf{HI_j}$) and formulas,

$$\mathbf{W_{so} = \Sigma_j\, HI_j * W_{so\,j}}$$

In this formulation it is commonly said that it allows calculating radiation limited yields, even if there is a temperature control over phenological stages and dry matter partitioning functions. As the crop is supposed to be well provided with water and nutrients it can be concluded that the expressed formulation corresponds to the calculation of a potential yield.

In models such as CERES – Maize (Yang et al, 2004) photosynthetic radiation at the top of the plant canopy on day **j** ($\mathbf{PAR_j}$) is assumed to be 50% of total solar radiation ($\mathbf{R_{gj}}$) as usual. Total intercepted photosynthetic radiation ($\mathbf{IPAR_j}$) is given as a function of **LAI**, with extinction coefficient **k** = 0.65, in the usual way given by,

$$\mathbf{IPAR_j = 0.5\, R_{gj}\, (1 - exp\,(- k * LAI_j))}$$

Net dry matter production is then computed by the RUE approach,

$$\mathbf{\Delta M_j = RUE * IPAR_j}$$

RUE values for maize crop used in the original version (Jones and Kiniry, 1986), were taken as equal to 5 grams dry matter/MJ of PAR but was reduced to 4.33 in a later version (Kiniry et al, 1997).

WATER AND NUTRIENT LIMITED YIELDS

Potentials yields, as we have discussed this far, are limited only by genetics, radiation and temperatures. They are supposed to be attainable in growing conditions in which crop has all the soil water and nutrients necessary to function properly. In addition crop field should be free of plagues and diseases. Such conditions are only found in carefully controlled environments although in real field conditions such conditions are nearly fulfilled in optimum irrigated and fertilised fields with a proper integrated management of plagues and diseases. Even in rainfed conditions without optimum irrigation practices such growing conditions can be approximated in some seasons of the year such as the second rainy period in Cuba that corresponds to the season September – November.

But even if yields obtained in real conditions with optimum irrigation practices or in the best season of the year, from the point of view of water supply, in rainfed conditions can approach potential yields that is not the general rule. Most of actual production yields are obtained in water and nutrient limited conditions that require new formulations for being simulated by crop models.

Eventually the same pathway used for modelling potential yields could be used for modelling water limited yields, if we had formulations to express how water limitations impact gross photosynthesis, respiration and other physiological processes in plants. It happens that such a formulation is avoided in most practical models, leading to a new reformulation of dry matter production in crop plants that involves the simultaneous use of the concepts of potential yields. As we said before, plants have to open stomata to capture ambient atmospheric carbon dioxide needed for photosynthesis, losing some water content in the process. This loss of internal constituent water is known as transpiration Water loss from plant tissues has to be compensated by water uptake from soil water content through the root system of the plant. Nutrients such as nitrogen, phosphorus and potassium diluted in that soil solution get into the plant with that water. As you can see already, the calculation of water loss in the transpiration process and its replenishing by soil water uptake will require finding adequate solutions to the equations of water balance of the soil – plant system.

In this approach CO_2 uptake by leaves is assumed proportional to water loss through transpiration in such a way that the ratio of transpiration rate (**T**) to growth rate (**P**) remains practically constant under a wide range of environmental conditions. Designating potential rates by $\mathbf{T}_{pot}$ and $\mathbf{P}_{pot}$ and actual (water limited) rates by $\mathbf{T}_{act}$ and $\mathbf{P}_{act}$ this leads to,

$$\textbf{Transpiration coefficient} = \mathbf{CT} = \mathbf{T}_{pot\ j} / \mathbf{P}_{pot\ j} = \mathbf{T}_{act\ j} / \mathbf{P}_{act\ j} = \mathbf{K}_{BT}$$

$$\mathbf{P}_{act\ j}\ \textbf{(water limited)} = \mathbf{T}_{act\ j} / \mathbf{CT} = \mathbf{K}_{BT}\ \mathbf{T}_{act\ j}$$

A formulation such as this is used in different versions of the Wofost models. Doorenbos and Kassam (1979) use a variant of this approach through the use of the equation following, applied to the entire growth cycle,

$$(1 - (P_{act} / P_{pot})) = k_y (1 - (E_{act} / E_{pot}))$$

In this formulation $\mathbf{E}_{pot}$ and $\mathbf{E}_{act}$ are actual and potential crop evapotranspiration derived from a water balance calculation made using the very well known FAO crop coefficients described in Doorenbos and Pruitt (1977). Variable $\mathbf{k}_y$ expresses the actual relative crop resistance to drought conditions and has values in the range (0.8 – 1.2).
CropSyst model uses the expression given by,

$$\mathbf{P}_{act\ j}\ \textbf{(water limited)} = \mathbf{K}_{BT} * \mathbf{T}_{act\ j} / \mathbf{VPD}$$

Where $\mathbf{K}_{BT}$ is the biomass – transpiration coefficient (kPa), $\mathbf{T}_{act}$ is measured in kg water/m^2 – day and $\mathbf{P}_{act}$ is measured in kg dry matter/m^2 – day. **VPD** is the atmospheric water vapour deficit expressed in kPa and given by atmospheric saturated water vapour tension minus actual water vapour tension,

$$\mathbf{VPD = e_s - e}$$

The calculation of potential and actual transpiration rates is usually done partitioning potential and actual evapotranspiration using the **LAI** formulation given by,

$$\mathbf{T_{0\,j} = E_0 \,(1 - \exp\,(- k * LAI))}$$

$$\mathbf{T_{act\,j} = E_a \,(1 - \exp\,(- k * LAI))}$$

The calculation of crop potential (maximum) evapotranspiration is possible knowing phenological stage, crop coefficients and environmental factors, but the calculation of $\mathbf{E}_a$ usually requires additional knowledge of soil water content and the solution of the soil - plant water balance equations.

Methods for obtaining the solution of soil – plant water balance equations are numerous and can differ very much from one model to the other (Sivakumar et al. 1991). No general method to solve the water balance equations will be discussed in this Chapter.

Nutrient limited yield is an actual subject of research in the modelling community. Some models of the Wofost family calculate final nutrient limited yield without giving as output a detailed description of how nutrient limitations affect different developmental stages of the crop (Keulen, 1990). The calculations of these nutrient limited yields require using linear yield – nutrient uptake by roots. In a crop model such as CropSyst,

$$\mathbf{A = (N_{p\,critical} - N_p) \,/\, (N_{p\,critical} - N_{p\,min})}$$

$$\mathbf{B_N = B\,(1 - A)}$$

Where **B** is water and radiation limited growth as we have studied so far, $\mathbf{B}_N$ is nitrogen limited growth, $\mathbf{N}_p$ is actual plant nitrogen content, $\mathbf{N}_{p\,min}$ is minimum admissible plant nitrogen content below which further growth is impossible and $\mathbf{N}_{p\,critical}$ is a critical value with the following meaning,

If $\mathbf{N}_p < \mathbf{N}_{p\,critical}$ then $\mathbf{B}_N <$ B and growth is nitrogen limited

If $\mathbf{N}_p >= \mathbf{N}_{p\,critical}$ then $\mathbf{B}_N = \mathbf{B}$ and further growth is not limited by nitrogen

As stated by this formulation, the addition of nitrogen fertilizer beyond the point in which $\mathbf{N}_p$ reaches the minimum value $\mathbf{N}_{p\,critical}$ is devoid of sense and will not promote further growth and crop yields. Then growth will be conditioned by radiation and soil water only. An interesting comparative analysis of the main ways of simulating crop growth discussed in this Chapter can be read in Steduto (2006).

To completely define the impact of nutrients, nitrogen in this case, on crop growth and yield, the solution of a soil – plant nitrogen balance equation is required. As stated by Donatelli and Stockle (1999), the nitrogen balance has more uncertainties and it is more complex to study and model than the water balance.

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TABLES AND FIGURES FOR CHAPTER 4

Table 4.1 Duration of phenological phases for maize (Doorenbos and Kassam, 1979)

Duration (d)	15 – 25	25 – 40	15 – 20	35 – 45	10 – 15

Table 4.2 Growth habit of soybean

Determinate growth habit	The terminal bud ceases vegetative activity when flowering begins.
Semi-Determinate growth habit	The terminal bud continues vegetative growth after flowering but terminates this growth before indeterminate types.
Indeterminate growth habit	The terminal bud continues vegetative activity throughout the growing season.
Maturity in relation to growth habit	For inspection purposes, maturity means that at least 90% of the plants in the inspected field have dropped their leaves.

Table 4.3 Species Characteristics (adaptation of Table 51, page 182, from Oldeman y Frere (1982)).

Parameter	**Type 1**	**Type 2**	**Type 3**	**Type 4**
Photosynthesis	C_3 cold climate	C_3 warm climate	C_4 cold climate	C_4 warm climate
$\mathbf{P_m}$	20 - 30	40 - 50	70 - 100	70 - 100
$\mathbf{I_s}$	0.2 – 0.6	0.3 – 0.8	> 1.0	> 1.0
T optimal	15 - 20	25 - 30	20 – 30	30 - 35
Species	Wheat, potato	Soybean, rice, cassava and sweet potato	Sorghum and maize	Millet, maize, sorghum and sugarcane

$\mathbf{P_m}$ – Maximum photosynthesis at optimum temperature is absorbed mg CO_2 / (dm^2 – hour)
$\mathbf{I_s}$ – Intensity of photosynthetic radiation (PAR) which reaches the value $\mathbf{P_m}$ in cal / cm^2 – min
T optimal – Optimal temperature in Celsius at which the largest value of $\mathbf{P_m}$ is reached.

Table 4.4: Dry matter partitioning functions for maize as used in CROP41.dat file of WOFOST 4.1 crop model (Diepen et al, 1988).

Beta values for different organs						
DVS	0.0	1.10	2.00			
β^r_j	0.40	0.0	0.0			
DVS	0.0	0.48	0.90	1.25	1.37	2.00
β^t_j	0.62	0.62	0.28	0.0	0.0	0.0
DVS	0.0	0.48	0.90	1.25	1.37	2.00
β^h_j	0.38	0.38	0.72	0.24	0.0	0.0
DVS	0.0	0.48	0.90	1.25	1.37	2.00
β^f_j	0.0	0.0	0.0	0.76	1.00	1.00

In WOFOST 4.1 (Diepen et al, 1988) phenological stage is indicated by variable **DVS**.

Table 4.5: Harvest Index (**HI**) for some crops in the case of potential and irrigated yields as given by Doorenbos y Kassam (1979).

Crops	**Minimum value of H**	**Maximum value of H**
Maize	0.35	0.45
Potato	0.55	0.65
Tomato	0.25	0.35
Soybean	0.30	0.40

In simple models as FAO Agrometeorological Zones Model dry matter partitioning functions are substituted by Harvest Index (**HI**) representing the useful fraction of total crop biomass.

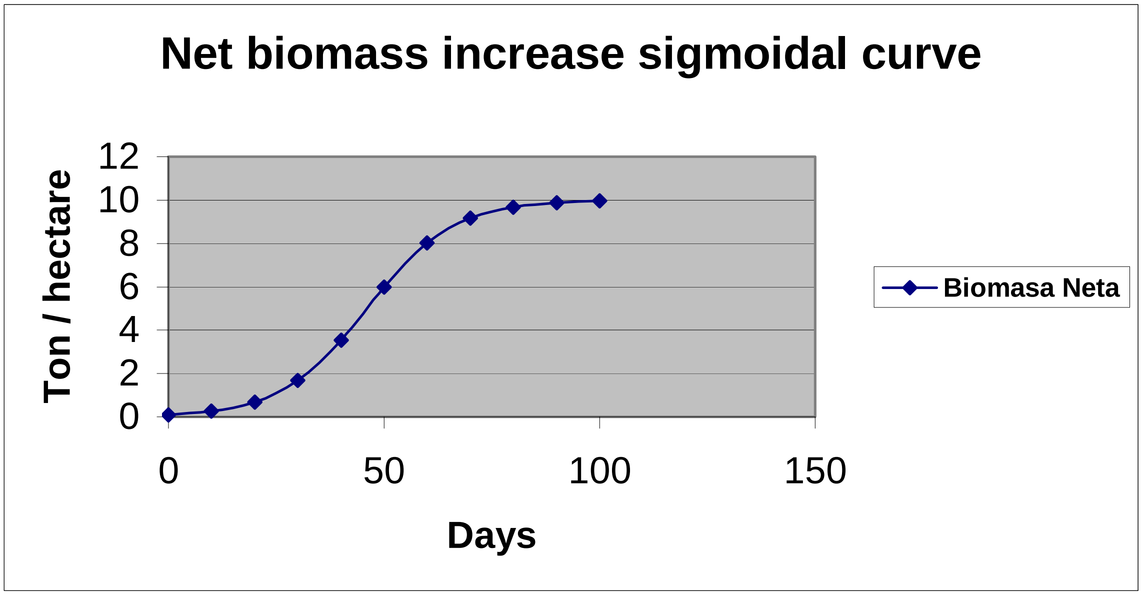

Fig. 4.1: Net biomass increase sigmoid curve for a crop with a one hundred days cycle

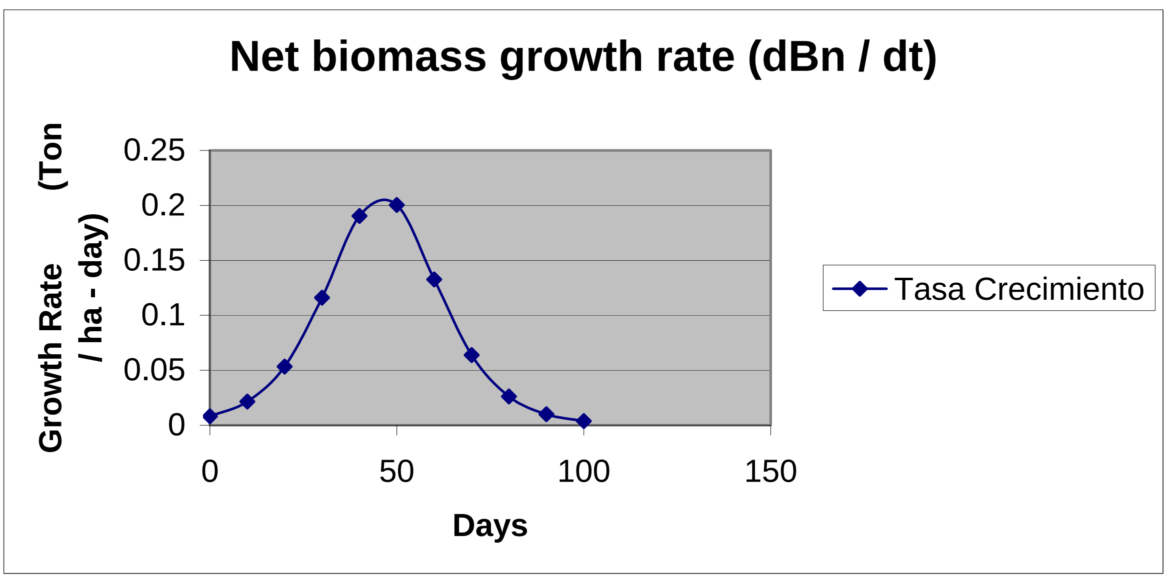

Fig. 4.2: Growth rate for a crop with a 100 days cycle

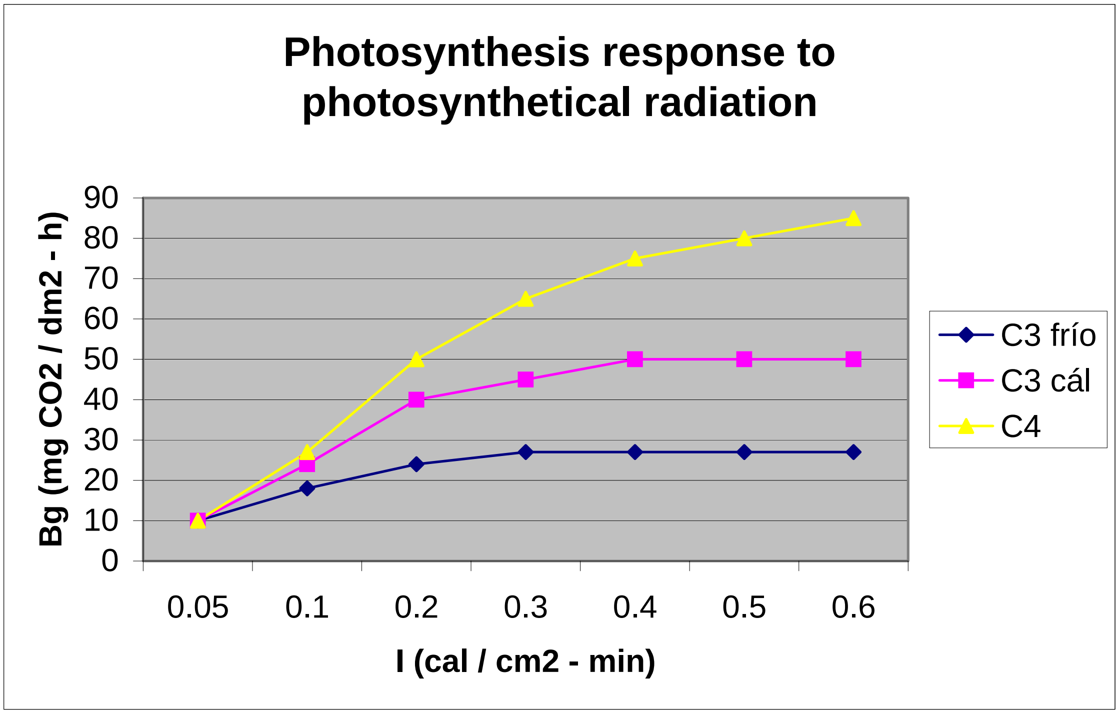

Figure 4.3: Response curves of photosynthesis (mg CO_2 per leaf square decimetre per hour) to photosynthetically active solar radiation for different groups. They are of the Michaelis –Menten kind.

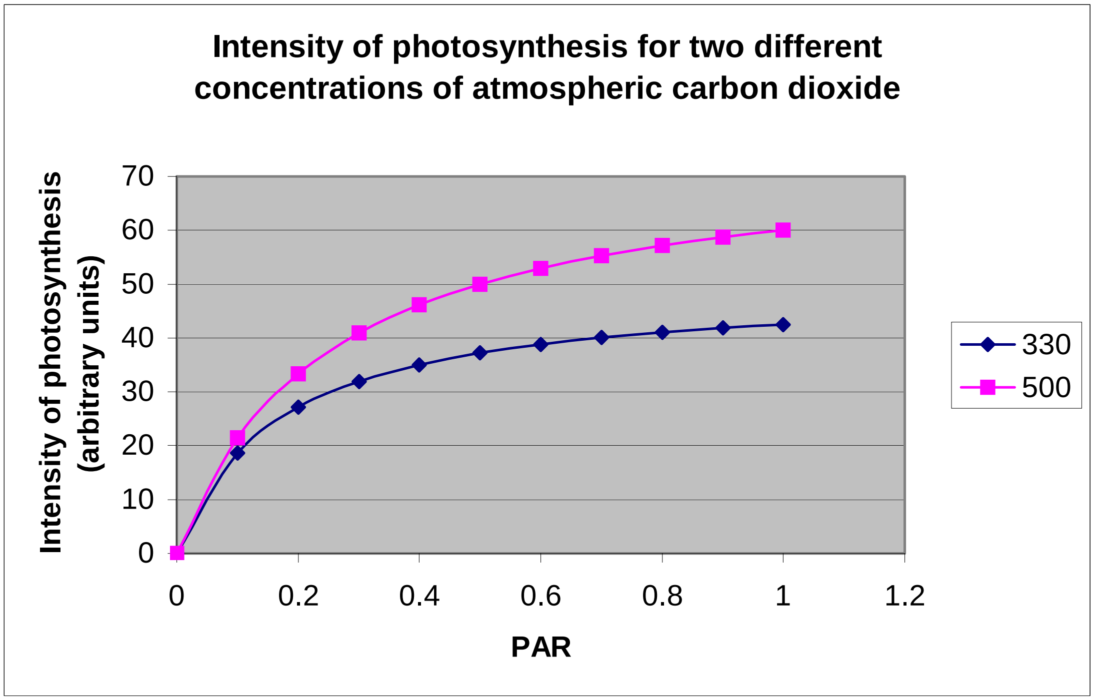

Figure 4.4: Photosynthesis intensity dependence on photosynthetic solar radiation intensity for a C_3 species at two different CO_2 atmospheric concentrations in arbitrary units, using Budyko (1980) formula

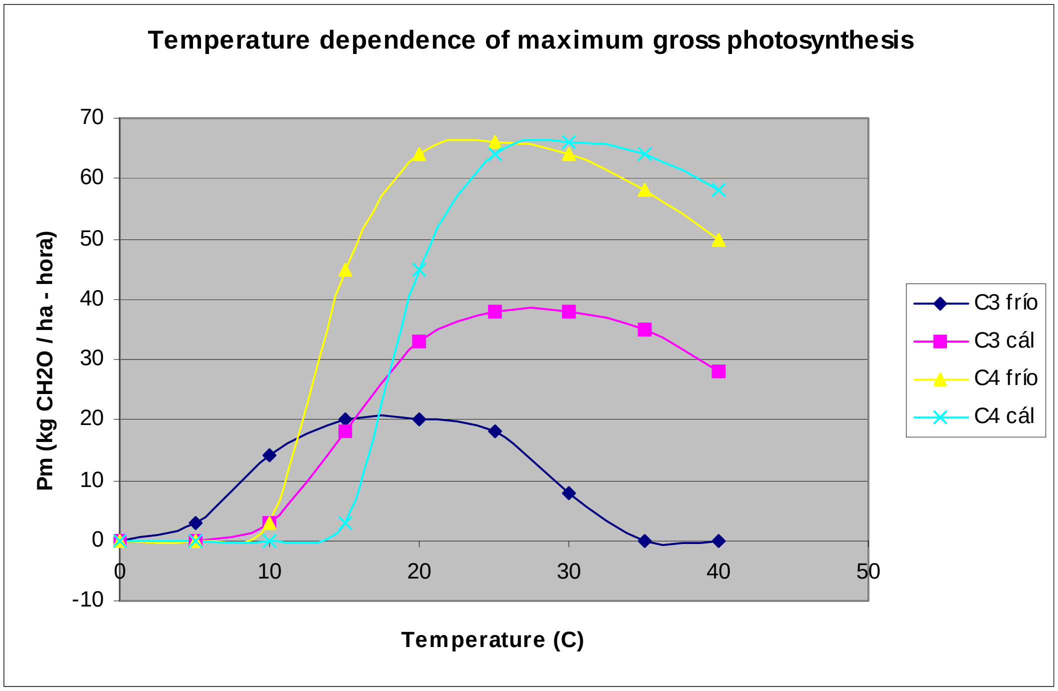

Figure 4.5: Response curves of $\mathbf{P_m}$ to temperature, kg of sugars per hectare per hour, for the four main groups. Adaptation of figure 88, page 183, in Oldeman and Frere (1982)

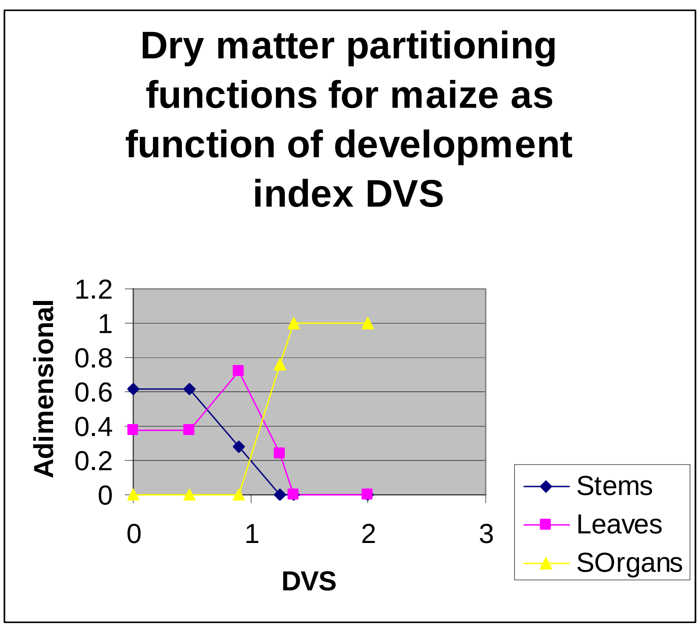

Figure 4.6: Dry matter partitioning functions for maize as function of the development index DVS. Roots excluded. Original data from Diepen et al. (1988)

CHAPTER 5

THE FAO AGROECOLOGICAL ZONES MODEL

Chapter 5:

1. Introduction
   - Some Definitions of Useful Crop Yields
2. The FAO Classification of Crops
3. The Nexialist approach of combining available knowledge
4. The FAO Agroecological Zones Model
   - Introduction
   - Potential yields
   - Water limited yields
5. Tabulated input data

INTRODUCTION

The authors of this workbook are very much aware that all the necessary information about calculation methods to estimate potential evapotranspiration and solve crop water balance procedures is not given explicitly here. The multiplicity and complexity of existent procedures to solve these two problems are such that to include them explicitly would make the chapter too lengthy. Scientific literature referenced in this Chapter and Chapter 2 provides an extensive set of methodologies which should help to achieve these goals.

Beside this, only manually solved FAO AEZM requires the explicit calculation of potential evapotranspiration and water balance terms, but even this model is now available as a software tool named CROPWAT (FAO, 1992) which makes all these calculations internally. The WOFOST and DSSAT families of crop models do their own internal calculation of these parameters using genetical, soil and climatic input data. The user of these models must, generally, admit that the creators knew what definitions and calculating procedures were best suited to the purposes of the models.

Some Definitions of Useful Crop Yields

In relation to crop models it is very common and useful to define diverse kinds of crop yields reflecting different environmental and management conditions in which these different crop yields would be obtained. These sets of definitions will not only allow us to study the impact of climate change in one or other kind of yield when we would not be able to do so in real field ones, but also allows models to simulate the influence of one or other condition or set of them upon final (dry matter) yield of crops. A preliminary set of definitions follows:

- **Potential yields** are obtainable yields in actual temperature and solar radiation conditions. All the rest of requirements are totally satisfied. They are genetical, temperature and radiation limited yields. Usually obtainable only in carefully designed experimental conditions at laboratories and agricultural research institutions. Soil conditions specifications are absolutely unnecessary because water and nutrients are automatically assigned by model algorithms without taking real soil parameters into account.

- **Irrigated yields** are obtainable yields in actual temperature and solar radiation conditions plus irrigation. All the rest of requirements are totally satisfied. They are genetical, temperature, radiation and water limited yields. If irrigation is optimal there are no water limitations and they might coincide with potential yields. Soil conditions must be specified only in relation to its water holding capacity as nutrients are automatically assigned to the crop internally. According to the irrigation management specified by the user an irrigated yield can be as high as a potential yield and as low as a rainfed yield. This is a consequence of the actual amount and temporal distribution of water supplied to the crop as specified by the user (partial satisfaction of crop water requirements).

- **Rainfed** yields are obtainable yields in actual temperature, solar radiation and precipitation conditions without any irrigation. All the rest of requirements are totally satisfied. They are genetical, temperature, radiation and water limited yields. If natural precipitation and type of soil are optimal they might coincide with optimal irrigated and potential yields.

- **Real yields** try to take additionally into account nutrients, pests, diseases and management conditions. They are limited by everything you can imagine and generally no model does that exactly, given the diversity of conditions.

Impact assessments are usually done at first on the basis of potential and water limited yields. This multiplicity of yields gives rise to a set of indexes definitions that can be very useful in actual assessments, as follows:

Technological efficiency of actual production is defined as,

$$\mathbf{T_e = actual\ mean\ crop\ yield/potential\ yield = Y_a / Y_p}$$

For potato production this index equals to 0.45 in the Netherlands and 0.46 in the state of Washington (U.S.A.), according to Beukema and Zaag (1990). A preliminary assessment using SUBSTOR-Potato, as included in DSSAT, for the United Kingdom gave values of $\mathbf{T_e}$ near to 0.36 – 0.45 (Carlos Berna Esteban, personal communication February 2008).

This same index has been related to the quotient given by real crop evapotranspiration divided by potential crop evapotranspiration in FAO Agroecological Zones Model (AEZM). This relationship was expressed as:

$$\mathbf{(1 - (Y_a / Y_p)) = k_y * (1 - (ETa / ETp))}$$

The use of this ratio in AEZM will be discussed below in this same chapter (Fischer et al, 2000). The reader should be aware that in this context $\mathbf{T_e}$ is taken as a technological efficiency related to water limitation alone and not a true technological efficiency. This last concept should include all technological limitations affecting optimum crop growth.

The concept of technological efficiency gives rise to a very interesting paradox. This concerns the fact that in the presence of climate change, potential yields could be decreasing while actual (real) field yields could be rising, if we increase agricultural technological efficiency simultaneously. That is why Rivero (2001) included a scenario for agricultural technological efficiency in his cross – sectoral integrated impact model MIIA 1.0 and 2.0.

THE FAO CLASSIFICATION OF CROPS

Even if FAO classification of crops leading to five kinds of plants given by cold climate C_3, warm climate C_3, cold climate C_4, warm climate C_4 and succulent (crassulacean) C_4 plants was somewhat discussed in the previous chapter it seems convenient to add information about it in this section. We will leave succulent plants out of our actual analysis and will work with a four group's classification of crop plants. The reader should be aware that this classification leads us to work with graphical representations of the response of plants to light intensity and phototemperature (Figures 4.3 and 4.5) in such a way that, by instance, all different cold climate C_3 crop plants or varieties of the same plant (cultivars) will be considered to have exactly the same response curves. This fact is not true and it means an oversimplification of the subject at hand.

Different crops belonging to the same group will have different response curves and different $\mathbf{P}_{\mathbf{m}}$ values, the same fact will be encountered among different varieties of the same crop (Heemst, 1988). In some models as WOFOST this circumstance is circumvented by specifying the actual value and temperature dependence of $\mathbf{P}_{\mathbf{m}}$ for each crop or variety in its input data files. This can also be done with the simple stationary model **AEZM** by simply using actual experimental or referenced values for the necessary variables instead of using an interpolation procedure over the given (exemplified) response curves.

As we will appreciate now this classification does not directly provide a method for dealing with the impact of increased carbon dioxide atmospheric concentrations on crop responses related to the intensity of photosynthetic reactions and the correspondent water needs. This would be very important to stress the fact that C_3 and C_4 plants will have very different responses to the carbon dioxide fertilization effect. That does not mean the user cannot devise a suitable way for taking those effects into account by using the proper response curves. Usual versions of the WOFOST model do not have that possibility built into neither, but it was shown by Wolf et al (1993) that the model could approximately take the fertilization effect into account by the soundly based manipulation of crop input parameters related to photosynthesis and water economy.

THE NEXIALIST APPROACH OF COMBINING AVAILABLE KNOWLEDGE

As we see how a crop model is progressively built, and what assumptions and mathematical expressions are used for the derivation of results, we will be able to comprehend that a crop model is not a disciplinary tool, because it is generally built as a puzzle combining different pieces of knowledge belonging to many different disciplines. This fact is more visible as model and decision tools complexity increases trying to behave as whole units in which the user is every time more distant and unconscious of what the model is assuming and calculating by him. Very advanced models can use only one air humidity parameter or use sunshine hours as input because they are able to derive the rest of the humidity parameters (meteorology) and solar radiation values (astronomy) internally. This knowledge is combined with ecological, physiological and agronomical knowledge to give plant biomass behaviour with time and final yields as well as irrigation water needs and management influence on results.

Some would think that a crop model could be considered a multidisciplinary, transdisciplinary or holistic tool, but the authors of this workbook prefer to see crop models as nexialist tools in the original sense (devoid of dualism) given by Vogt (1950). According to this author the science of nexialism can better be described as applied whole-ism. In our native country it is common to name a gadget made from very different pieces coming from many, often unexpected, origins as "a Frankenstein".

THE FAO (AEZ) AGROECOLOGICAL ZONES MODEL

Introduction

Crop models could be classified in many ways, but we will be classifying them here according to the way in which precedent information has been used and how clear that information is visible to the user. Guided by this way of thinking, crop models and model families could be classified as transparent, translucid and opaque. The three families of models will be discussed in this workbook.

Transparent models state explicitly all assumptions and formulas involved in the calculation of final results. This is done in such a way that the reader may immediately see its advantages and limitations being able to modify assumptions and equations used and decide about the, always limited, usefulness of the stated model for solving his particular problems. The **FAO Agroecological Zones Models** (**AEZM**), originally devised by Kassam (1977), is a transparent model. So transparent that users can make calculations by hand without even a computer or sophisticated hand calculator. Given the different versions available in different publications as Oldeman and Frere (1982), Doorenbos and Kassam (1979), Beukema and Zaag (1990) and others, we could call **AEZM** a family of crop models. **AEZM** is a stationary model in the sense that the model assumes a certain time dependent behaviour of the crop, but does not give time dependent solutions and outputs. The fact that for some steps of the calculations the user is required to access some sets of figures and tabulated data – not explicitly dependent of the model equations themselves – leaves invariably the transparency of the model to a level that it can be assimilated by farmers and middle level technicians. They do not need to have been specifically trained in higher mathematics and computing science. These are transparent boxes in which all the wheels can be clearly seen.

Translucent models are intermediary ones in which technical documentation is sufficiently clear and profuse as to allow the trained specialist to follow the assumptions, logic, and scientific basis of the processes involved. This technical documentation makes explicit the source programs (usually FORTRAN) from which detailed calculations procedures can be derived and the interactive way in which the model itself is run allows additional information as to the way the model has been elaborated (Diepen et al, 1988). Anyway, these kinds of models, usually time-dependent dynamic ones, require highly trained specialists with rather high computer science knowledge. The **WOFOST** family (**WOFOST 4.1** and **7.1.2**) belongs to these kinds of models which we could name as grey boxes, because only a very well trained eye can see the wheels turning inside and make necessary modifications in input/output as to tailor the models to his specific needs. A translucent model is usually obtained as documented software ready for being run in a PC.

Opaque models are not necessarily independent models, but models linked to other subsystems to form, as a whole, a product known as an analytical tool or a decision-support system. Generally, more than one dynamical crop model is embedded in the decision tool. Technical documentation available hardly refers to the crop models themselves and no source code is generally available. Even being merged into a very complex and sophisticated software full of auxiliary and extensive additional tools the original models are not visible at all and cannot be tampered with. No source code is generally available and the packet is only documented as a whole while the models themselves are not documented at all, even if they can be found (with a lot of difficulties) in published reference literature. Even to experienced and highly trained users the implicit models are little more than black boxes with wheels that cannot be seen at all. Much more than a superficial knowledge of crop modelling concepts and computer science is needed to allow for the arrival at sound conclusions by using very advanced scientific tools available as software packets. The most popular of these complex black boxes are the different members of the DSSAT family (DSSAT 3.0, 3.5 and 4.0), documented in a four volume User's Manual (Tsuji et al, 1994). This family is still growing.

All these families will be discussed in this workbook. This will be done in a progressive way, so the student and practitioner can go step by step from conceptual and theoretical discussions to the most complex of modelling tools in an orderly fashion. The experience of the authors tell us that using a complex modelling tool without having been properly trained in this way most often than not will only lead to (at least apparently) contradictory results and misinterpretations.

Potential Yields

The **AEZM** methodology for the calculation of potential net biomass and yields is derived from Kassam (1977). There are different publications about this model that present slightly different versions of it. Additionally, some reports explaining the model contain typographic errors which make mathematical expressions and figures hardly usable at all. In this workbook we will be presenting **AEZM** model as discussed by Fischer et al (2000), discounting typographical errors in Oldeman and Frere (1982) these two formulations are the most valid when compared to the initial formulation of Kassam (1977). This model, based on eco-physiological principles already discussed in previous Chapters, is outlined below:

To calculate the net biomass production ($\mathbf{B_n}$) of a crop, an estimation of the gross biomass production ($\mathbf{B_g}$) and respiration loss (**R**) are required:

$$\mathbf{B_n = B_g - R}$$

The equation relating the rate of net biomass production ($\mathbf{b_n}$) to the rate of gross biomass production ($\mathbf{b_g}$) and the respiration rate (**r**) is:

$$\mathbf{b_n = b_g - r}$$

The maximum rate of net biomass production ($\mathbf{b_{n\,m}}$) is reached when the crop fully covers the ground surface. The period of maximum net crop growth, i.e., the point in time when maximum net biomass increments occur is indicated by the inflection point of the cumulative (sigmoid) growth curve. When the first derivative of net biomass growth is plotted against time (days) the resulting graph resembles a normal (bell shaped) distribution curve. The model assumes that the average rate of net biomass production ($\mathbf{b_{n\,a}}$) over the entire growth cycle is half the maximum growth rate, i.e., $\mathbf{b_{n\,a} = 0.5\ b_{n\,m}}$.

The net biomass production for a crop of **N** days ($\mathbf{B_n}$) is then:

$$\mathbf{B_n = 0.5\ b_{n\,m}\ N}$$

The maximum rate of gross biomass production ($\mathbf{b_{g\,m}}$) is related to the maximum net rate of C_2 exchange of leaves ($\mathbf{P_m}$) which is dependent on temperature, the photosynthesis pathway of the crop, and the level of atmospheric CO_2 concentration.

For a standard crop, i.e., a crop in adaptability group 1 (**Table 5.3**) with $\mathbf{P_m = 20}$ k /ha - hr and a leaf area index of **LAI = 5**, the rate of gross biomass production $\mathbf{b_{g\,m}}$ is calculated from the equation:

$$\mathbf{b_{g\,m} = F\ b_o + (1 - F)\ b_c}$$

Where:

F = the fraction of the daytime, the sky is clouded, given by

$$\mathbf{F = (A_c - 0.5\ R_g) / (0.8\ A_c)}$$

Where A_c (or **PAR**) is the maximum active incoming short-wave radiation on clear days (de Wit, 1965), and R_g is incoming short-wave radiation (both are measured in cal/cm ^{2} - day).

b_o = gross dry matter production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg/ha - day) (de Wit, 1965)

b_c = gross dry matter production rate of a standard crop for a given location and time of the year on a perfectly clear day, (kg/ha - day) (de Wit, 1965)

Working values of A_c, b_o and b_c are shown in **Table 5.1** where intermediate data may be interpolated. More complete tabulated data can be found in the references given at the end of this chapter. The **AEZM** model requires also a determination of P_m that should be done knowing mean phototemperature (T_f) for the whole growth cycle, adaptability group (1 – 4) and **Figure 4.5**.

When P_m is greater than 20 kg/ha - hr, b_{gm} is given by the equation (Oldeman and Frere, 1982):

$$b_{gm} = (1 + 0.025 (P_m - 20)) F * b_o + (1 + 0.010 (P_m - 20) * (1 - F) * b_c$$

Bur when P_m is less than 20 kg / ha - hr, b_{gm} is calculated according to:

$$b_{gm} = (1 - 0.010 (20 - P_m)) F * b_o + (1 - 0.005 (20 - P_m)) * (1 - F) b_c$$

To calculate the maximum rate of net biomass production (b_{nm}), the maximum rate of gross biomass production (b_{gm}) and the rate of respiration (r_m) are required. Here, growth respiration is considered a linear function of the rate of gross biomass production (McCree, 1974), and maintenance respiration a linear function of net biomass that has already been accumulated (B_m) When the rate of gross biomass production is b_{gm}, the respiration rate r_m is:

$$r_m = k\, b_{gm} + c_t B_m$$

Where **k** and **c** are the proportionality constants for growth respiration and maintenance respiration respectively, and B_m is the net biomass accumulated at the time of maximum rate of net biomass production. For both legume and non-legume crops **k** equals 0.28.

However, c_t is temperature dependent and differs for the two crop groups (legumes and not legumes). At 30 degrees Celsius, factor c_{30} for a legume crop equals **0.0283** and for a non-legume crop **0.0108**. The temperature dependence of c_t for both crop groups is modelled with a quadratic function of the mean (ordinary) temperature (**T**) of the whole growth cycle:

$$c_t = c_{30} (0.0044 + 0.0019\, T + 0.0010\, T^2$$

It is assumed that the cumulative net biomass B_m of the crop (i.e., biomass at the inflection point of the cumulative growth curve) equals half the net biomass that would be accumulated at the end of the crop's growth cycle. Therefore, we set $B_m = 0.5\, B_n$, and using (3), B_m for a crop of **N** days is determined according to:

$$B_m = 0.25\, b_{nm} N$$

By combining the respiration equation with the equation for the rate of gross photosynthesis, the maximum rate of net biomass production (**$b_{n\,m}$**) or the rate of net dry matter production at full cover for a crop of **N** days becomes:

$$b_{n\,m} = 0.72\, b_{g\,m} / (1 + 0.25\, c_t\, N)$$

Finally, the net biomass production (**B_n**) for a crop of **N** days, where **$0.5\, b_{n\,m}$** is the seasonal average rate of net biomass production, can be derived as:

$$B_n = (0.36\, b_{g\,m}\, L) / (1 / N + 0.25\, c_t)$$

$$B_n = (0.36\, b_{g\,m}\, N\, L) / (1 + 0.25\, N\, c_t)$$

Where:

$b_{g\,m}$ = maximum rate of gross biomass production at leaf area index (**LAI**) equal 5.0
L = growth ratio, equal to the ratio of **$b_{g\,m}$** at actual **LAI** to **$b_{g\,m}$** at **LAI** equal 5.0
N = length of normal growth cycle
c_t = maintenance respiration, dependent on both crop and temperature according to equation (8)

Parameter **L** may be derived from the equations,

If **L < 5** then,

$L = -0.0307 * LAI^2 + 0.3549 * LAI - 0.0111$ (with correlation coefficient R^2 equal to **0.9993**)

But if **L = 5** or **L > 5** then,

L = 1

Potential yield (**Y_p**) is estimated from net biomass (**B_n**) using the equation:

$$Y_p = HI * B_n$$

Where:

HI = harvest index, i.e., proportion of the net biomass of a crop that is economically useful (**Table 4.5**).

Thus, climate and crop characteristics that apply in the computation of net biomass and yield are: (a) heat and radiation regime over the crop cycle, (b) crop adaptability group to determine applicable rate of photosynthesis **P_m**, (c) length of growth cycle (from emergence to physiological maturity), (d) length of yield formation period, (e) leaf area index at maximum growth rate, and (f) harvest index.

Tabulated input data necessary for the calculation of **A_c**, **b_o** and **b_c** can be seen in **Table 5.1**. Other versions of these data can be obtained from Fischer et al (2000), Beukema and Zaag (1990) and other sources.

One Example of AEZM Application to potato yields in Camagüey, Cuba.

Let us calculate potential yield of potatoes in Camagüey, Cuba, knowing that this crop is planted at the end of November and has its emergence in December 1 being harvested at February 1 with **N** = 93 days. Latitude of Camagüey (21.4 North) is taken (approximately) as 20 degrees North. Mean December – February 1961 – 90 measured values of R_g equals 14.488 MJ m ^{2} (equivalent to 346.60 cal/cm ^{2}) while measured mean $\mathbf{T_{max}}$ and $\mathbf{T_{min}}$ for the same period on site are equal to 28.37 and 17.73 degrees Celsius respectively.
Mean phototemperature:

$$\mathbf{T_f = 0.25\ T_{min} + 0.75\ T_{max} = 25.71\ C}$$

Mean temperature:

$$\mathbf{T = (17.73 + 28.37) / 2 = 23.05\ C}$$

From **Table 5.1** we have that,

Mean $\mathbf{A_c}$ = 260 cal/cm ^{2} – day, **Mean** $\mathbf{b_c}$ = 343.3 kg/ha – day and **Mean** $\mathbf{b_o}$ = 175.67 kg/ha – day respectively. Then we have that,

$$\mathbf{F = (A_c - 0.5\ R_g) / (0.8\ A_c) = (260 – 0.5 * 346.60) / (0.8 * 260) = 86.7 / 208 = 0.417}$$

From **Table 4.3** and **Figure 4.5** shown in Chapter 4 we can easily see that potato is a $\mathbf{C_3}$ cold climate crop, or Type 1 crop according to FAO classification, and that for this type of crops at optimal temperature $\mathbf{P_m}$ = 20 kg CH2 /ha – hour. But at $\mathbf{T_f}$ = 25.71C the corresponding value of $\mathbf{P_m}$ = 18.0 kg CH2O/ha – hour would be necessary. Then we have that:

$$\mathbf{b_{g\,m} = (1 – 0.010\ (20 - P_m))\ F * b_o + (1 – 0.005\ (20 - P_m)) * (1 – F) * b_c}$$

$$\mathbf{b_{g\,m} = 0.98 * 0.417 * 175.67 + 0.99 * 0.583 * 343.3}$$

$$\mathbf{b_{g\,m} = 71.789 + 198.142 = 269.92\ kg\ CH20 / ha- day}$$

Respiration losses are then calculated as,

$$\mathbf{c_t = c_{30}\ (0.0044 + 0.0019\ T + 0.0010\ T^2) = 0.0108\ (0.0044 + 0.0019 * 23.05 + 0.0010 * 23.05^2)}$$

$$\mathbf{c_t = 0.0108 * 0.5795 = 0.0063}$$

With these values, assuming we can already calculate net biomass production as,

$$\mathbf{B_n = (0.36\ b_{g\,m}\ N\ L) / (1 + 0.25\ N\ c_t) = (0.36 * 269.92 * 93 * L) / (1 + 0.25 * 93 * 0.0063)}$$

$$\mathbf{B_n = 9036.921\ L / 1.146475 = 7882.354\ L}$$

If **L > = 1** we can assume **L = 1** but if actual attained **L** is less than **5,** then we can derive **L** from the previous given equation or from **Table 5.3**. Then, assuming **L = 1** for our case, we have that,

$$B_n = 7882.354 \text{ kg (Dry Matter /ha} = 7.882 \text{ Ton DM/ha}$$

Assuming a Harvest Index of **0.60** as derived from **Table 4.5**, the total potential potato (tuber) yield would be,

$$Y_p = HI * B_n = 4.729 \text{ Ton DM/ha}$$

Actual fresh tuber yield of potatoes require an adjustment to take into account the water content of tubers that, in Cuba, is approximately equal to 80 per cent, according to the expression,

$$\text{Fresh Tuber Yield} = 100 * \text{Dry Matter Yield} / (100 - \text{Water Content})$$

$$FTY = 100 * 4.729 / (100 - 80) = 5 * 4.729 = 23.647 \text{ Ton FT Weight / ha}$$

As fresh tuber yields obtained in Camagüey by experimented farmers are approximately equal to **15.643 Ton FT Weight/ha** this would imply a (rather high) technological efficiency of,

$$T_e = Y_a / Y_p = 15.643 / 23.647 = 0.66$$

The reader should be aware that potential yields (all kinds of yields, in fact) obtained with different procedures and models will be different, notwithstanding the fact that the user takes all the precautions for using the same input data. This introduces additional uncertainties in any assessment, only that not related now with climate change scenarios, but with the different nature of the impact models themselves. Intercomparison workshops on global climate models seem to be rather common (Wigley, 2003), but these authors are not aware of similar workshops in relation to the impact models used in agricultural assessments.

The use of different impact (crop) models in a specific assessment should be avoided because of the additional uncertainties that would be introduced. In an assessment study, the results of the chosen crop model should be compared only with itself running it across the whole set of chosen climate change scenarios in different places, types of soil, and seasons of the year. Any sensible crop model will reflect better the impact of changing environmental conditions than actual yields obtained and reported by farmers and governmental institutions.

The intercomparison of crop models, including its calibration in local conditions, should be done in a previous stage allowing the impact team to select the final crop model they are going to use in the assessment itself. Real validation of a particular crop model often requires investments and resources hardly available in developing countries. Besides, if there is such a thing as a “best crop model” it will not necessarily coincide with the “allowable or usable” model because of the very different set of input data models needed to behave as the “best one”.

Water Limited Yields

The calculation of moisture limited yields follows the procedures described in FAO (1992), known as the CROPWAT method. In this approach, the crop-specific potential evapotranspiration $\mathbf{E_{0c}}$ is related to reference evapotranspiration $\mathbf{E_0}$ as,

$$E_{0c} = k_c E_0$$

Where $\mathbf{k_c}$ is estimated from a piecewise linear function (**Figure 5.1**).

This function is parameterized by means of seven parameters. Four coefficients, **d1, … , d4**, are related to the characteristics of the crop cycle, denoting the length (in days) of four crop development stages (analogues to phenological phases specifically devised for the purpose at hand), namely: initial stage, vegetative stage, reproductive stage, and maturation stage. The use of these crop (evapotranspiration) coefficients ($\mathbf{k}_c$) might be problematic because they might not coincide in different publications. The reader is urged to go through the last subsection (Tabulated Input Data) of this Chapter in order to understand the meaning of these coefficients and the differences found in available tabulated data.

Still another three parameters, $\mathbf{k1}_c$, $\mathbf{k2}_c$ and $\mathbf{k3}_c$, define this relationship, respectively, for the initial stage, the reproductive phase, and the end of the maturation stage (**Tables 5.4 and 5.5**).

Let $\mathbf{D}_1$ **to** $\mathbf{D}_4$ denote the days belonging to each of the four crop growth stages,

$$\mathbf{D_1 = \{j \mid 1 <= j <= d1\}}$$

$$\mathbf{D_2 = \{j \mid d1 < j <= d1 + d2\}}$$

$$\mathbf{D_3 = \{j \mid d1 + d2 < j <= d1 + d2 + d3\}}$$

$$\mathbf{D_4 = \{j \mid d1 + d2 + d3 < j <= d1 + d2 + d3 + d4\}}$$

Then the value of $\mathbf{k}_c$ for a particular day **j** is defined by:

$$\mathbf{k_{c\,j} = k1_c} \qquad \text{if } \mathbf{j}\ \boldsymbol{\varepsilon}\ \mathbf{D_1}$$

$$\mathbf{k_{c\,j} = k1_c + (j - d1) * ((k2_c - k1_c) / d2)} \qquad \text{if } \mathbf{j}\ \boldsymbol{\varepsilon}\ \mathbf{D_2}$$

$$\mathbf{k_{c\,j} = k2_c} \qquad \text{if } \mathbf{j}\ \boldsymbol{\varepsilon}\ \mathbf{D_3}$$

$$\mathbf{k_{c\,j} = k2_c + (j - (d1 + d2 + d3)) * ((k3_c - k2_c) / d4)} \qquad \text{if } \mathbf{j}\ \boldsymbol{\varepsilon}\ \mathbf{D_4}$$

Using these equations, crop-specific potential evapotranspiration over the four crop growth stages, $\mathbf{TE}_{0\,c\,k}$, and the entire crop cycle, $\mathbf{TE}_{0\,c}$, can be calculated:

$$\mathbf{TE_{0\,c\,k} = \Sigma\ (j\ \varepsilon\ D_k)\ k_{c\,j} * E_{0\,j}} \qquad \mathbf{k} = 1, ..., 4$$

$$\mathbf{d0 = d1 + d2 + d3 + d4}$$

$$\mathbf{TE_{0\,c} = \Sigma\ (j = 1\ to\ d0)\ k_{c\,j} * E_{0\,j}}$$

In a similar way, applying a crop-specific soil water balance, actual evapotranspiration ($\mathbf{E}_a$) is calculated as:

$$\mathbf{TE_{a\,c\,k} = \Sigma\ (j\ \varepsilon\ D_k)\ E_{a\,c\,j}} \qquad \mathbf{k} = 1, ..., 4$$

$$\mathbf{TE_{a\,c} = \Sigma\ (j = 1\ to\ d0)\ E_{a\,c\,j}}$$

Where $\mathbf{E}_{a\,c\,j}$ is determined according to:

$$\mathbf{W_{c\,j+1} = min\ (W_{c\,j} + P_j + E_{a\,c\,j}\ ,\ Sa)}$$

$$\mathbf{If\ (W_{c\,j} + P_{j}) * d >= Sa * d * (1 - p_{c\,j})\ then}$$

$$\mathbf{E_{a\,c\,j} = E_{0\,c\,j}}$$

Else

$$\mathbf{E_{a\,c\,j} = \rho_{j} * E_{0\,c\,j}}$$

With,

$$\mathbf{\rho_{j} = E_{a\,c\,j} / E_{0\,c\,j} = (W_{c\,j} + P_{j}) / (Sa * (1 - p_{c\,j}))}$$

j – Number of days in year

Sa – Available soil moisture holding capacity (mm /m)

d – Rooting depth (m)

$\mathbf{p_{c\,j}}$ – Soil water depletion fraction below which $\mathbf{E_{a} < E_{0}}$

$\mathbf{p_{j}}$ – Actual evapotranspiration proportionality factor.

Sa and **d** are defined by the respective values of the soil units in individual grid-cells. The computation of water-limited yield $\mathbf{Y_{a}}$ is now easily obtained, following FAO (1979 and 1992). A set of values for the parameter $\mathbf{k_{y}}$ can be seen in **Table 5.6**.

$$\mathbf{(1 - (Y_{a} / Y_{p})) = k_{y}\ (1 - (TE_{a\,c} / TE_{0\,c}))}$$

We evaluate this expression in two variants, first over the entire growth cycle and then according to individual growth stages. The more severe of the two conditions determines $\mathbf{Y_{a}}$. The respective reduction multipliers $\mathbf{f_{0}}$ and $\mathbf{f_{1}}$ are defined by,

$$\mathbf{f_{0} = 1 - k_{0\,y} * (1 - (TE_{a\,c} / TE_{0\,c})),}$$

And

$$\mathbf{f_{1} = PRODUCT\ \Pi\ (k = 1\ to\ 4)\ (1 - k_{y\,k} * (1 - (TE_{a\,c\,k} / TE_{0\,c\,k})))}$$

Where the coefficient expressing the sensitivity of crop yield to moisture deficit, $\mathbf{k_{y}}$, are based on FAO (1992)

Applying the expressions for these multipliers to potential yield from the original equation, we obtain the final results,

$$\mathbf{Y_{a} = min\ (f_{1}, f_{2}) * Y_{p}}$$

The parameters for lengths of crop stages, crop-specific evapotranspiration, and for sensitivity of yield to moisture deficit are derived from tabulated data provided in this workbook or in the referenced literature.

TABULATED INPUT DATA

Tabulated input data for FAO AEZM is profuse in different publications that come not only from FAO. Only schematic and for illustrating and exercising purposes data have been provided in this workbook, so the reader should go to the referenced literature when he decides to make use of this model. Let us see now some relevant points.

First we must be aware that the expression defining actual crop canopy potential evapotranspiration, given by,

$$\mathbf{E_{0\,c} = k_c\, E_0}$$

Implies crop potential evapotranspiration will not be the same for each of the defined growth stages.

Second, and still more important is the fact that, as coefficients $\mathbf{k_c}$ are not restricted to the numerical interval (0 - 1), crop potential evapotranspiration may be higher than the originally (supposedly atmospheric property) potential evapotranspiration $\mathbf{E_0}$.

The causes of it reside in the fact that $\mathbf{k_c}$ are empirically derived coefficients obtained from field irrigation experiments, they are not derived from theoretical ecology or plant physiology, and in the fact that the so – called (reference) potential evapotranspiration ($\mathbf{E_0}$) may have been calculated from a plethora of different approximated procedures (literally dozens of them).

The same irrigation experiment will yield different set of values for $\mathbf{k_c}$ if potential evapotranspiration $\mathbf{E_0}$ is calculated by the Modified Penman procedure (Doorenbos and Pruitt, 1977) or by the Penman – Monteith one (Fischer et al, 2000). The user of AZM model should ascertain that he will be using the actual $\mathbf{k_c}$ values corresponding to the potential evapotranspiration methodological calculation he plans to use. There will be a lot of methods for estimating (reference) potential evapotranspiration, such as the Budyko's approach (Sellers, 1965), for which a corresponding dataset of crop coefficients $\mathbf{k_c}$ will not be found in the available scientific literature.

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TABLES FOR CHAPTER FIVE

Table 5.1 Photosynthetically active radiation in clear days (A_c) and gross photosynthetic rate for a canopy cover of a cold climate C_3 crop with P_m = 20 kg CH_2O / ha – hour and LAI = 5 in clear (b_c) and completely overcast days (b_o) by latitude and months. Intermediate data may be interpolated, from Doorenbos and Kassam (1988)

North	**Var.**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
South		**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**
0 deg	**A_c**	343	360	369	364	349	337	343	357	368	365	349	337
	b_c	413	424	429	426	417	410	413	422	429	427	418	410
	b_o	219	226	230	228	221	216	218	225	230	228	222	216
10	**A_c**	299	332	359	375	377	374	375	377	369	345	311	291
	b_c	376	401	422	437	440	440	440	439	431	411	385	370
	b_o	197	212	225	234	236	235	236	235	230	218	203	193
20	**A_c**	249	293	337	375	394	400	399	386	357	313	264	238
	b_c	334	371	407	439	460	468	465	451	425	387	348	325
	b_o	170	193	215	235	246	250	249	242	226	203	178	164
30	**A_c**	191	245	303	363	400	417	411	384	333	270	210	179
	b_c	281	333	385	437	471	489	483	456	412	356	299	269
	b_o	137	168	200	232	251	261	258	243	216	182	148	130
40	**A_c**	131	190	260	339	396	422	413	369	298	220	151	118
	b_c	219	283	353	427	480	506	497	455	390	314	241	204
	b_o	99	137	178	223	253	268	263	239	200	155	112	91

Note: Units of A_c in cal / cm^2 – day but units of b_c and b_o in en kg / ha – day.

Table 5.2 Harvest Index (**HI**) for some crops, valid in the case of potential and optimally irrigated management conditions, from Doorenbos and Kassam (1988)

Crops	**Product**	**Min. HI**	**Max. HI**	**Crops**	**Product**	**Min. H**	**Max. H**
Maize	Grain	0.35	0.45	**Onion**	Bulb	0.70	0.80
Potato	Tuber	0.55	0.65	**Pea**	Grain	0.30	0.40
Tomato	Fruit	0.25	0.35	**Pepper**	Fruit	0.20	0.40
Soybean	Grain	0.30	0.40	**Pineapple**	Fruit	0.50	0.60
Bean	Grain	0.25	0.35	**Rice**	Grain	0.40	0.50
Cabbage	Head	0.60	0.70	**Sorghum**	Grain	0.30	0.40
Cotton	Fibre	0.08	0.12	**S. beet**	Sugar	0.35	0.45
Peanut	Grain	0.25	0.35	**Sugarcane**	Sugar	0.20	0.30
Sunflower	Seed	0.20	0.30	**Tobacco**	Leaf	0.50	0.60
Wheat	Grain	0.35	0.45	**Alfalfa**	Hay	0.40	0.90

Table 5.3 Values of **L** as function of the maximum attained **LAI** during crop growth period, from Oldeman and Frere, (1982)

LAI	**0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**
L	0	0.15	0.3	0.45	0.58	0.70	0.78	0.85	0.91	0.96	1.0

Table 5.4 Crop (evapotranspiration) critical coefficients corresponding to the four growing stages of corn in dry climates with light to moderate winds and $\mathbf{E}_0$ = 8.4 mm/day in the initial stage (Cairo, Egypt), from Doorenbos and Pruitt (1977). These values allow building the necessary graphical representation of $\mathbf{k}_c$.

Parameter	$\mathbf{k1}_c$	$\mathbf{k2}_c$	$\mathbf{k3}_c$
Values	0.35	1.15	0.60

Table 5.5 Duration in days for the four growing stages of corn in dry climates with $\mathbf{E}_0$ = 8.4 mm/day in the initial stage (Cairo, Egypt), from Doorenbos and Pruitt (1977).

Stage	**Initial**	**Vegetative**	**Reproductive**	**Maturation**
Duration	20 days	35 days	40 days	30 days

Table 5.6 Representative values of the coefficient $\mathbf{k}_y$ (whole growth cycle) reflecting the relative sensitivity of soil water stress on final yields for some crops. From Doorenbos and Kassam (1979)

Crop	**Values of $\mathbf{k}_y$ (whole growth cycle)**
Corn	1.25
Potato	1.10
Sorghum	0.90
Soybean	0.85
Sugarcane	1.20

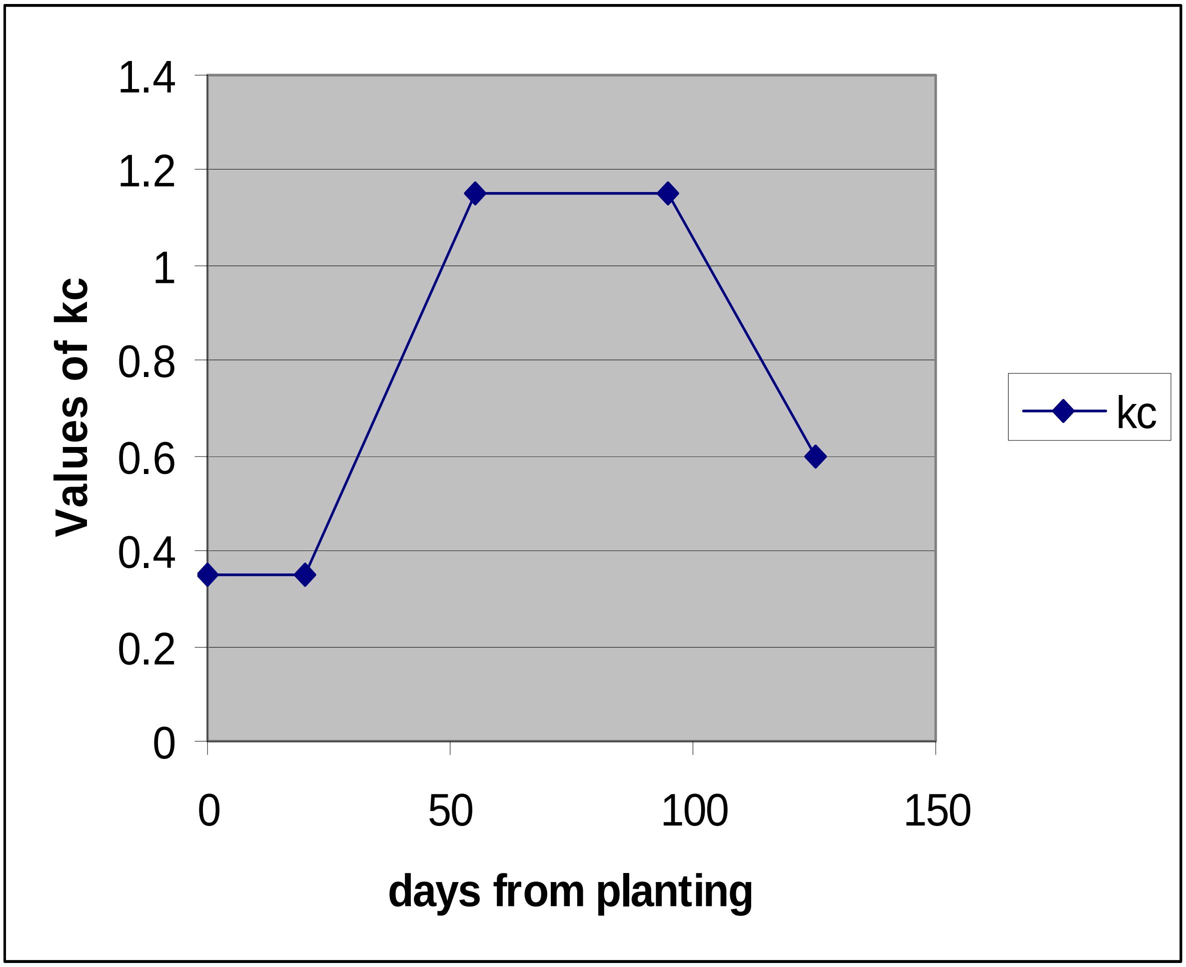

Figure 5.1: Graphical representation of **k $_c$** built using appropriate values tabulated in **Tables 5.4** and 5.**5** for corn cultivated in Cairo (Egypt).

CHAPTER 6

IMPACT ASSESSMENTS ON WATER RESOURCES

Chapter 6: Impact assessments on water resources

1. Introduction
2. Impact assessments on water resources
3. Some simple approaches

Includes "Case Study Number 1: Impact of Climate Change on Water Resources"

INTRODUCTION

Climate change can have a serious negative effect on water resources. A great deal of emerged lands suffer either from scarce water resources or sweet water supply, while others are already wetlands with hostile environments and subjected to frequent floods that cause a lot of damage to human communities and loss of lives. In the case of agriculture great civilizations flourished in those regions where the water supply had been favourable and later disappeared when the resource became scarce and unable to sustain the necessary food production derived from agriculture – including crops, livestock, and fisheries.

Climate change impact assessments on water resources are generally done by a different group of specialists than the one in charge of the agricultural sector. In fact, water resources and agriculture sectors are usually discussed independently in published handbooks, while those two areas of responsibility are under different national authorities most of the time. The water resources sector is important and complex enough to merit an independent workbook and workshop of a similar magnitude to this one devoted to agriculture. That is why, at a first glance, this chapter does not seem to belong to this workbook.

To the contrary, those reasons are among the ones that justify the need of including a chapter about water resources in a workbook for the agricultural sector. The use of water is so inherent to food production activities and adaptation measures and technologies in the agricultural sector that the authors of this workbook are convinced that an agricultural assessment cannot be done in the necessary depth and scope if the team devoted to this purpose does not take into account the problem of water resources in their assessment. In addition to that fact an agricultural assessment team will be lacking the necessary vision to effectively participate in any cross-sectoral integrated assessment with the water resource sector, if that team has not an elementary comprehension of the subjects and methodologies belonging to the water resource sector and of the expected impact of climate change on future water availability for agricultural purposes.

IMPACT ASSESSMENTS ON WATER RESOURCES

Climate change impact assessments on water resources are usually made at the basin level, but a region larger than one basin can be studied as an aggregate of adjacent ones or even as a whole (Planos et al 1999). These assessments usually rely on the solution of the water balance equations. Different to the already discussed Budyko-Sellers approach to the solution of the water balance equation, these assessments usually include additional water reservoirs other than the soil–aquifers and natural and man-made artificial reservoirs. Instead of studying only the runoff term of the water balance equation, these complex assessment methodologies and models also study how the runoff water is distributed into and from these multiple reservoirs. River flow and artificial regulating systems for water distribution among human and natural users are also explored.

Further information about actual methodologies used in water resources assessment is available in many handbooks and published literature including that which is easily available in the web (Benioff et al, 1996; Kalma and Calder, 1994; Sivakumar et al, 1991; Demuth et al, 2006; Yates et al, 2005 a and b).

An agricultural assessment team could get somewhat lost in their analysis of the impacts of climate change, especially when studying irrigated crops and in the stage of recommending strategies and adaptation measures. Such a team should be at least be able to make elementary appraisals of the water resources that can be expected for the same climate change scenarios they have been using in the agricultural sector.

Simple approaches to a water resource assessment will be exposed in the next section. The usefulness of such approaches will be better appreciated when an assessment team comes to the task of making integrated impact assessments.

SOME SIMPLE APPROACHES

An assessment of water resources could start by using the water balance equation in the form,

$$\mathbf{w_2 = P + w_1 - E - S}$$

In applying the Budyko-Sellers procedure discussed in Chapter 2 to an **N** years daily or monthly times series of values of potential evapotranspiration $\mathbf{E_{0k}}$ and precipitation $\mathbf{P_k}$, all the corresponding values of $\mathbf{E_k}$ and $\mathbf{S_k}$ would be obtained. The statistical analysis of such an output dataset would give us an assessment of actual and expected impact of climate variability and change on water resources.

A similar approach could be applied even if we know only the twelve mean (multiannual) monthly values of $\mathbf{E_0}$ and **P**. Such a cyclic interactive approach to the solution of the water balance equation is described in Sellers (1965).

What is most interesting about such a solution to the water balance equation is the fact that you do not need to know the initial $\mathbf{w_1}$ necessary in the first step of the interactive process. If, as in the first case, you are using a long time series for monthly or daily values of the input variables, the system will forget the initial input value of $\mathbf{w_1}$ in a short lapse of time. This means that the output values are the same regardless of the initial soil water content you start with, because after a short lapse of time the values of the output variables will be independent of whatever initial value of $\mathbf{w_1}$ you started from. If you are using the second (cyclic) choice, then after calculations of December are done you use main values for January etc. as if these values pertained to a new year until values of the output parameters for a corresponding month (usually in the first semester) start repeating the corresponding month of the previous year. In both cases you may say that the procedure has converged to a solution.

In this second approach the initial $\mathbf{w_1}$ value for January will usually be much different to the one you started the procedure with when finding a solution to the water balance equation.

These kinds of procedures have been successfully used in Camagüey for more than 15 years as part of an Early Warning System for Agricultural Drought (Rivero et al, 1996) and in the experimental stage of the developing Early Warning System for Hydrological Drought. All these procedures show additional difficulties when it comes to integrating point values to areal values corresponding to a water basin.

A similar approach to the solution of the water balance equation was done by Planos et al (1999) using the Turc's approach for water basins. Being a totally independent pathway to the solution of a water resources assessment, it is satisfying to observe that results obtained with different simple methods, yield similar results for the same areas or water basins. This can be taken as a demonstration that the basic implied assumptions are essentially correct and can be used for practical purposes.

The Simplest Approaches

The runoff ratio

Many historical approaches have been done trying to find simple ways for estimating the so-called runoff ratio (**S / P**) lacking the necessary measured dataset in water basins.

The behaviour of the runoff ratio is such that it has values very different across large continental areas (Sellers, 1965). Notwithstanding this, the analysis shows that similar relationships of this parameter can be classified by similar areas. Runoff ratios can go from very low values in drylands to higher values in areas with wet climates, but it would be dependent also of topography in an undetermined way. Working with data from the United States, Sellers arrived at the expression given by,

$$\mathbf{S / P = f * P}$$

$$\mathbf{S = f * P^{2}}$$

Plotted values for coefficient f (ranging from 0.005 to 0.02 inches $^{-2}$) were mapped. This approach could then be used to estimate **S** at any intermediate point. To build the corresponding map measured data from 152 watersheds were used. The necessity of an initial runoff dataset for determining the corresponding values of parameter **f** which would be used for building maps of this coefficient renders this method almost useless in developing countries lacking the necessary hydrological infrastructure.

However, we could still make an estimation of **S** by a simpler direct climatological procedure such as the one that will be discussed in the next section and determine parameter **f** by a direct regression analysis with measured precipitation values. An elementary test of the possibility of this approach was made by one of these authors for Camagüey obtaining a very high correlation coefficient between **P** and **S**. Another interesting conclusion of this experiment was that the exponent of **P** in the final regression formula was slightly larger than 2 (It was 2.4, in fact.).

The existence of a high correlation coefficient between precipitation and runoff in a given locality can be traced to the fact that **E**, as well as some other terms and indexes derived from the water balance equation, are highly conditioned by the mean values of the radiation balance $\mathbf{R_0}$. That the annual values of the radiation balance for a given place has a rather low dispersion means that – for some theoretical considerations – it could be taken as a nearly constant parameter. With this consideration we can easily see that most of the dispersion of runoff values at any place should be ascribed to the rather high dispersion of precipitation values. A more detailed discussion of this topic was made in Rivero et al (1999).

The Budyko approach

In an effort to make an elementary assessment of water resources in actual and future climate, we will start with the multiannual averaged water balance equation for a water basin already studied in Chapter 2, that is:

$$\mathbf{P = E + S}$$

Already in the very beginning of the twentieth century Schreiber (1904) proposed the following solution to this equation as,

$$\mathbf{S = P \exp(- E_0 / P)}$$

$$\mathbf{E = P - S}$$

This approach was followed by the one given by Oldekop (1911) as,

$$\mathbf{S = P [1 - (E_0 / P) \tanh (P / E_0)]}$$

$$\mathbf{E = P - S}$$

Both attempts were mixed by Budyko (Sellers, 1965) taking the geometric mean of both expressions and obtaining the following one,

$$\mathbf{S = P \{1 - [(E_0 / P) * (1 - \cosh (E_0 / P) + \sinh (E_0 / P)) \tanh (P / E_0)]^{1/2}]\}}$$

$$\mathbf{E = P - S}$$

Additionally, Budyko made the following assumption related to potential evapotranspiration and to the definition of his radiative index of dryness (**B**),

$$\mathbf{E_0 = R_0 / L}$$

$$\mathbf{B = R_0 / (L * P)}$$

Reaching the following final expressions,

$$\mathbf{S = P \{1 - [B * (1 - \cosh (B) + \sinh (B) \tanh (1 / B))]^{1/2}\}}$$

$$\mathbf{E = P - S}$$

This happens to be one of the simpler ways of estimating mean annual runoff and real evapotranspiration available in the scientific literature. The reader could think that these expressions are too simple and that some complicated software program or computer executable files will be necessary for doing even preliminary assessment of these terms. But it happens that this approach is good enough if you can live with rough estimates with an estimated error of 10-20%.

Rivero et al (2005) made estimates of runoff in water basins in Camagüey for different climate change scenarios using the three given formulas. Results obtained agreed very well with independent estimates made by Planos et al (1999) using the Turc's approach. Observe that in this comparison one indirect method was compared with other indirect ones. A direct comparison with measured (observed) data has not been feasible yet.

CASE STUDY 1: Preliminary assessment of the impact on water resources in Camagüey, Cuba

Following criteria expressed by Rivero et al (2005), the MAGICC/SCENGEN system using IS92a greenhouse emissions scenario and both HadCM2 and ECHAM4 global climate models with different climate sensitivities was used to build climate change scenarios for the province of Camagüey during the 21st century. Another additional climate change scenario was created by the simple procedure of extrapolating trends in temperature and precipitation valid for the period 1976 – 2004.

Four simple impact models based on the general approaches explained in previous sections were used to derive a numerical description of the expected changes in hydrological potential of water basins in the province of Camagüey, Cuba. Results derived from all simple impact models were alike in the whole set of climate change scenarios and led to a systematic decrease of hydrological potential in water basins in the province (Tables 6.1 – 6.5). As this specially tailored assessment gave very similar results to those obtained by Planos et al (1999), which were obtained by a completely different water balance approach in the eastern and central region of Cuba, it helped to raise confidence in the use of simple and very simple models for assessing the impact of climate change on water resources (Rivero y Rivero, 2005).

Final comments

When using different approaches to the assessment of water resources, net primary productivity of ecosystems, crop yields and similar methodologies employing climate indexes the concept of potential evapotranspiration ($\mathbf{E_0}$) comes to the fore in many, sometimes different hidden ways.

The problem is that the concept of potential evapotranspiration has evolved during a long time period as well as the methodologies and formulas used to estimate its values. Even different crop biophysical models use different formulas for $\mathbf{E_0}$ in their internal calculations. If someone chooses to select the most modern and recommended formulation for estimating $\mathbf{E_0}$ – the Penman – Monteith formula – then he/she will need a very complete dataset for a set of climate variables that were not available to scientists during historical times.

Those scientists used different formulas for calculating potential evapotranspiration and – we can be sure of that – every different formula for calculation of $\mathbf{E_0}$ gives different values than those obtained with another formula. You cannot ever be sure that a climate index estimated with one or another formula for this term can be used with the corresponding classification devised by its original author. Even the crop coefficients $\mathbf{k_c}$ used and recommended by FAO had to be changed when this organization changed its previously recommended modified Penman approach (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979) to the Penman –Monteith approach (Allen et al, 1998). In fact, maybe it would be better to use all derived relationships including $\mathbf{E_0}$ using the original meaning and formula that was used by its author when he derived them.

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TABLES FOR CHAPTER SIX

Table 6.1: Hydrological potential in percent of the reference climate (1961 – 90), obtained with four simple impact models (**M1 – M4)** for climate change scenario **E1**.

Impact Model	2010	2030	2050	2075	2100
M1	93.0	87.0	81.0	73.0	67.0
M2	92.0	85.0	78.0	70.0	62.0
M3	93.0	86.0	80.0	72.0	65.0
M4	96.0	92.0	88.0	83.0	78.0

Table 6.2: Hydrological potential in percent of the reference climate (1961 – 90), obtained with four simple impact models (**M1 – M4)** for climate change scenario **E2**.

Impact Model	2010	2030	2050	2075	2100
M1	95.0	90.0	85.0	78.0	73.0
M2	94.0	88.0	82.0	75.0	69.0
M3	94.0	89.0	84.0	77.0	71.0
M4	97.0	94.0	91.0	87.0	84.0

Table 6.3: Hydrological potential in percent of the reference climate (1961 – 90), obtained with four simple impact models (**M1 – M4)** for climate change scenario **E3**

Impact Model	2010	2030	2050	2075	2100
M1	91.0	82.0	73.0	63.0	53.0
M2	89.0	79.0	70.0	59.0	49.0
M3	90.0	81.0	72.0	61.0	52.0
M4	94.0	89.0	83.0	76.0	70.0

Table 6.4: Hydrological potential in percent of the reference climate (1961 – 90), obtained with four simple impact models (**M1 – M4)** for climate change scenario **E4**

Impact Model	2010	2030	2050	2075	2100
M1	93.0	86.0	79.0	70.0	62.0
M2	91.0	83.0	75.0	66.0	58.0
M3	92.0	85.0	78.0	68.0	60.0
M4	96.0	92.0	87.0	82.0	77.0

Table 6.5: Hydrological potential in percent of the reference climate (1961-1990), obtained with four Simple impact models (**M1-M4**) for climate change scenario (extrapolated trends) **E5**

Impact Model	**2010**	**2030**	**2050**	**2075**	**2100**
M1	76.0	62.0	49.0	35.0	23.0
M2	72.0	58.0	45.0	32.0	22.0
M3	74.0	61.0	48.0	34.0	22.0
M4	81.0	69.0	59.0	47.0	36.0

CHAPTER 7

INTEGRATED IMPACT ASSESSMENTS: THE MIIA MODEL

Chapter 7: Integrated impact assessments

1. Introduction
2. Cross - Sectoral agriculture/water resources impact assessments
3. The MIIA model
4. A final comment about technological efficiency

Includes "Case Study Number 2: Integrated Impact of Climate Change on Irrigated Crops**"**
Includes "Case Study Number 3: Integrated Impact of Climate Change on Irrigated Crops with Technological Adaptation Measures**"**

INTRODUCTION

The subject of integrated impact assessments has been extensively addressed in popular handbooks and guidelines for climate change impact assessment and adaptation (Benioff et al, 1996; UNEP/IES, 1998). A detailed approach to the classification of slightly different interpretations of the term can be found in Parry and Carter (1998). Notwithstanding the most national assessments are not integrated ones. This could derive from the fact that many of the available methodologies and tools deal with integrated assessment at a regional or global level, but this can be partially ascribed to the fact that most of the available tools are designed to use economical or monetary values as integrating parameters and thus require much expertise and information about these fields.

In this case the name of this chapter may lead to misinterpretation, because we will not be looking at integrated assessments at higher than local levels and will not be using an economical point of view either. That is because we are convinced that an integrated assessment should first be conducted also at a – biophysical – level having nothing to do with regional or global integration or with economic values. As one of these authors stated in a recent workshop (Rivero, R. E., 2008):

"Back in the mid-nineties a group of authors recommended for developing countries: If you expect negative impacts from climate change in the agriculture sector then:

1. The government should withdraw from interfering in food production issues.
2. Farmers should adapt themselves through spontaneous (market) adaptations.
3. The now excessive agricultural labour force could be redistributed in other sectors.
4. If you lack food enough for your people then … go and buy it in the global market. "

That is not our point of view because market laws have been condemning hundreds of millions of people. An integrated assessment should be directed to assess if and how food production in a given area is going to be enough to sustain the lives of people living there and not its marketable value. We must produce food enough for everybody first and see how market laws can be made to function afterwards. Total food production will then be our integrating parameter on a local basis.

We list now a small set of examples in which an integrated assessment should be done on this basis:

First: The best planting date for potatoes in Camagüey is around the first of December, but planting cannot be done simultaneously in the entire area to be planted, so planting as such will be done during a certain time period depending on available technology and labour force. As different planting dates lead to different crop yields, you should not assume that all the area is planted simultaneously in an integrated assessment.

Second: For being able to plant potatoes on the best planting days in Camagüey, farmers have to prepare the soil first. The preparation of soil depends on the workability of it. The workability of soil in this season of the year depends on the very variable amount of rain and the distribution of rainy days in November which is not a planting month. In practice this means that some years you can plant on December 1st, but in other years you would be planting as late as December 31st. An integrated assessment would be needed here to take into account the probabilities that the planting date may begin at any specified day in December. An analysis of workability of the soil should be done independently – this analysis would not even include a crop model - and integrated with the crop model results.

Third: In order to assess the impact of climate change on rice production in Camagüey you first create a one hundred years long climate change scenario. Then, following the standard procedure of the so-called seasonal analysis you run a crop model for those one hundred years and carry out a statistical analysis of results concerning the expected behaviour of rice production in that area. Then you realize that during one hundred years the model has been using the same soil characteristics that you gave as input and that are only valid in the reference climate conditions. Flooded rice is a very aggressive managed crop that can lead to soil degradation and changes in all its physical and chemical properties, but the standard procedures used have completely omitted this analysis.

An integrated assessment should be done using a sequence analysis during one hundred years with a model able to simulate the evolution of soil properties as well as crop behaviour and responses to it. Or you could simulate soil evolution almost independently using a specialized soil – vegetative cover model as CENTURY (Parton et al, 1992 a). The integration of impacts here is not an easy task for any climate change impact assessment team.

Fourth: In a sugar cane producing region you will find a set of plots planted with different varieties (They are necessarily different for the so-called "primavera" and "frío" planting seasons in Cuba.) Some of those plots will consist of "caña planta" or "caña nueva" planted directly from stalks while others will be first, second, or third "ratoon" crops. The main planting seasons last for a few months each and at harvest time each plot is harvested with a different age or time in the field (12 to 24 months). The relative proportions of these different field conditions vary from one region to another.

An integrated assessment that takes into account all these circumstances can become a real nightmare for a climate change impact team, so we finish here leaving the reader to dwell upon the importance and complexity of integrated local assessments.

Prerequisites for making an integrated assessment

Prerequisites for making an integrated assessment are so simple that one cannot imagine how many times they are forgotten. To omit these simple prerequisites will lead to failure and final results that cannot be integrated at all.

First: An integrated assessment should be planned from the very beginning. If each sector makes its particular assessment without a collectively planned way in which each one is going to do that, no final expert judgement or workshop will be able to integrate results obtained this way in a single unified approach to the problem at hand.

Second: To make an integrated assessment all sectors involved should agree to use the same climate change scenarios and future dates. This means that they should be working with the same greenhouse gases emissions scenarios, global climate models and time horizons.

Third: An integrated assessment may be done using integrated tools such as are provided in literature or through a series of expert judgements rounds. A lack of sophisticated integrating tool should not be a reason for not doing an integrated assessment.

Integration of sectoral or cross sectoral results obtained with different climate change scenarios and time horizons would be a sterile exercise, no matter which integrating method is used.

CROSS - SECTORAL AGRICULTURE / WATER RESOURCES IMPACT ASSESSMENTS

Agricultural activities, all of them including crops, livestock and fisheries, are not possible without water supply. When we speak about a sectoral agricultural assessment the issue of water is implied in the term, because you cannot do agriculture without using water in many different ways. A given crop can be planted in many different substrates leading to ordinary traditional agriculture based on soils, but also to hydroponics and organoponics – now very much used in Cuba. All of them require a water supply and expenditure.

The necessity of a water supply to agriculture is evident when we look at physiological processes that occur in plants during their life cycle. They were studied in Chapter 5. The same would apply if we were studying the life cycles of living beings related to livestock and fisheries. Even in the so-called rainfed agriculture, water is being constantly supplied to the agroecosystem by nature in the form of rain.

As to adaptation measures to the negative impact of climate change in cases where rainfed yields are going to be reduced because of increasing aridity, the option of applying irrigation to crops is the one that most often comes to the mind of farmers and decision-makers. Many times this is done without analysis, if in future conditions there would be the necessary amount of water for irrigation purposes. The assessment of future water availability for irrigation requires a parallel assessment of the water resources sector. Notwithstanding this, many national communications contain separate assessments of the agriculture and the water resources sectors, without any integration between them.

Cross sectoral agriculture/water resources assessments methodologies are not abundant in published literature and handbooks, even if there are models such as WEAP in which a hydrological model is linked to water use in agriculture through a demand and supply interaction including the introduction of priorities related to the satisfaction of water needs by different users.

The MIIA model, to be introduced below, is a theoretical simple model in which an attempt is made as to integrate both the impact of climate change on crop yields and the impact on water availability on total crop production. This model is not introduced here as a tool to be learnt and used, but as a reasoning conceptual process that highlights the possible integrated impact of climate change on food production derived not only from the two sectors at hand, but also on additional considerations relative to agricultural technology and population increase.

Even if the assumptions made in the MIIA formulation can be considered too restricted, its way of taking many possible factors into consideration can provide a tool which can be used to realize very illustrating "gedanken" experiments.

THE MIAA MODEL

Introduction

The impact of climate change on crop yields can, in principle, be done with any suitable crop model. But not every crop model will have the necessary versatility to simulate all physiological processes and management options as to allow us to integrate the results with knowledge obtained from simultaneous assessments made in other related fields or sectors. That is why in this chapter all simulations are supposed to be done using a version of DSSAT (Tsuji et al, 1994). In fact, DSSAT 3.0 was the decision support system that we used first for testing the basic ideas contained in our Model for Integrated Impact on Agriculture (MIIA 1.0) such as it was first presented in Rivero (2001).

We must assert that every crop model is an integrated tool in itself. Having as main output crop simulated yields, a crop model integrates the impact of climate, soil and management on final yields. Only that the model in itself cannot take into account if the proposed management options chosen are feasible or estimate what will be the actual crop production attainable with a chosen management option. It happens that, in fact, total production depends not only on mean yields, but also on other factors such as the planted area. A given management option could be used in some limited field area, but not in a larger one. That would lead to the necessity of establishing a given management option in a fraction of total planted area and another management option in the rest of the available planting area.

In discussing the structure and concepts of the MIIA model the reader should be aware that what is going to be exposed here could be done separately in many almost independent modules and the different results could be integrated at the end. In fact, such a version of the model could be more versatile and generally valid than the MIIA model that is going to be discussed and even more amenable to improvements and to the addition of processes not included here in this workbook. Only that the beauty of concepts and integration of ideas into one and only one final analytical formula would be lost in the process, that is not a likable way of looking at things for theoretical physicists such as the author of the model. In this sense the discussed version of MIIA should be looked at like "an integrated toy model" in the same sense used by Thorndike (1992), Fung (1992) and Parton et al (1992 b).

From the point of view of a particular farmer, yield is a very important aspect because it will be very closely related with one cost/benefit assessment. But for a government striving to achieve food security for its people without having to refer to the costly and painful process of buying food in a volatile and unstable world market, total and per capita food production could be a more important integrating parameter. The reader should avoid the rather usual assumption leading to the use of money as the integrating parameter in an integrated assessment. Total and per capita food production, water use, or any similar factor can be the main objective of an integrated assessment.

Preliminary Calculations and Assessments

Assume that we are making a climate change impact assessment in a closed basin, in the sense that no water flow exists through the boundaries of the basin at hand. Let us suppose, because it was originally planned that way, that in different previously made sectoral assessments we have obtained a series of projected potential (totally irrigated) crop yields and specific irrigation water needed to obtain those yields for a set of climate change scenarios given by $\mathbf{Y}_1, \mathbf{Y}_2 \ldots \mathbf{Y}_N$, in kg DM/ha, and $\mathbf{H}_1, \mathbf{H}_2 \ldots \mathbf{H}_N$ in kg

H_2O/ha. This is a common outcome of an agriculture climate change impact assessment made by using some advanced crop model as those included in the DSSAT family. Additionally, we have obtained also in a water resources impact assessment the following series of hydrological potentials for the same climate change scenarios $\mathbf{F}_1$, $\mathbf{F}_2$ … $\mathbf{F}_N$. How to make such assessments has been discussed in previous chapters of this workbook.

There are some crops that are very sensitive to water stress or tend to be cultivated in flooded conditions for other reasons related to management. Typical examples of cases like these have been the case of potato and rice in Cuba. The management conditions of potato are equivalent to say that whenever soil water drops below some specified fraction of field capacity, a fraction that is crop dependent and can be set in the range of 0.60 – 0.80 depending on the crop, irrigation water is applied to raise soil water content to field capacity. Flooded rice is cultivated in such a way that whenever field conditions fulfill some specified limiting amount of water, irrigation is applied to restore standard management values.

These management conditions can be simulated by crop models embedded in the different versions of the decision support tools of the DSSAT family, allowing the user to obtain the corresponding sets of $\mathbf{Y}\ \mathbf{j}$ and $\mathbf{H}\ \mathbf{j}$ values for any climate change scenario. Even if these management conditions seem to be very restrictive, it happens that they have been applied to extensive areas of potato and rice crops in Cuba for many years.

When a crop is managed in this way you can assert that total production is limited by the availability of irrigation water, because this availability controls the area that can be planted in such management conditions. This constraint has been affecting total planted area in some producing regions which have seen a decrease of total production in periods of descending trends in precipitation and the establishment of droughts leading to decreased runoff and, consequently, harvested water in reservoirs.

Runoff and Harvested Water

In original, pristine, water basins all precipitation water appears as natural evapotranspiration and runoff. This runoff is harvested by nature in lakes, wetlands, aquifers, snow and ice covers and other natural reservoirs including the largest one of all, the sea. Such original and pristine water basins are rather scarce nowadays because anthropogenic activities have been increasing in time in such a way that many water basins are actually managed by human communities through artificial reservoirs and water management structures and systems. In heavily managed basins water harvested is redistributed by man to satisfy a lot of diverse societal demands including irrigation, domestic and industrial uses. These structures also work in controlling runoff in such a way as to avoid the risks of flooding during periods of very heavy rains and assuring the availability of water for human uses during droughts and dry periods.

In the limiting case of very heavily managed water basins we could assume that the long period mean value of harvested water is roughly equivalent to mean runoff values derived from a water resources assessment (**F**). In this limiting case we could also consider that mean annual harvested water is completely distributed by management to different end users including irrigation, human and animal consumption, domestic and industrial ones. This line of thinking leads to the following equation of conservation of harvested water,

$$\mathbf{F} = \mathbf{C} + \mathbf{U}$$

Where **C** is total harvested water allotted to irrigation purposes and **U** is the aggregated amount of water allotted to other users. This last term could be expressed as a sum of different terms reflecting every conceivable water use of human societies, including that amount of water dedicated to keep coastal and other natural ecosystems in good health. These particular values will not be discussed here because decision-makers could take any particular decision about its relative values without any consequence to the following discussion which we have named the principle of equipartition of water.

The value of the fraction **U / C** is conditioned by human and society decisions and cannot be derived from nature's laws. Future societies could choose to make this fraction take any value from a very large one – meaning that practically no amount of water is allotted to irrigation – to a very low one meaning that agriculture will be the most important economic activity in the basin. This evidently is a large source of uncertainty in future socioeconomic scenarios leading to a wide set of potential impacts that make it very difficult to take future decisions about the process of adaptation to climate change.

The Principle of Equipartition of Water

Let us assume the validity of the following principle of equipartition of water in its weak form: In all future climate change scenarios the impact of changes in hydrological potential of a water basin will be evenly distributed between the amount of water allotted to irrigation and the aggregated amount of water allotted to the rest of water uses in the basin. The reader must observe that this weak form of the principle still allows decision-makers to make any redistribution of harvested water among all other final users different from crops.

The mathematical expression reflecting this statement can be written as,

$$\mathbf{A = U / C = constant}$$

This relationship is assumed to be valid for all future climate change scenarios. Even if future decisions have to be taken as to what to do with the available harvested water in a basin, this principle of equipartition of water could be used to guide the thinking about the expected consequences from climate change variations in the hydrological potential of a water basin.

The Hydrological Potential Ratio

Let's now assume that we have an actual reference climate and a future climate scenario in which the hydrological potential can be written as,

$$\mathbf{F_1 = C_1 + U_1}$$

$$\mathbf{F_2 = C_2 + U_2}$$

Calculating the ratio,

$$\mathbf{F_0 = (F_2 / F_1)}$$

$$\mathbf{F_0 = (C_2 + U_2) / (C_1 + U_1)}$$

$$\mathbf{F_0 = (C_2 / C_1) \{[1 + (U_2 / C_2)] / [1 + (U_1 / C_1)]\}}$$

$$\mathbf{F_0 = (C_2 / C_1) [(1 + A) / (1 + A)]}$$

$$\mathbf{F_0 = (C_2 / C_1) = C_0}$$

We arrive at a very important conclusion expressing the fact that the ratio of future to actual available water for irrigation purposes is equal to the ratio of future to actual hydrological potential for the basin at hand. The available water for irrigation purposes will put an additional constraint on the arable land area that can be managed in such irrigated conditions. The analysis has allowed us to express an unknown future ratio (**C_2/C_1**) as a function of a ratio (**F_2/F_1**) that can be easily derived from a climate change impact assessment.

But even at this stage the assessment itself has to be made taking into account the possibility of finding extreme cases when the equipartition principle cannot be directly applied as will be discussed in the following section.

Particular cases

Some extreme cases can be analyzed when operating with the expression,

$$\mathbf{F_0 = (C_2 / C_1) \{[1 + (U_2 / C_2)] / [1 + (U_1 / C_1)]\}}$$

These particular cases will now be examined.

- **The rainfed case**

Future climate change scenarios could be so drastic that decision makers would have to decide not to use irrigation at all at some future date. That would mean specifying **$C_2 = 0$** and making indefinite the quotient **U_2/C_2**. Instead of trying to take the limit of such expression this case is most easily analyzed making **$C_2 = 0$** since the very beginning, leading to the results,

$$\mathbf{F_1 = C_1 + U_1}$$

$$\mathbf{F_2 = U_2}$$

$$\mathbf{F_0 = U_2 / (C_1 + U_1) = (U_2 / U_1) \{1 / [1 + (C_1 / U_1)]\}}$$

This interesting pathway is associated with the fact of going from an irrigated agricultural management to a rainfed one. The continuation of the MIIA model including a mixed irrigated/rainfed management system was done by Rivero et al (2005 a) and will be discussed in another section of this chapter. In fact, such a pathway constitutes the main difference between the MIIA 1.0 and MIIA 2.0 impact models.

- **Water use for irrigation purposes only**

In some specific basins water use other than for irrigation purposes can be so relatively small as to be a second order term negligible in mathematical expressions. This is particularly true for dams and surface reservoirs that were built to satisfy agricultural purposes only and are not used for any other human activity, except maybe fishing. In this very simple extreme case **$U_1 = U_2 = 0$** and **$F_0 = C_0$** holds.

If in such a case a new water user is planned to exist at a future climate change scenario then **$U_1 = 0$** but **U_2** would be different than zero, leading to the following expression,

$$\mathbf{F_0 = (C_2/C_1) [1 + (U_2/C_2)]}$$

This situation would require a different analysis because now the available irrigation water would decrease faster than the hydrological potential of the basin. This is an obvious consequence of the violation of the equipartition principle.

Total Production in an Agricultural Basin: The Basic MIIA Expression

In order to simplify the analysis it will be assumed that there is only one crop cultivated in such irrigation conditions in the water basin. It can be seen that the MIIA approach could be extended to more than one crop with relative ease, but that will not be done here because our principal aim is that of highlighting circumstances leading to the need of making integrated assessments. It is also to show that the impact on total crop production derived from an integrated assessment may be different from the direct impact of climate change on yields only. In an integrated assessment there will emerge also new possibilities of finding adaptation options.

We find that in an actual as well as in a future climate planting area for the crop at hand, there could be limited water for irrigation. Actual ($\mathbf{P_1}$) and future ($\mathbf{P_2}$) potential crop production would be given by,

$$\mathbf{P_1 = Y_1 * A_1}$$

$$\mathbf{P_2 = Y_2 * A_2}$$

$$\mathbf{P_0 = (P_2 / P_1) = (Y_2 * A_2) / (Y_1 * A_1) = Y_0 * (A_2 / A_1)}$$

But it happens that in both cases we can state that,

$$\mathbf{C_1 = H_1 * A_1}$$

$$\mathbf{C_2 = H_2 * A_2}$$

$$\mathbf{C_0 = (C_2 / C_1) = (1 / H_0) * (A_2 / A_1)}$$

Then substituting ($\mathbf{A_2/A_1}$) from this last expression in the above formula for $\mathbf{P_0}$, we can reach the basic integrating MIIA formula as,

$$\mathbf{P_0 = Y_0\, H_0\, C_0 = Y_0\, H_0\, F_0}$$

The reader should observe that we have defined $\mathbf{H_0}$ as ($\mathbf{H_1/H_2}$) instead of the previously used convention for this kind of ratio. This has been done only to preserve a multiplicative form for the final analytic expression, but is not mandatory and could have been done in the normal way without changing any basic concept or result.

The basic MIIA expression now shows that the ratio of future and actual total crop production depends not only on the ratio of yields, but also on the ratio of irrigation water use per unit area and on the ratio of future and actual irrigation water availability.

Additional Scenarios

Using a basic expression valid only for potential crop production may be not too attractive for stakeholders and decision-makers. Values of total production nearer to those actually obtained with the limitations of technology can be estimated using the concept, already studied, of technological efficiency of crop production ($\mathbf{\Phi}$). We remind the reader that the value of $\mathbf{\Phi}$ is restricted to the range (0 – 1). This can be done in such a way that real yields ($\mathbf{Y'}$) can be approximated as functions of potential yields ($\mathbf{Y}$),

$$\mathbf{Y' = \Phi * Y}$$

Leading to the stating of a new basic formula given by,

$$\mathbf{P_0 = \Phi_0 Y_0 H_0 C_0 = \Phi_0 Y_0 H_0 F_0}$$

Given the fact that future technological efficiency cannot be derived from known variables, the use of this formula is linked to the creation of scenarios for technological efficiency. Such kinds of scenarios could be created on the basis of technical perspectives for the development of agricultural sciences or could be simply stated in a similar way as it had traditionally been done for the so-called synthetic (incremental) climate change scenarios.

Total crop production could give less useful information than per capita crop production (**K**). Total crop production could even be increasing while per capita production could be decreasing – leading to hunger and social unrest - for the same climate change scenarios, if population (**T**) growth offsets the effect of increasing total production.

The introduction of a socioeconomic scenario including population growth leads to a new MIIA expression given by,

$$\mathbf{K_0 = \Phi_0 Y_0 T_0 H_0 C_0 = \Phi_0 Y_0 T_0 H_0 F_0}$$

In a similar way the basic MIIA approach can be extended to include additional relevant factors. A mixed irrigated/rainfed crop system will be now discussed in the following section. The discussed approach and formulas constitute the basic content of the MIIA 1.0 model (Rivero, 2001).

A MIIA Approach to a Mixed Irrigated/Rainfed Crop System

In a climate change scenario leading to a decrease in the hydrological potential of a water basin an assessment using the MIIA approach will reflect the fact that, as time goes on, the actual planting area in the specified irrigation management option will decrease with time. The MIIA approach to a mixed irrigated/rainfed system will just take into consideration that the area that can no longer be irrigated could still be planted in rainfed conditions. The analysis to be done could consider that the lost irrigated area is going to be planted with a different crop, but we will state only the case in which the rainfed crop is the same irrigated one, knowing that this does not imply that rainfed or flooded varieties (cultivars) will be the same. In fact, generally they will be different varieties of the same crop. This procedure, of course, could not be applied to potato in Cuba because rainfed potato in our climate conditions will not be feasible with known varieties (There is a possibility about such procedure being feasible with a C_4 potato variety.) but it can surely be done with known rice varieties.

In the above discussed basic MIIA expression future total and per capita irrigated production can be calculated as,

$$\mathbf{P_2 = (\Phi_0 Y_0 H_0 F_0)\, P_1}$$

$$\mathbf{K_2 = (\Phi_0 Y_0 T_0 H_0 F_0)\, K_1}$$

If we assume that (practically) all the initial planted area $\mathbf{A_1}$ is irrigated, then any future planted area in this management condition will be given by.

$$\mathbf{A_2 = C_0 H_0 A_1 = F_0 H_0 A_1}$$

Thus the area given by $\mathbf{A_{2s} = A_1 - A_2}$ can be considered as free to be planted in rainfed conditions giving an additional rainfed production ($\mathbf{PR_2}$) given by,

$$\mathbf{A_1 - A_2 = A_1 - F_0\, H_0\, A_1 = (1 - F_0\, H_0)\, A_1}$$

$$\mathbf{PR_2 = (1 - F_0\, H_0)\, A_1\, YR_2}$$

In this last expression $\mathbf{YR_2}$ is future rainfed yield of the crop at hand and can include or not another multiplicative term taking into account a rainfed technological efficiency of production. Assuming this kind of adaptation strategy future total crop production will now come not as $\mathbf{P_2}$ (corresponding only to irrigated production) but as,

$$\mathbf{TP_2 = P_2 + PR_2 = (\Phi_0\, Y_0\, H_0\, F_0)\, P_1 + (1 - F_0\, H_0)\, A_1\, YR_2}$$

This last expression, that can be expanded to include a technological efficiency scenario and a population growth scenario, has been named as the basic MIIA 2 formula.

The mixed irrigated/rainfed rice production system has been studied by Rivero et al (2005 a). A variant of such adaptation strategy to rice production in Cuba has been applied with the name of people's rice programme. This programme is giving now almost one – half of Cuban rice production, while before 1990 practically one hundred per cent of all rice production in our country was obtained in flooded management conditions.

The reader might feel awkward seeing that these expressions are not expressed as a quotient. This will be done immediately to give,

$$\mathbf{TP_0 = TP_2 / TP_1 = TP_2 / P_1 = \Phi_0\, Y_0\, H_0\, F_0 + [(1 - F_0\, H_0)\, A_1\, YR_2] / P_1}$$

On the basis of the previous discussions the reader may now explore new pathways for generating further approaches to the subject of integrated assessments at the local level. A further expansion of these lines of thought was done by Rivero et al (2005 b) extending the application of MIIA to the study of climate change impact on livestock.

MIAA CASE STUDIES

In the following sections we will be discussing two case studies that used the MIIA approach to estimate the integrated impact on irrigated crops, because of a future climate change scenario leading both to a decrease in potential yields associated with a rise in temperature and with a decrease of available water for irrigation derived from an increasing trend in aridity and a decrease in hydrological potential in water basins.

In both cases climate change scenarios were created using the MAGICC/SCENGEN system with IS92a greenhouse gases emissions scenarios and HadCM2 global climate model for future 30 years periods centred in 2010, 2030, 2050 and 2100.

Case Study 2: the case of potato in Sierra de Cubitas, Camagüey

Potato crops have been traditionally grown in the northern plains of Camagüey within the context of high level inputs agriculture. Being a cold climate C_3 crop potato can only be grown in winter from December to March which is also the dry season in Cuba. Potato is grown in a large flat area of red soils with a very large infiltration capacity and thus requiring a huge amount of irrigation water that, at least in principle, must be able to guarantee that soil moisture does not go below 80% of soil field capacity. The climate responses of potato combined with its needs of easily available soil water make it a very sensitive crop to expected climate change in a region as even in actual climate the crop is cultivated in marginal climate conditions.

Using the results obtained by simulating crop growth during the growing season with the help of the SUBSTOR-Potato crop model available in DSSAT 3.0, with special attention to simulated yields and irrigation water needs, combined with an independent assessment of the impact of climate change on hydrological potential made by Planos et al (1999) the authors were able to applied the MIIA 1.0 version of the integrated model to assess the expected impact of climate change in total and per capita crop production in the basin. Results were obtained adding or not expected scenarios for technological efficiency and population growth (Rivero, 2001).

Conclusions obtained showed that a drastic decrease in total and per capita potato production would be associated with the expected climate change scenarios. The impact on crop production would be even stronger than what would be expected from the decrease in yields only (Fig. 7.1) meaning that under these new conditions the growing of potato in that area would become impossible because the results obtained would not justify the effort and would constitute a useless expenditure of financial resources. Even the highest foreseeable technological efficiencies would not be able to counteract the very negative impacts of climate change in this area. Adaptation measures consisting in growing potato in other regions with better climate conditions and soils with a higher soil moisture retention capacity would be needed to justify the cultivation of potato. In fact warm winters and very severe droughts during the 2003 – 2005 periods had already halted potato growth in the area during the last three years.

Case Study 3: the case of flooded rice in the southern coastal plains of Camagüey, Cuba.

During many years flooded management conditions were the only ones in which large scale rice production was done in Cuba. Under the actual trends of larger climate variability, severe drought episodes, and competence with other users, the problem of available water for irrigation purposes have reduced drastically planted rice areas and total production for this crop. The rice production region in southern costal plains in Camagüey were studied in order to assess the integrated impact of climate change in total production and the expected results of some adaptations options involving changes in management of the crop. Results obtained with process-based crop models and an independent assessment of climate change impact on hydrological potential of the related water basins conducted by Rivero and Rivero (2005) were integrated using the MIIA 2.0 model (Rivero et al, 2005 a).

Results obtained showed that not only total flooded rice production would decrease continuously during the 21st century, but that an adaptation measure consisting in growing rainfed rice in areas equivalent to those that will have no future water available for flooded management could reduce the expected decreasing trend in irrigated crop production (Fig. 7.2). Such change in management conditions obviously would demand the use of different rice cultivars adapted to rainfed conditions and limited irrigation needs besides the introduction of different production technologies. Not as a consequence of these studies, but as a parallel development, governmental agricultural authorities have been developing what is known as People's Rice Program. Under this programme the growing of rice has been generalized and distributed in more suitable environmental conditions under technologies that are less water demanding. Such a programme now contributes about 50% of total rice production in traditional areas.

A FINAL COMMENT ABOUT TECHNOLOGICAL EFFICIENCY

Very frequently published scientific literature and workbooks remark that there is usually an ascending trend in yields of many crops and that actual production data time series should be detrended in order to further clarify the impact of climate variability on actual yields. The author of this chapter is not convinced of the fact that there exists an actual generalized ascending trend in yields across the world and thinks that this could be a reality in highly developed countries that cannot be readily extended to developing countries.

The associated question is that, whenever this trend is present, its cause should be attributed to an increase in technological efficiency and that we could take this trend to derive future scenarios for this important parameter. The answer to that question is a conclusive no.

An ascending trend in crop yields has been documented in available We-based documents for one or another crop in one or another production region of the world. But analyzing the history of those crop productions in the given regions, it can be seen that the ascending trend has been some times associated with the introduction of new crop varieties. The concept of technological efficiency used in this book does not allow the introduction of new varieties simply because when a new variety is introduced in field production, we are also changing the potential yield of the crop in the same climate environment.

This means that our concept of technological efficiency should be applied to each crop variety or cultivar in an independent way. The implication is that there may be an ascending trend in actual yields without any improvement in technological efficiency and obtained by the simple procedure of introducing into production varieties or cultivars with higher potential yields.

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FIGURES FOR CASE STUDIES IN CHAPTER SEVEN

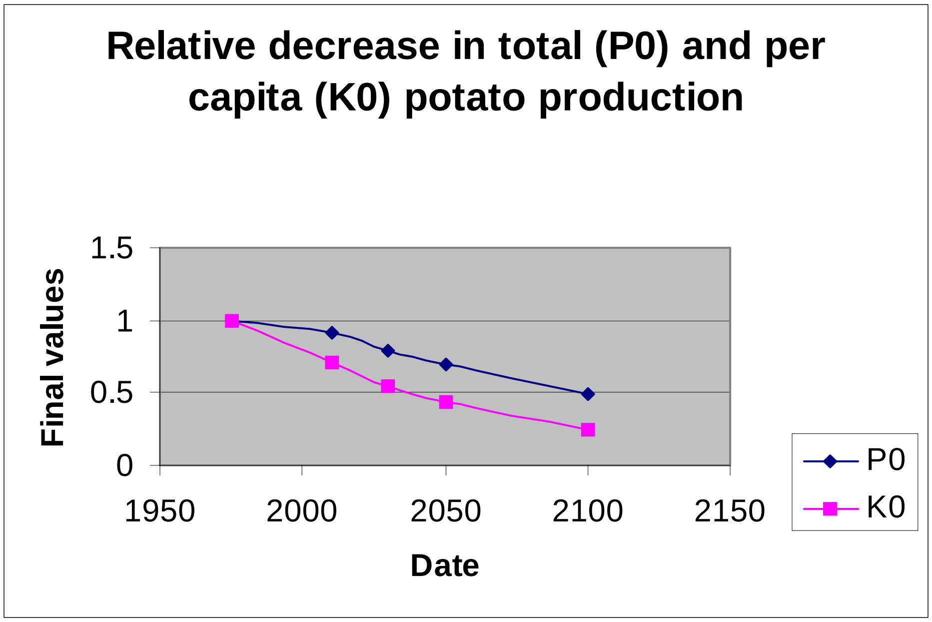

Figure 7.1: Relative decrease in total and per capita potato production in Sierra de Cubitas, Camagüey, taking into account the CO_2 fertilization effect, as predicted by the MIIA 1.0 integrated model.

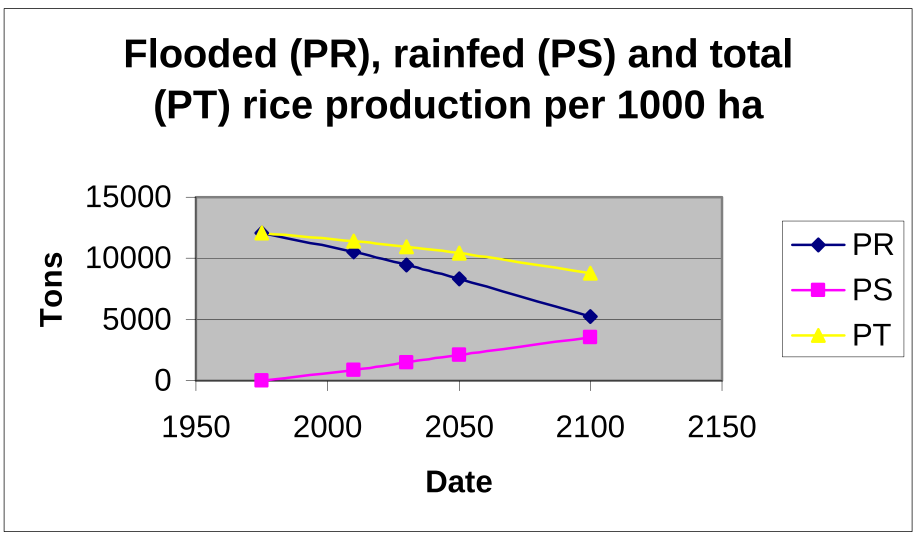

Figure 7.2: Flooded (PR), rainfed (PS) and total (PT) combined rice production for the southern coastal plains in Camagüey, Cuba, as predicted by the MIIA 2.0 integrated impact model with adaptation measures.

CHAPTER 8

THE USE OF BIOCLIMATIC INDEXES IN IMPACT ASSESSMENTS

Chapter 8: The use of bioclimatic indexes in impact assessments.

1. Introduction
2. Aridity Indexes
3. Net Primary Productivity of Forests
❖ The Chikugo Model
4. Human and animal comfort indexes

INTRODUCTION

The existence and meaning of a somewhat large set of climate indexes have been discussed in previous chapters, even if we are going to see more of them in this one. It happens that they can be very useful for making preliminary assessments in cases when we are looking for some results that may guide us in more comprehensive studies or we lack the complete necessary climate dataset for using a more complex and detailed crop model. This last circumstance may be due to the fact that as in Bultot's kind climate change scenarios, we have at hand only a limited climate dataset given mainly by temperature and precipitation. In fact this is a very common circumstance when we are using scenarios created with the MAGICC/ SCENGEN system.

The use of climate indexes in agricultural or natural ecosystems impact assessments is rarely done for a limited (point) locality, a circumstance very frequent when we are using process–based crop models. Climate indexes are naturally related to areal, regional or national assessments, because they are scalar quantities that can be easily converted to isograms in maps depicting spatial variations of the study object and thus allowing appreciation of derived conclusions at a glance. Speaking of spatial variability of some numerical magnitude associated to some specific conceptual interpretation in modern times always leads people to think in terms of Geographical Information Systems (GIS) and its associated technological and knowledge complexities. The reader must never forget that GIS are only a modern achievement and that a map of practically every conceivable variable can always be done manually following the standard rules of scalar analysis as they apply to the magnitude of the task at hand. Nobody needs to become a specialist in GIS in order to make a useful map of a climate index and obtaining the necessary conclusions from it.

Conclusions derived from spatial representations of a climate index are most of the time inferred from the index values and not directly calculated from them. This is particularly the case of aridity indexes or Holdridge's Life Zones. Notwithstanding this, that is not the case of some indexes such as the Riabchikov's indexes and other ones because such kinds of indexes can be directly transformed to net primary productivity of ecosystems, or to some other directly meaningful biological concept, before making the final assessment map. In fact, net primary productivity of ecosystems calculated by using such indexes or Lieth's formulas could be considered as climate indexes instead because they rarely take into account other factors such as soil properties or human intervention on landscapes.

ARIDITY INDEXES

Aridity indexes are part of a very large family. Besides those already defined and mentioned in previous chapters we could consider the moisture index of Thornthwaite (1948), the Lang's index (Santos et al., 2005) and the De Martonne, Selianinov, Stentz, Vysotski and Ivanov indexes (Riabchikov, 1975).

The reader should be aware that the generality of these indexes is equivalent to the UNEP aridity index ($\mathbf{P / E_0}$) or the inverse of it. It just happens that these – let us say primitive or pioneering – indexes were created in historical times when the concept of potential evapotranspiration was not clearly defined or very precise methods to estimate it had not been established. The Riabchikov's index is an exception of this norm.

An aridity index generally varies between two extremes, one representing very drylands or deserts and the other representing very wet forests or jungles. Its spatial variation on a map representing a given time period allows us to determine how aridity goes from very high values in deserts to very low values in jungles.

The time variation of the aridity index for a given region represents whether climate and landscape are evolving towards drier or wetter climates and landscapes. In this last form, using climate change scenarios for different future dates, an assessment can be done. Using most aridity indexes climate change impacts can be inferred.

If climate is evolving towards the dry end of the climate index, then the danger of desertification processes grows, these processes happen to be associated to a reduction in the net primary productivity of natural ecosystems, a loss of organic matter, and other processes of soil degradation (wind erosion and salinization) and a scarcity of water resources. If climate is evolving towards the wet end of the climate index, then a rise in net primary productivity and water resources can be inferred. Formation of new wetlands in topographically suitable regions could be predicted.

These kinds of climate indexes have been widely used in Cuba for assessment purposes by Rivero et al (1995); Rivero et al (1996 a); Rivero et al (1999) and for operational systems able to perform the early warning of agricultural droughts (Rivero et al, 1996 b). Some of these assessments were made as part of climate change impact assessments, while others were used for purposes related to the definition of areas prone to desertification as part of reports having to do with the United Nations Convention to Combat Desertification (CCD, 1995). Maps of the aridity index made by Rivero et al (1995) by traditional manual scalar analysis were later transformed to a digitized gridded form and used to estimate vulnerability indexes to natural menaces and disasters associated to food production in the eastern region of Cuba.

Using a high resolution gridded dataset for annual mean temperature and precipitation in Cuba during 1961-90 and climate change scenarios created with MAGICC/SCENGEN 2.4 using the IS92a greenhouse gases emissions scenario and the coupled ocean – atmosphere HadCM2 general circulation model, Rivero et al (1999) made a study of the time and spatial distribution of the UNEP aridity index ($\mathbf{P / E_0}$). Results were displayed using a system analogous to a GIS (CLIMCUBA) that was created by Roger R. Rivero Jaspe in 1998.

Main results obtained in this study (Fig. 8.1 and 8.2) allowed the determination of which regions of Cuba possess dry subhumid and drier climates prone to desertification processes, that is, they have an aridity index near or less than 0.65. In the chosen climate change scenario these regions will extend in area and become drier. In addition to this, new areas with dry subhumid climates prone to desertification processes will appear in regions where this problem was nonexistent in the reference climate conditions (Fig. 8.2).

NET PRIMARY PRODUCTIVITY OF FORESTS AND TERRESTRIAL ECOSYSTEMS

Net primary productivity of forests and natural terrestrial ecosystems can also be studied using climate indexes. The first attempt of doing so in Cuba was made by Garcia and Rivero (1997); Rivero et al (1997). These pioneering studies were made using the Riabchikov index.

The methodology of Holdridge's Life Zones has been recommended (Benioff et al, 1996) and used in many countries (Perdomo et al, 1996). This methodology was applied by Rivero et al, (1999) in Cuba using the same technology and climate change scenarios already described in the previous section. In analyzing maps for these Life Zones corresponding to actual reference climate (Fig. 8.3) and a future one (Fig. 8.4) it can be seen how life zones corresponding to dry and very dry forests increase in area with time along the whole 21st century in Cuba at the expense of actual wet forests. The displacement in time of ecotones is evident in these two representations.

Riabchikov hydrobiothermical potential was also used by Rivero et al (1999) to study net primary productivity (**NPP**) of natural ecosystems in actual (Fig. 8.5) and future climates (Fig. 8.6) corresponding to the same climate change scenarios. The corresponding decreases of NPP as actual biomes evolve toward drier ones which could then be estimated for the whole country (INSMET, 2001). These studies were complemented using algorithms for estimating the Potential Biomass Density (**PBD**) of forests based on the procedure described by Iverson et al (1993).

All these assessment techniques using climate indexes were compiled in a computer program now known as Terrestrial Ecosystems Impact Model (**TEIM**). The use of this program was first presented in 2007 at the CCCCC/INSMET Training Workshop on Biophysical Models and Climate Change Impact Assessment on Agriculture, 30th January – 9th February, 2007, in Georgetown, Guyana.

The use of these techniques usually involves the determination of the yearly growing season of ecosystems. For middle latitudes this season could be defined as the time period between the last killing frost in spring and the first killing frost in autumn (USDA, 1941) and it would be controlled by temperature. In warmer tropical climates the growth period would be mainly controlled by precipitation and soil moisture. Months pertaining to the growth period can be determined using the relationships proposed by Iverson et al (1993) or by the monthly ($\mathbf{P/E_0}$) relationships used by FAO (Oldeman and Frere, 1982; FAO, 1985).

Another and maybe more direct way for using climate indexes to estimate net primary productivity of natural ecosystems would be using the so-called Chikugo Model now described in the next section. This model was previously seen in Chapter 2.

The Chikugo Model

As an example of how relevant terms of the biomass balance equations may be calculated we state here what has been commonly named as the Chikugo Model (Gommes et al, 2007). According to this model (Gommes et al, 2007; Uchijima, 1985)) we have that,

$$\mathbf{NPP = 6.938 * 10^{-7} * R_0 * exp\,[-3.6 * 10^{-14} (R_0 / P)^2]}$$

In using this formula one must be aware that **NPP** is expressed in g DM/m ^{2} – year, $\mathbf{R_0}$ is expressed in J / m ^{2} and **P** in millimetres (kg/m ^{2}). We can see that this formula could be expressed in terms of the original Budyko's radiative index of dryness (**B**) if we made the corresponding change in measuring units. That leads us to,

$$NPP = 0.29 * R_0 \exp(-0.216 * B^2)$$

Where now R_0 is measured in Kcal/cm ^{2} and the Budyko radiative index of dryness is calculated in its original form with R_0 measured in Kcal/cm ^{2}, **P** in centimetres and **L** = 0.59 Kcal/cm ^{3}. This model apparently owes its name to The Chikugo Water Basin in Kyushu, Japan. It is one of a family of popular and useful models for the estimation of **NPP** in natural ecosystems that also includes the Miami model (Lieth, 1972) and the Montreal model (Lieth and Box, 1972).

HUMAN AND ANIMAL COMFORT INDEXES

Comfort indexes are bioclimatic ones and can be associated with the general conditions of animal and human beings in response to stressful (adverse) climate conditions. They are usually complex as is the case of the rest of climate indexes associated with plant and ecosystems responses to stressful climate conditions. These indexes differ from those associated with plants productivity because animals may have some kind of internal mechanisms that comes into action in stress conditions. Among those mechanisms we can mention the internal generation and conservation of heat through different processes such as shivering and surface vasoconstriction as well as the activation of heat loss mechanisms, panting and perspiration.

Climate conditions such as they are depicted by one or more bioclimatic index can create stress in the affected animals, usually thermal stress, but this is not the only one possible. This general denomination of stress is usually associated with more complex and diverse responses affecting physiological processes, comfort, mood, and behaviour. The whole complex of responses to climate stress generally leads to a decrease in productivity and a general weakening, including those related to immunological defences, which make living organisms more susceptible to contracting infectious diseases and many kinds of health disorders.

Comfort Indexes for Animals

Some comfort indexes related to animal behaviour and productivity has been discussed by Otengi (1994). Within the context of this section we will be concentrating on the very well known Temperature Humidity Index (**THI**) for cattle. The definition of this index differs in different publications since, it seems that for the first time, its values were correlated with daily mean milk production for temperate climate cattle breeds (mainly Holstein) in the United States.

Rodriguez et al. (2007) made a study about the future evolution of the temperature humidity index for cattle in Camagüey, Cuba, during the 21st century using climate change scenarios based on the HadCM3 global climate model with A1C-MiniCAM greenhouse emissions scenario available in MAGICC-SCENGEN 4.1. The THI definition was taken as (Hahn, 1999),

$$THI = (0.81 * T) + (HR * (T - 14.4)) + 46.2$$

Where,

T = Dry bulb temperature in °C

HR = Relative Humidity in fractions of unit

This index was classified according to the scheme (WMO, 1989; Jones and Hennessy, 2000),

- Mild stress (THI between 75 and 78.9)
- Moderate stress (THI between 79 y 83.9)

- Severe stress (THI equal or greater than 84)

The expected behaviour of this index during the actual century for all the months of the year (Table 9.1) and the daily thermal stress duration in hours for the scenarios in question (Table 9.2) reflects the fact that expected climate conditions will be very stressful for cattle no matter the breed to which they belongs.

Human Comfort Indexes

There are many human comfort indexes that have been defined through the history of meteorology. Most of them have been related to the well being and subjective sensations experimented by human beings in different environments. Many of the studies related to subjective sensations of well being and mood experienced by people under different climatic environments have been made for a better understanding and design of air conditioning systems. Experimental subjects have generally been persons that were born and lived in temperate latitudes, so very little information about human responses living in tropical developing countries to adverse comfort index values is available. This fact introduces new uncertainties in using such comfort indexes because of the process known as adaptation to stressful conditions in individuals born in the tropics. Notwithstanding this, these authors have lived all their life in tropical and subtropical environments and our subjective knowledge tells us that climate stressful conditions are also very frequently felt by people born in such environments. The problem of different sets of values causing different responses according to the acclimatization of different subjects in different latitudes remains open.

Up until this point the reader could be speculating that these bioclimatic indexes would better be discussed in a health sector assessment study and they could be right even if in many countries no one had attempted to do that in their national communications. But that would be exactly our point of view if those health sector studies addressed the problem of human labor productivity of farmers and agricultural workers in tropical countries.

Even in actual reference climate conditions agricultural human labour in the open is very stressful in tropical climates. Climate change will worsen those stressful conditions associated with higher temperatures and water vapour pressures. That will lead to a decrease of human productivity in agricultural work, a decrease in workers awareness that could also be associated with health related issues.

Common bioclimatic indexes used in Cuba have been described by Rivero et al, (2005). Their mathematical expressions and classifications are listed below:

Fototemperature (T_f) and **nictotemperature** (T_n),

$$T_f = 0.75\, T_{max} + 0.25\, T_{min}$$
$$T_n = 0.25\, T_{max} + 0.75\, T_{min}$$

Suffocating Heat Index (Lecha et al, 1994)

$$SHI = (e - 18.8) / 2$$

Air Enthalpy (Paz, 1987)

$$ENT = .24 * T + (597.4 + .43 * T) * r$$

Effective Temperature (ET)

$$\mathbf{ET = .4 * (T + T_w) + 4.8}$$

Equivalent Effective Temperature (Osorio et al., 1988)

$$\mathbf{EET = 37 - ((37 - T) / D) - .0029 * T * (100 - H)}$$

Wind Cooling Power

$$\mathbf{WCP = 10 * (.378 + .22783 * (V \wedge .62)) * (36.7 - T_w)}$$

Oxygen Air Density (OAD)

$$\mathbf{OAD = 80.51 * (p - e) / (T + 273.15)}$$

In these formulas relevant parameters are,

$$\mathbf{V1 = 1.76 + .27 * V}$$
$$\mathbf{D = .68 - .0014 * H + (.75 / V1)}$$
$$\mathbf{e = e_s * H / 100}$$
$$\mathbf{r = .622 * e / p}$$

H – Relative humidity
V – Wind speed
T – Temperature
R – Mixing ratio
$\mathbf{e_s}$ – Saturation vapour pressure
e – Air vapour pressure
p – Atmospheric pressure
$\mathbf{T_w}$ – Wet bulb temperature

These bioclimatic indexes are generally classified in different ranges playing the role of climatic provinces in climate indexes. As a guide to users the classification used in the Cuban National Climate Centre (Rivero et al, 2005) is shown below,

Effective (ET) and Equivalent Effective Temperature (EET)

TE <= 12.0 ºC - very cold
12.0 < TE <= 17.0 ºC - cold
17.0 < TE <= 22.0 ºC - cool
22.0 < TE <= 25.0 ºC - comfortable
25.0 < TE <= 28.0 ºC - warm
TE > 28.0 ºC – very warm

Suffocating Heat Index:

SHI <= 1 – There is not suffocating heat
1 < SHI <= 3 - Weak
3 < SHI <= 5 - Moderated
5 < SHI <= 7 - Strong

7 < SHI <= 9 - Extreme
9 < SHI - Extremely Extreme

The "Extremely Extreme" range had not been defined in scientific literature because there were not conditions for so much heat in Cuban reference climate. But it was shown that such conditions will appear in future ones due to climate change.

Oxygen Air Density

This is not really a comfort index because such indexes usually refer to heat stress. But it happens that the subjective sensation of lacking enough air (oxygen really) for respiration is a most uncomfortable one and can be very harmful to people with asthma, hypertension, headache and migraine. It is classified by the following scheme,

OAD <= 265 g / m^3 – hypoxia conditions
265 < OAD <= 270 g / m^3 - normal oxygenation conditions
OAD > 270 g / m^3 – hyperoxia conditions

Wind Cooling Power

WCP <= 100 – very low
100 < WCP <= 200 – low
200 < WCP <= 300 – moderate
300 < WCP <= 400 – high
WCP > 400 – very high

Air Enthalpy does not have an associated classification scheme.

A study was conducted about the future behaviour of these indexes in expected climate conditions in Camagüey, Cuba, during the 21st century (Rivero et al, 2005). Climate change scenarios were made with the MAGICC/SCENGEN system, HadCM2 global climate model and IS92a greenhouse gases emissions scenario.

Future values of all bioclimatic indexes will evolve toward highly thermal stressful conditions to humans, especially for agricultural workers in the fields (Table 8.1). This will require rather innovative adaptation strategies for agricultural manual labour. Naturally these effects will be less noticeable in January (Fig. 8.7) than in July (Fig. 8.8). Since the middle of the century a new climate, now unknown to us, will be emerging in tropical regions.

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TABLES AND FIGURES FOR CHAPTER 8

Table 8.1. Evolution of the Temperature Humidity Index (THI) in Cuba during the 21st century.

Camagüey	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	71,6	72,0	73,5	74,9	76,8	78,3	79,3	79,4	79,0	77,5	75,0	72,5
2025	72,8	73,3	74,6	75,8	78,0	79,4	80,4	80,6	80,3	78,7	76,1	73,5
2050	74,2	75,0	76,2	77,2	79,6	81,1	82,2	81,9	82,0	80,3	77,6	75,0
2075	75,5	76,6	77,6	78,5	81,0	82,5	83,6	83,4	83,6	82,0	79,1	76,3
2100	76,5	77,6	78,4	79,3	82,0	83,5	84,6	84,2	84,4	82,8	79,9	77,1
Jimaguayú												
Baseline	71,7	72,0	73,5	74,8	76,8	78,3	79,2	79,4	79,0	77,6	75,0	72,6
2025	72,8	73,3	74,6	75,7	78,0	79,5	80,4	80,6	80,3	78,7	76,2	73,5
2050	74,3	75,0	76,2	77,1	79,6	81,1	82,1	81,9	81,9	80,4	77,7	75,0
2075	75,6	76,6	77,6	78,4	81,0	82,5	83,6	83,4	83,6	82,0	79,1	76,3
2100	76,5	77,5	78,4	79,2	82,0	83,5	84,5	84,2	84,4	82,8	80,0	77,1
Vertientes												
Baseline	71,5	72,1	73,2	74,3	76,7	78,5	79,1	79,5	79,0	77,7	75,5	72,9
2025	72,6	73,4	74,3	75,3	77,8	79,6	80,3	80,6	80,3	78,8	76,7	73,9
2050	74,1	75,1	75,9	76,7	79,4	81,3	82,0	81,9	82,0	80,5	78,2	75,4
2075	75,4	76,7	77,3	77,9	80,9	82,7	83,5	83,4	83,6	82,1	79,6	76,7
2100	76,4	77,7	78,1	78,7	81,8	83,7	84,4	84,2	84,4	83,0	80,5	77,5

Table 8.2. Duration in hours of the day fraction with thermal stress in cattle during the 21st century.

Camagüey	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	10,2	10,7	12,4	13,7	15,5	16,0	16,7	16,9	16,4	15,7	13,8	11,1
2025	11,6	12,2	13,5	14,4	16,1	17,5	19,2	19,9	19,1	16,3	14,5	12,3
2050	13,1	13,7	14,7	15,7	18,4	21,0	23,1	22,7	22,8	19,6	16,0	13,6
2075	13,9	14,8	15,8	17,2	20,7	23,0	23,9	23,8	23,9	22,2	18,1	14,7
2100	14,8	16,1	17,1	18,3	22,0	23,5	24,0	23,9	24,0	23,0	19,3	15,6
Jimaguayú												
Baseline	10,1	10,6	12,4	13,7	15,5	16,0	16,4	16,6	16,1	15,7	14,0	11,1
2025	11,6	12,2	13,5	14,4	16,0	17,4	19,1	19,8	19,0	16,2	14,7	12,4
2050	13,2	13,8	14,7	15,5	18,2	21,1	23,2	22,7	22,9	19,7	16,0	13,7
2075	14,0	14,8	15,7	17,0	20,8	23,1	23,9	23,9	23,9	22,4	18,0	14,9
2100	14,8	16,0	17,0	18,1	22,2	23,6	24,0	24,0	24,0	23,1	19,3	15,7
Vertientes												
Baseline	9,9	10,5	11,9	13,1	15,5	16,4	16,4	17,1	16,5	15,9	14,5	11,6
2025	11,2	12,1	13,2	14,0	16,2	18,0	18,6	19,7	19,0	16,8	15,4	12,7
2050	12,8	13,9	14,5	15,2	18,1	21,1	22,9	22,7	22,7	19,8	16,4	14,1
2075	13,9	15,2	15,7	16,6	20,3	23,1	23,9	23,9	23,9	22,5	18,5	15,2
2100	14,8	16,1	16,7	17,6	21,6	23,6	24,0	24,0	24,0	23,2	19,9	15,9

Table 8.3: Mean monthly values for bioclimatic indexes in Camagüey for January and July, according to the climate change scenario induced from IS92a greenhouse gases emission scenario a HadCM2 global climate model.

	1981 - 90	2010	2030	2050	2075	2100
JANUARY						
EET	19.21	19.54	19.88	20.32	20.77	21.21
ET	22.32	22.55	22.78	23.10	23.41	23.72
SHI	1.84	2.04	2.25	2.53	2.82	3.12
ENT	13.88	14.11	14.34	14.65	14.96	15.28
WCP	133.82	131.35	128.94	125.73	122.48	119.24
OAD	269.50	269.12	268.73	268.22	267.70	267.18
T_f	25.38	25.68	25.98	26.38	26.78	27.18
T_n	20.48	20.78	21.08	21.48	21.88	22.28
JULY						
EET	24.49	25.16	25.83	26.49	27.27	28.17
ET	26.09	26.57	27.05	27.53	28.09	28.72
SHI	5.46	5.98	6.53	7.08	7.76	8.56
ENT	17.76	18.30	18.86	19.42	20.10	20.90
WCP	94.95	89.92	84.83	79.65	73.77	67.22
OAD	263.28	262.48	261.67	260.85	259.89	258.78
T_f	30.18	30.78	31.38	31.98	32.68	33.48
T_n	25.20	25.80	26.40	27.00	27.70	28.50

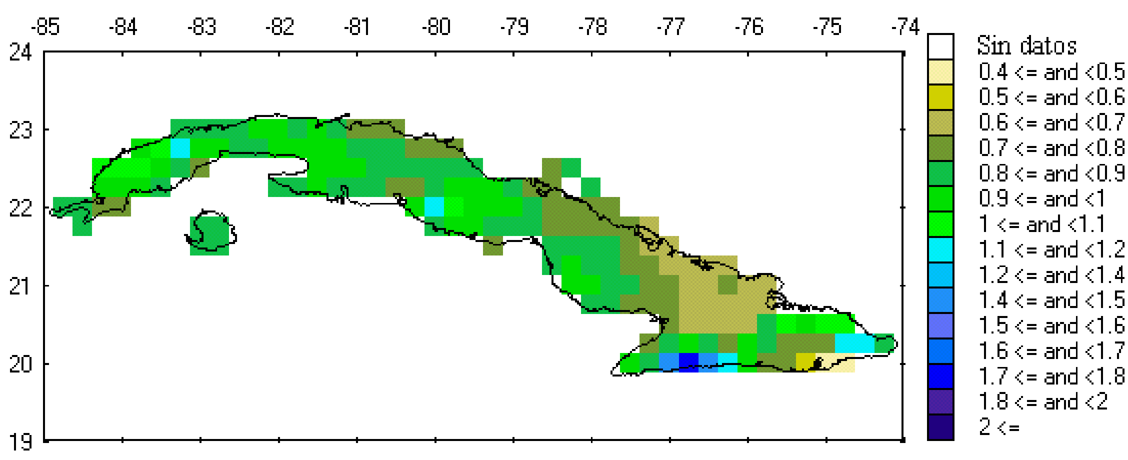


Fig. 8.1: UNEP aridity index (P / E_0) in Cuba for the period 1961 - 90

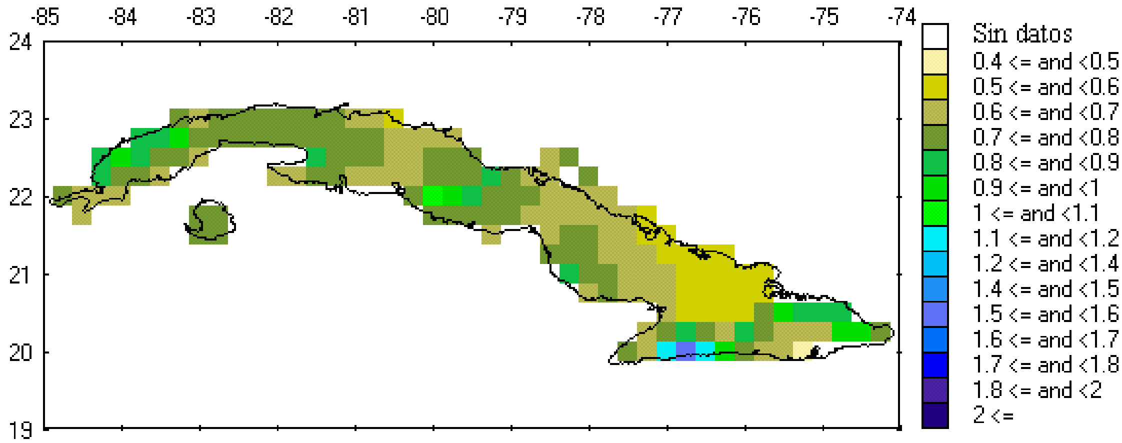


Fig. 8.2: UNEP aridity index (P / E_0) in Cuba for the period centred around 2100

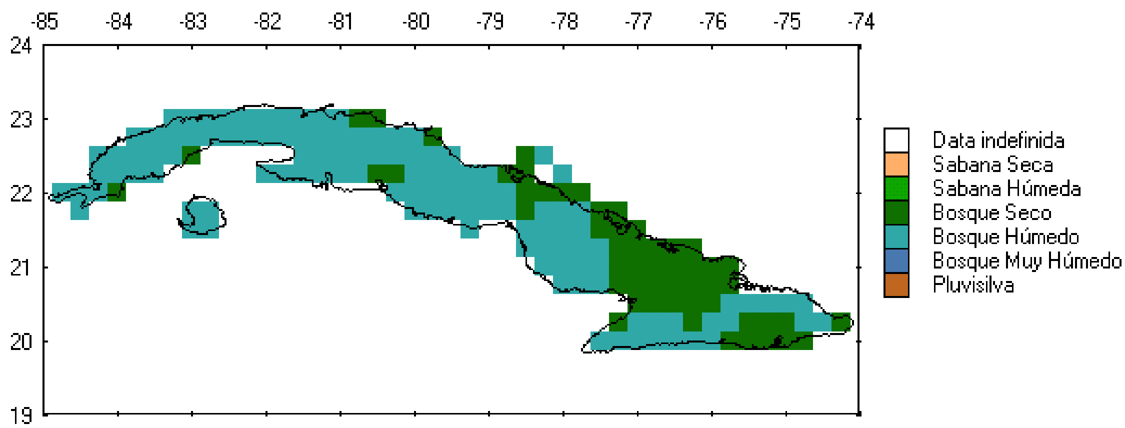


Fig. 8.3: Holdridge's life zones in Cuba for the period 1961 – 90

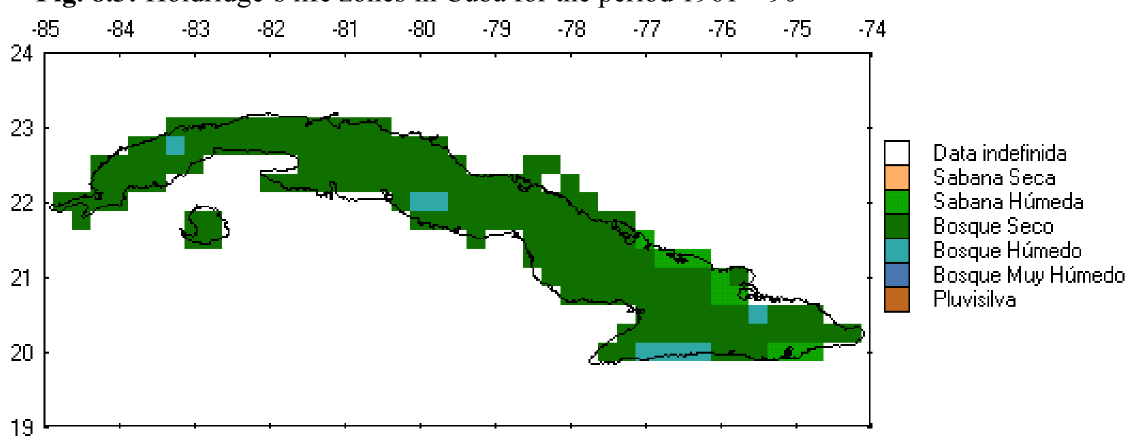


Fig. 8.4: Holdridge's life zones in Cuba for the period centred around 2100

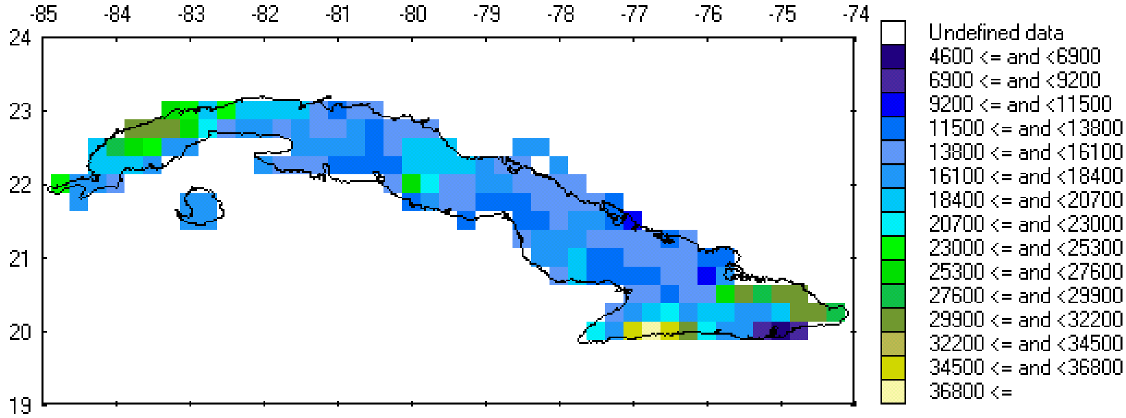


Fig.8.5: Net primary productivity (kg/ha) in Cuba for the period 1961 – 90

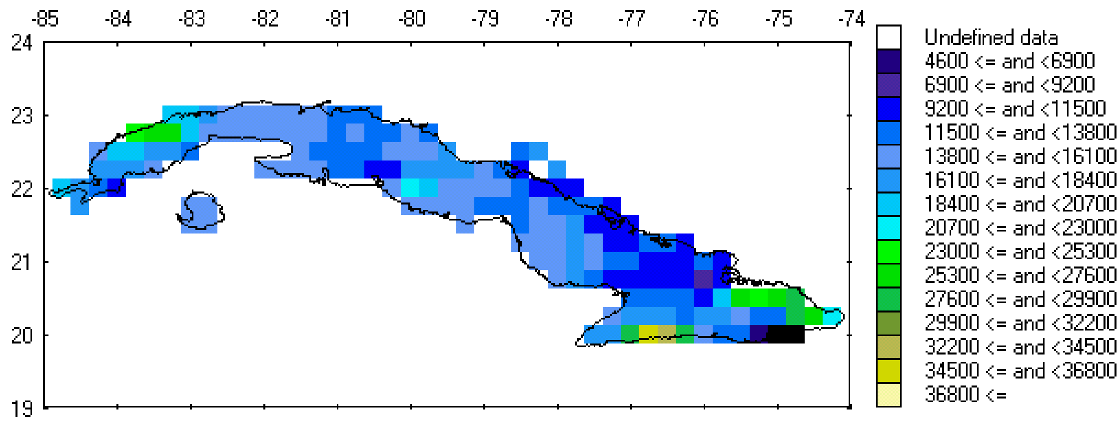
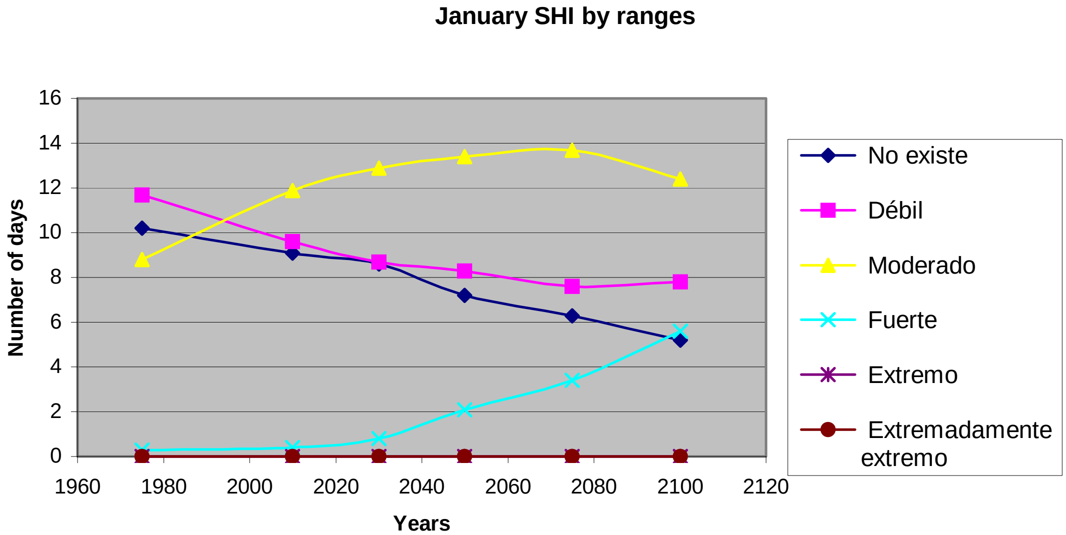


Fig. 8.6: Net primary productivity (kg/ha) in Cuba for the period centred around 2100



Fig

. 8.7: Number of days with indicated value of SHI for January during the 21st century in Camagüey.

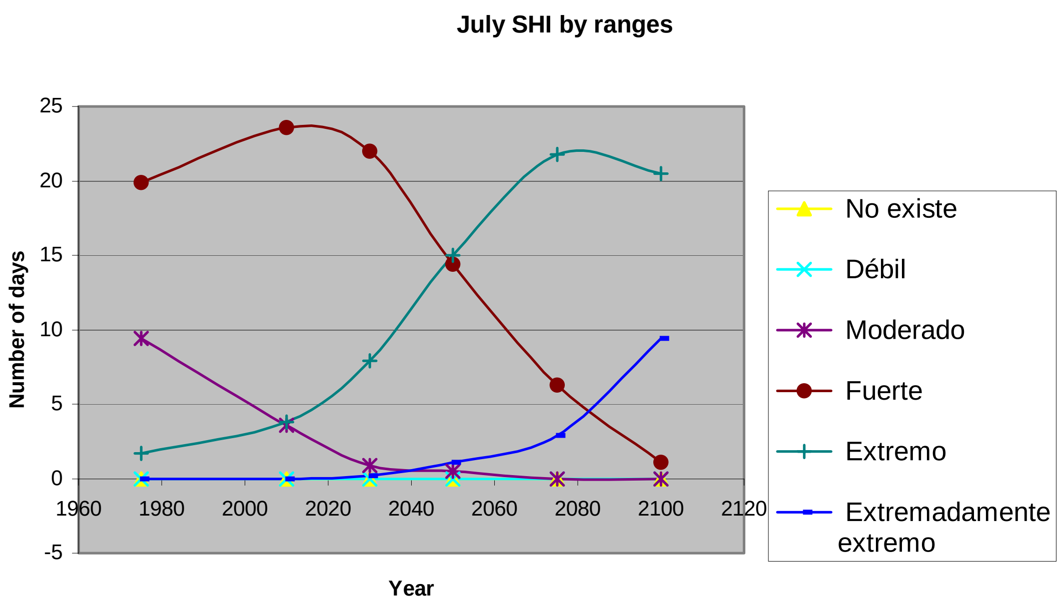


Fig. 8.8: Number of days with indicated value of SHI for July during the 21st century in Camagüey.

CHAPTER 9

THE WOFOST MODEL: VERSION 4.1

CHAPTER 9. The WOFOST Model: Version 4.1

INTRODUCTION

WOFOST 4.1 is probably the most documented version of the WOFOST family models (Diepen et al, 1988). This family of models is based on the Netherlands School of crop modelling known as the Wageningen School of thought created over the foundation of theoretical ecology built by C. de Wit and his collaborators. One of its authors is Prof. H. van Keulen who first made a rice crop model in the seventies (Oldeman and Frere, 1982) and to whom we are deeply grateful for having introduced us to the field of crop modelling and lending us the model and necessary documentation for being able to use it profitably. The name of this model comes from the name of the institution in which it was created, namely the Centre for **Wo**rld **Fo**od **St**udies in Wageningen, Netherlands.

This family of models are a logical continuation of simpler models such as AEZM discussed in Chapter 6. Basic theory supporting the model follow the lines discussed in Chapter 5 of this workbook. The family of models can be described as **generic** because all different crops are simulated on the same basic principles, while other specialized models such as CERES – Wheat and SUBSTOR –POTATO are made in such a way that they can only simulate wheat or potato, using different approaches in each case. But being generic is not a limitation for the WOFOST family, because in the model algorithms themselves the capacity for distinguishing one crop from another has been built. Its input file CROP41.DAT contains the pertinent information that allows the model to distinguish between wheat and potato (WMO 1990; Heemst, 1988). Some characteristics of WOFOST are also discussed in Geijn et al (1993).

The AEZM model already discussed is also a generic one, but it differs from WOFOST in a very important aspect. AEZM is a **stationary model** that gives no information about the time evolution of the crop while WOFOST is a **dynamical model** executing daily simulation of all relevant growth and development stages of crops.

Model WOFOST was not originally designed to take into account CO2 atmospheric concentrations, so it would not simulate the carbon dioxide fertilization effect. Notwithstanding this that effect can be partly taken into account manipulating plant parameters provided in CROP41.DAT input file as done by Wolf and Diepen (1993); Rivero and Rivero (1998).

The reader should be aware that even if climate data inputs in file CLIM41.DAT are given as monthly values, this model has internal interpolation subroutines that allow him to make daily calculations giving output simulated values for every specified time lapse (daily, every five days, every ten days). The default lapse of time given by every ten days is the one most used by the authors of this workbook.

As the original source program was written in FORTRAN the user needs to be very careful and precise in changing WOFOST input data files, because FORTRAN format procedures are very exacting and any minor change in the format of input data files will lead to the abortion of the program. It would not understand all the necessary input values.

NECESSARY FILES AND REQUIREMENTS

The necessary files must all be written in the same subdirectory. This subdirectory may be l in the root directory as well as inside any other one. Practically any central processor (CPU) and RAM will do. WOFOST 4.1 was designed to work on a MS-DOS platform but, taking whatever practical measures are needed, the authors of this workbook have run the model in Windows'95, Windows'98, Windows'2000 and Windows XP operating system.

The set of useful files comprising WOFOST is given by:

WOFOST.EXE
MAKEMENU.EXE
REALRAIN.EXE
PRNF.EXE
MENU.DAT
CLIM41.DAT
CROP41.DAT
SOIL41.DAT
REALRD.DAT

MAKEMENU.EXE is an executable file allowing the user to make changes and amendments in file MENU.DAT, but in case of emergency those changes can be done with any usual text editor. REALRAIN.EXE is another executable file that posts in the monitor screen an input data form with the adequate format for any number of years with daily rain values the user may want to create as file REALRD.DAT. Daily rain values must be entered manually. PRNF is an executable file allowing file WOFOST.OUT to be printed in three independent pages containing potential yield, water limited yield and final summary of results.

We can conclude then that, if we are not interested in using daily rain data files, the essential set of files needed to run WOFOST is given by:

WOFOST.EXE
MENU.DAT
CLIM41.DAT
CROP41.DAT
SOIL41.DAT

If one of these files is missing the user would not be able to run the WOFOST 4.1 model.

FILES CONTENT DESCRIPTION AND MODIFICATION BY USERS

All input files can be modified by users using a suitable text editor. This should be done with the utmost care because any modification of the original FORTRAN FORMAT will cause the program to be unable to run with the modified input file. If the user wants to add a new station, crop, cultivar or soil he should take one of the existing one in the different subsections, copy it and paste it at the end of the input file. Once that is done he can proceed to make necessary modifications in names and parameter values according to his needs. When that is done he will need to change file MENU.DAT or he would not be able to access and select the modified part of the input data file.

CLIM41.DAT File

This file contains **mean monthly values** of **minimum** and **maximum temperature** (Celsius), **global solar radiation** (M/m ^{2}), **water vapour pressure** (hPa), **wind speed** (m/s), **precipitation** (mm) and **number of rainy days** (days) in that order from left to right. All available stations are listed one below the other in this file. Listed numbers at the right of station identification name are the latitude of locality where measurements were done, its height (meters) above mean sea level and values for **a** and **b** in the Angstrom formula (Chapter 2). A copy of a file like that is listed below:

```
CAMAGUEY 1961-1990          21.4  122.  0.25  0.50
   17.4   28.1 13.850   22.1    3.4    29.     5.
   17.4   28.9 16.425   21.7    3.4    39.     5.
   18.3   30.2 19.797   22.7    3.7    40.     5.
   19.2   31.2 21.737   23.5    3.6    56.     5.
   20.6   31.6 20.267   26.3    3.1   174.    12.
   21.8   31.9 19.353   28.7    2.8   185.    14.
   22.3   32.8 21.381   29.0    3.3   100.    10.
   22.3   32.9 20.905   29.5    3.0   125.    12.
   22.2   32.3 18.402   29.6    2.3   152.    13.
   21.5   30.9 16.097   28.4    2.3   179.    13.
   20.1   29.1 14.421   25.8    3.1    69.     8.
   18.4   28.1 13.188   23.3    3.3    27.     5.
```

CROP41.DAT File

This is a very complex file containing all physiological information characteristic of all available crops. The meaning of each value written in this file is explained in a separate Excel file provided with the Workbook. Information pertinent to every available crop is listed one below the other. A copy of a section of a file like that is listed below:

```
Potato (late cv.)
 2 0 0     20.    7.   50.0   1.0    0.   0.40  1.00   3.0
   50.0   10.0 0.0333 0.0091    1.2  0.480  0.720  0.850  0.720  0.690
 0.0000 0.0000    2.0  0.030  0.007  0.010  0.015  0.030  0.020  0.020
 0.0085 0.0150 0.0220 0.0400 0.0011 0.0014 0.0055 0.0100
 0.0110 0.0130 0.0280 0.0380    0.   0.00
  8 12 12 12  6  8  6 10  4
    0.00   0.30   1.00   0.10   1.33   0.00   2.00   0.00
```

```
-.--
-.--
0.00   0.80    0.81   0.80    1.00   0.76    1.34   0.00    1.44   0.00
2.00   0.00
-.--
0.00   0.20    0.81   0.20    1.00   0.24    1.34   0.23    1.44   0.00
2.00   0.00
-.--
0.00   0.00    0.81   0.00    1.00   0.00    1.34   0.77    1.44   1.00
2.00   1.00
0.00 0.0032    1.30 0.0032    2.00 0.0015
-.--
0.00   0.00    7.00   1.00   18.00   1.00   30.00   0.00
-.--
0.00  40.00    1.57  40.00    2.00   0.00
-.--
0.00   0.00    7.00   0.00   19.00   1.00   29.00   1.00    37.00   0.00
-.--
0.00   0.00    3.00   1.00
```

SOIL41.DAT File

This is a somewhat complex file containing all hydrologically relevant information of all available soils. The meaning of each value written in this file is also explained in a separate Excel file provided with the Workbook. Information pertinent to every available soil is listed one below the other. A copy of a section of a file like that is listed below:

```
Medium to Coarse Sand (O5)
 20 26
   43.59   30.00   43.59
  -1.000  0.332   1.000  0.303   1.300  0.254   1.491  0.191   2.000  0.076
   2.400  0.046   2.700  0.035   3.400  0.020   4.204  0.010   6.000  0.004
   -.---
   0.000  2.349   1.000  1.639   1.300  0.823   1.491  0.049   1.700 -1.000
   2.000 -2.523   2.400 -3.796   2.700 -4.481   3.000 -5.143   3.400 -6.000
   3.700 -6.699   4.000 -7.284   4.204 -7.886
```

For the needs of WOFOST model soil is only a suitable medium for water storage. Soil texture (percentage of sand, silt, and clay present in the soil) is the only soil classification needed for this purpose. No other type of soil information is taken into account because, in great measure, texture can be used to derive hydro - physical characteristics of soils.

REALRD.DAT File

This is the file containing daily rain values for every available year. It resembles some kind of table with headings indicating locality and years horizontally as columns and 365 rows indicating every day of the year. The number of columns depends on the number of available years. It is a somewhat cumbersome format for making a copy of the file in this book.

Interactive executable file WOFOST.EXE and input file MENU.DAT will be described in the next section. They will not be discussed here.

RUNNING THE MODEL

To run WOFOST v 4.1 it is only necessary to launch program WOFOST.exe. This executable (stand – alone) file will read input data from MENU.DAT, CLIM41.DAT, CROP41.DAT and SOIL41.DAT data files written in ASCII format. Once this has been done the model will start its interactive user mode that will be described below.

Interacting with the program the user must be aware that:

- The model will calculate potential yield, water limited yields and nutrient limited yields.
- The necessary input data for calculating one or other of these types of yields is different.

First Interactive Mode and Menu Selections by Users

During the first part of the interactive process previous to the final model run, the program will be using information contained in file MENU.DAT. To clarify this, a complete (typical) copy of this last file is shown below:

```
 Potato (late cv.)
 Barley
 Cassava
 Chickpea
 Cotton
 Cowpea
 Field bean
 Groundnut
 Maize
 Millet, bulrush
 Mung bean
 Pigeon pea
 Rapeseed
 Rice HYV-IR8
 Sorghum
 Soybean
 Sugar beet
 Sugarcane
 Sunflower
 Sweet potato
 Tobacco
 Wheat, spring
X
 CAMAGUEY 1961-1990
 GEORGETOWN MEAN VALUES
X
 Medium to Coarse Sand (O5)
 Fine Sand (B1 + O1)
 Loamy Fine Sand (B2 + O2)
```

Very Loamy Fine Sand (B3 + O3)
Fine Sandy Loam (B4 + O4)
Silt (O15)
Light Loam (B7 + O8)
Loam (B8 + O9)
Heavy Loam (O10)
Clay Loam (B10 + O11)
Clay (B11 + O12)
Heavy Clay (B12 + O13)

As can be easily seen the first part of this file is a listing of available crops in file CROP41.DAT, the second one the codename of stations, localities, years from a locality or something similar with the necessary climate data in file CLIM41.DAT while the third part contains the codename of soils whose properties are available in file SOIL41.DAT.

The executable file first lists all available crops, but successively numbered from 1 to whatever number corresponds. In the original version that number would be 22, but the user can change that by adding or eliminating crops simultaneously in files CROP41.DAT and MENU.DAT. This can be done in any appropriate text editor program. This listing occupies two screens, as follows:

FIRST SCREEN

1. Potato (late cv.)
2. Barley
3. Cassava
4. Chickpea
5. Cotton
6. Cowpea
7. Field bean
8. Groundnut
9. Maize
10. Millet, bulrush
11. Mung bean
12. Pigeon pea
13. Rapeseed
14. Rice HYV-IR8
15. Sorghum
16. Soybean
17. Sugar beet
18. Sugarcane
19. Sunflower
20. Sweet potato

to continue press <Return>

SECOND SCREEN

21. Tobacco
22. Wheat, spring

Your choice please:

In the place directly to the right of the symbol < **:** > the user must type the number corresponding to the crop he wants to simulate with the model. Then if the reader wants Maize he must type < **9** > + **RETURN or ENTER**

Once this is done the program will make its first really difficult question given as:

Multiply duration of vegetative growth by

This must be interpreted as follows: In file CROP41.DAT there is the necessary information to estimate (using the proper biological clock) when the crop should flower or start making tubers in the case of crops such as potatoes. If the user types **RETURN or ENTER** the model will assume < **1** > by default. If the final flowering date does not coincide with the actual date measured in field conditions, then the next time that he runs the model the user must type a different number trying to match model predicted flowering dates with measured ones. If the user types a number greater than < **1** > the modelled crop will flower later than default, but if he types a number less than < **1** > the modelled crop will flower earlier than default. This process is called "calibration of the model", at least of the duration of its phenological stages, and will result in the coincidence of predicted and measured dates for flowering.

Once the user has typed a number here the program will ask its second tricky question given as:

Multiply duration of generative growth by

This is part of the same process, only that now the user must calibrate the crop biological clock with regard to the duration of the interval between flowering stage and crop maturity. The same explanation is valid here.

The reader must be aware that even if this is being done manually here (trial and error), once the appropriate values have been estimated the user will be able to make permanent adjustments in file CROP41.DAT. Once this is done he would not need to type anything here because the default values would have changed to match actual field conditions. This was briefly explained when discussing file CROP41.DAT.

Now the program will list available places with climate data as follows:

1. CAMAGUEY 1961-1990
2. GEORGETOWN MEAN VALUES

Your choice please:

The user must type the number of the station he wants to use in the following way:

< **2** > + **RETURN or ENTER**

That is, if he wants to simulate maize in Georgetown.

Now the program will present the list of available soil types in file SOIL41.DAT, as follows:

1. Medium to Coarse Sand (O5)
2. Fine Sand (B1 + O1)

3. Loamy Fine Sand (B2 + O2)
4. Very Loamy Fine Sand (B3 + O3)
5. Fine Sandy Loam (B4 + O4)
6. Silt (O15)
7. Light Loam (B7 + O8)
8. Loam (B8 + O9)
9. Heavy Loam (O10)
10. Clay Loam (B10 + O11)
11. Clay (B11 + O12)
12. Heavy Clay (B12 + O13)

Your choice please:

To select a definite soil the user must now type one of these numbers, let us say < **8** > if he wants to simulate a **Loam** soil:

< **8** > + **RETURN or ENTER**

With this action the user has ended the first interactive session with the program and he has entered all the necessary information the model needs **to calculate potential yield** of the chosen crop on the **specified climate conditions** given that **soil data is not relevant to this purpose**. A second session will begin now.

Second Interactive Mode and How to Answer Model Questions by Users

And it is now that the really cryptic questions begin:

monthly data with rainfall generator (0),
or daily rain data on file REALRD.DAT (1)

If the user type < **0** > + **RETURN or ENTER** here the program will estimate which days of the month were rainy days and how much it rained at every one of them. To do that the program will use an internal statistical weather generator of its own (not a trade mark one such as CLIMGEN or WGEN used by other models). To be able to generate this dataset the internal weather generator will need monthly rain values and number of rainy days actually written in file CLIM41.DAT. Let us assume that every time the user uses this option sequentially (We will see that later.) the internal weather generator will choose a different arrangement of days and amount of rain for every chosen day. A weather generator could be described as a dice throw made by the generator only that it is made according to its predefined statistical distribution functions and not on the classical dice binomial one.

If the user type < **0** > + **RETURN or ENTER** here the user needs to be sure that he has created previously a daily rain values file REALRD.DAT using the auxiliary executable program REALRAIN.exe. If REALRD.DAT file does not exist WOFOST run will abort.

Once this choice has been done the program will ask:

Maximum surface storage in cm

The program is asking what is the maximum amount of liquid water that may remain on the surface of the soil, without infiltrating to deep layers or running on the surface as runoff. If this value is greater than zero then ponds could exist in the soil surface. A value different from zero is indicated also for crops such as flooded rice. The reader must be aware that liquid water on the surface of the soil will evaporate at a different rate than soil water, so WOFOST must know this parameter for its water balance calculations. If we type **RETURN or ENTER** the default value for this parameter is < **0** >.

Then still another question comes:

No groundwater (0) or groundwater (1)

Entering numbers < **0** > or < **1** > here will lead to two different sets of questions that must be answered. This will be indicated as **Set < 1 >** and **Set < 0 >**, in reverse order, in the following paragraphs.

Set < 1 >

If the user enters < **1** > in the previous question the program will throw at him three additional (hidden) questions as follows:

initial groundwater table in cm

So the user should enter a value for this parameter. Then follows:

no drainage (0) or drainage (1)

If the user types < **0** > here there is no problem at all, but if he types < **1** > another bifurcation will take place and one more hidden question will appear on the screen:

drainage depth in cm

Once it has this information the program will not go through the **Set < 0 >** questions and will jump directly to the first question beyond **Set < 0 >** paragraphs. **Set < 1 >** ends here.

Set < 0 >

If the user types < **0** > or **RETURN or ENTER** in the given question the program will assume that groundwater is so deep that it has no interactions with the crop. Then it would require knowledge about initial soil moisture status asking:

initial available soil moisture in cm

Observe that soil moisture is given in centimetres and not in millimetres as usual in meteorology and hydrology. A value of < **0** > should never be entered because it will bring problems later in the simulation process. Entering a value to this question will end the bifurcation process in such a way that the rest of the questions will be the same for both cases. **Set < 0 >** ends here.

Once the user has gone out of the bifurcation process another common tricky question that could lead to confusion will be asked and a value must be typed:

maximum rooting depth (soil) in cm

The program user must not be confused here. Actual possible depths of roots for each crop are, let us say, genetically defined in file CROP41.DAT. A deeply rooting crop can reach one meter below ground so that value is not being asked here. The value that must be typed here is the maximum rooting depth that **a particular soil** will allow a given crop to reach. A soil may have only 20 cm depth of usable soil and an impervious rock layer or clayey hard pan at that depth that no rooting systems can penetrate. That is the value the program is asking for. If there is none then, type a large number such as 200 cm.

Then another question follows:

fraction of rain not infiltrating.
leading to runoff or surface storage

In actual field conditions a sizable fraction of rain may not enter the soil because infiltration is impeded by surface crusts created by conditions characteristic of that kind of soil and the wetting history of its antecedents. The formation of hard impervious surface layers is inimical to certain classes of clay lateritic soils and other types of soils after prolonged drought episodes. If that is the case, the user must type this fraction (a number between 0 and 1) here.

With this action the user has ended his second interactive session with the program and he has entered all the necessary information the model needs **to calculate water balance of the soil and water limited yield** of the chosen crop on the specified type of soil and climate conditions, because nutrient information is not relevant to this purpose. A third session will begin now.

Third Interactive Mode and How to Answer Model Questions by Users

It then becomes mandatory to type the nutrient necessary information for running the model. The reader should be aware that file SOIL41.DAT contains no nutrient information at all. Values for a lot of nutrients data are specified in file CROP41.DAT. As there is no (programmed) way that allows the model to distinguish between, let us say ammonium nitrate and urea, the user must enter the amount of nitrogen, phosphorus and potassium actually available in the soil including that given as fertilizers and not the amounts of ammonium nitrate, phosphate rock or potassium oxide. The questions are:

Nbase in kg/ha

A value for nitrogen must be entered here. The default value is zero. If the user enters < **0** > here, then nutrient limited yields will be **0.00** also.

recovery fraction of N-fertilizer

This represents the actual amount of nutrient (fraction of total value entered in the previous question) available to the crop that is not immobilized by chemical processes in the ground. The default value is < **0.5** >

Pbase in kg/ha

A value for phosphorus must be entered here. The default value is zero. If the user enters < **0** > here, then nutrient limited yields will be **0.00** also.

recovery fraction of P-fertilizer

This represents the actual amount of nutrient available to the crop. The default value is < **0.1** >

Kbase in kg/ha

A value for potassium must be entered here. The default value is zero. If the user enters < **0** > here, then nutrient limited yields will be **0.00** also.

Recovery fraction of K-fertilizer

This represents the actual amount of nutrient available to the crop. The default value is < **0.5** >.

With this action the user has ended his third interactive session with the program and he has entered all the necessary information the model needs **to calculate nutrient limited yield** of the chosen crop on the specified type of soil and climate conditions as well as conditions of nutrients availability.

Final Interactive Session

And now a very important question should be answered. The user must be very alert because this question does not appear on the screen at the usual place on which the rest of the questions did, but somewhat displaced to the right. Many times users type ENTER automatically instead of typing an adequate number here and the program aborts. We stress first that the program is not asking us for a planting date but an emergence day, which is the day in which crop plants actually emerge from the ground. The process of seed germination under ground is not simulated at all. Second, we stress that this is not an ordinary calendar day (1^{st} July or something like that) but a **Julian Day** from 1 to 365. This means that if the crop plants emerged on 10 February, the user should enter the number < **41** > here. Leap years are not considered, so there is not a Julian Day equal to 366.

Start date (Day number)

And now a final decision should be made choosing in what form we want the final modelling results. They are all variants of writing a file named WOFOST.OUT

Output to: 1. Screen
2. File WOFOST.OUT
3. Printer

- - - >

If we enter number < **1** > here, then file WOFOST.OUT will be displayed in the monitor screen. Entering number < **2** > here will write file WOFOST.OUT in ASCII format on the same disk subdirectory where the executable file was called. WOFOST is able to write only one file named WOFOST.OUT on disk, so the user must have renamed any file with that name already written on it. Entering number < **3** > will print file WOFOST.OUT in a sheet of paper. Be sure to have a printer connected on line.

Once this final decision has been taken the program will run the model and obtain its first results. What happens then will be dependent on certain answers you already gave to WOFOST.

If you chose to use the weather generator, WOFOST will run and ask you:

A next run with newly generated rainfall, no (0) or yes (1)

Entering < **1** > here will cause the program to run a new set of water limited simulations, and thus the user can obtain as many water limited simulations as he wants. Entering < **0** > will allow WOFOST to proceed to the end.

Already finishing WOFOST asks a final question yet:

Start again?, no (0) or yes (1)

The meaning of this question and the necessary answers need no further explanations.

ANALYSIS AND INTERPRETATION OF FINAL RESULTS

Analyzing output file WOFOST.OUT

File WOFOST.OUT is the only output file built by the model, but it can be seen on the screen, recorded on disk or printed. The most difficult thing here about interpretation of the information given by it is due to the fact that actual variables printed are abbreviations of words and phrases which is typical of the FORTRAN language where variable names can have no more than eight characters (older versions). This will not be so difficult to the reader of this workbook, because abbreviations used suggest the name of the relevant parameters that have been discussed in previous chapters. The file itself will be discussed now by sections.

Potential yield simulation

```
WOFOST.OUT/Version 4.1 Last update May 1987  VARP1=1.00 VARP2=1.00

 POTENTIAL CROP PRODUCTION
 =========================
  CAMAGUEY 1961-1990          Maize                             Start day 180

 DAY  ID   WLV    WST    WSO    LAI   DVS   RD    T   GASS   MRES    DMI   TAGP
 180   0    7.     5.     0.    .03   .00  10.  .00    8.9     .4    6.1     12.
 190  10  112.    69.     0.    .36   .26  22.  .08  116.6    6.3   78.5    181.
 200  20 1041.   641.     0.   2.89   .52  34.  .38  564.2   55.9  360.9   1682.
 210  30 2633.  2313.     0.   6.53   .78  46.  .49  712.1  151.1  394.6   4972.
 219  39 3281.  4360.   138.   7.42  1.01  57.  .50  716.7  216.1  352.1   8075.
 220  40 3307.  4553.   221.   7.42  1.03  58.  .49  716.0  221.7  348.0   8416.
 230  50 3251.  5862.  1908.   6.92  1.26  62.  .48  698.4  263.1  310.5  11714.
 240  60 3023.  6051.  4606.   6.32  1.49  62.  .45  651.1  288.3  261.3  14600.
 250  70 2887.  5045.  6996.   5.97  1.72  62.  .42  582.9  288.5  211.9  16991.
 260  80 2218.  4122.  8427.   4.34  1.94  62.  .36  249.4  249.4     .0  18422.
 263  83 1724.  3880.  8427.   3.22  2.01  62.  .32     .0     .0     .0  18422.

 SUMMARY :
 DAYS   TWRT    TWLV    TWST    TWSO     TAGP   GASST   MREST  HINDEX TRC    WUSE
   39   1569.   3944.   6051.   8427.  18422.  42597.  14495.    .46 167.   30.7
   83
```

The meaning of **VARP1 = 1.00** and **VARP2 = 1.00** indicate that the user used the default option **ENTER** or **RETURN**, meaning < **1** > in this case, to answer questions about multiplying the duration of vegetative and generative stage by something. As this was the option chosen the program used its default values for **A** and **B** (or an analogue option) contained in input file CROP41.DAT. Seeing this table the user cannot say if the model has been calibrated or not even if in this case that has not been done. Obviously climate data comes from Camagüey corresponding to the (mean) period 1961 – 90, the simulated crop was maize (corn) and emergence day for this crop was Julian Day 180 (June 29th).

The first column contains actual **Julian Days** (JD) after emergence in 10 days intervals while second column indicates days elapsed after crop emergence. The reader will notice that **JD 219** does not correspond to a ten-day interval. That is because **JD 219** actually is flowering (anthesis) day for the crop in this simulation. That can be inferred also looking at **column 7** (**DVS**) containing the development stage index because in that date the reported value is very near **1.00**.

He will also notice that last reported date (**JD 263**) does not correspond to a ten-day interval. In this case the user must go to column **DVS** to find there the value **2.00** indicating the crop reached maturity and can be harvested. That is so because in some cases simulation may have ended by other reasons such as "**no living leaves**" or other causes that ended the simulation before the crop reached maturity. This last case is most common with indeterminate growth habit crops as potatoes.

Columns **3 – 5** are easy to identify as:

WLV – Weight of leaving leaves (kg/ha DM)

WST – Weight of living stems (kg/ha DM)

WST – Weight of storage organs (kg/ha DM)

Columns **6 – 8** are also easy, representing,

LAI – Leaf Area Index (m ^{2} leaf/m ^{2} ground)

DVS – Development stage index (from 0 to 2)

RD – Root depth (cm)

The rest of columns represent:

T - Actual values for crop transpiration in cm/day

GASS – Gross assimilation (photosynthesis) in kg CH2O/ha - day

MRES – Maintenance respiration in kg CH2O/ha - day

DMI – Dry matter daily increase in kg DM/ha - day

TAGP – Total aboveground production (no roots included) until specified date in kg DM/ha

Finally, the potential yield simulation generates a **Summary of Results**. It is easily seen that the initial or final capital **T** means **Total** and that:

TWRT – Total DM weight of roots (kg/ha)

TWLV – Total DM weight of leaves (kg/ha)

TWST – Total DM weight of stems (kg/ha)

TWSO – Total DM weight of storage organs (kg/ha)

TAGP – Total DM aboveground production **(**kg/ha**)**

GASST – Total gross assimilation (kg/ha)

MREST – Total maintenance respiration (kg/ha)

HINDEX – Harvest Index (no dimensions)

TRC – Transpiration coefficient given as kg of transpired H20 per kg of produced DM (kg/kg)

WUSE – Total transpired water (cm)

It can be verified that **HINDEX = TWSO/ (TWLV + TWST + TWSO).**

Water limited yield simulations

The water limited yield output variables are somewhat harder to identify. Notwithstanding this, the user can easily recognize in the following tables that the simulated crop was maize (corn) and that the simulation was done for Camagüey with mean climate data corresponding to 1961 – 90, a loam soil and that crop emergence was on JD 180. At the extreme upper right it can be seen that daily rain values were derived from monthly data using a weather generator, that the fixed fraction of rain that did not infiltrate was chosen as zero by the user and that maximum allowable surface water storage was selected as zero.

Root depth was limited by soil (as given by user) to 40 cm and that was the actual root depth reached by crop plants in the experiment. No groundwater was available to the crop and initial available soil water was equal to 10.0 cm. But it may be somewhat harder to identify the following terms:

SM0 – Volumetric soil moisture content at saturation (cm^3 H2O/cm^3 soil)

SMFC – Volumetric soil moisture content at field capacity (cm^3 H2O/cm^3 soil)

SMW – Volumetric soil moisture content at wilting point (cm^3 H2O/cm^3 soil)

WAW – Available water (water content at field capacity minus water content at wilting point) in cm

It is very important to note that the output file is telling us that these are results corresponding to the first year of the simulation. Reading to the end of this subsection the user is reminded that he threw the dice four times and that, for the model, is equivalent to having run four different years with a different distribution of rainy days and amount of rain corresponding to each one of them.

At the top of the columns of the table there are abbreviations of variable names. Many of them have already been explained, but it is now necessary to add the following:

RAIN – Accumulated rain value from emergence to specified date (cm).

EVAP – Evaporated water from soil plus water surface on corresponding date (cm/day)

SM – Volumetric soil moisture at specified date (cm^3 H2O/cm^3 soil)

SS – Surface storage of water (cm)

W + WLOW – amount of water in root zone plus water below root zone, but in the rootable zone (cm)

Below is a SUMMARY in which a water balance of the whole system and the root zone is presented. The reader should be able to write down the water balances equations solved and used to check the law of conservation of mass, in this case, applied to water.

```
1WATER LIMITED CROP PRODUCTION, Year    1                              Start day 180
 ============================                                        monthly raindata
  CAMAGUEY 1961-1990            Maize                                 fixed fraction
 Loam (B8 + O9)                    RDMso= 40.    no groundwater      NOTinf= .00
   SM0= .401 SMFC= .287 SMW= .099    RDM= 40.       WAV= 10.0         SSmax=  .0

 DAY  ID   WLV    WST    WSO    LAI   RD    RAIN     T  EVAP    SM     SS W+WLOW
 180   0    7.     5.     0.    .03   10.     .0   .00   .37   .287    .0  11.5
 190  10   47.    30.     0.    .15   22.   11.2   .03   .29   .238    .0  10.4
 200  20  580.   359.     0.   1.60   34.   12.5   .27   .12   .189    .0   8.1
 210  30 1464.  1313.     0.   3.59   40.   12.8   .16   .03   .128    .0   5.1
 219  39 1290.  1541.     6.   3.02   40.   13.2   .05   .03   .109    .0   4.4
 220  40 1257.  1541.     6.   2.93   40.   13.3   .06   .03   .111    .0   4.4
 230  50 1158.  1988.   712.   2.59   40.   16.7   .19   .05   .140    .0   5.6
 240  60 1113.  2103.  2920.   2.48   40.   26.6   .32   .12   .301    .0  12.0
 250  70 1069.  1753.  4855.   2.37   40.   33.2   .29   .12   .291    .0  11.6
 260  80  668.  1432.  5922.   1.40   40.   39.6   .20   .17   .286    .0  11.4
 263  83  364.  1348.  5922.    .71   40.   41.8   .11   .22   .283    .0  11.3

 SUMMARY :
 DAYS   TWRT    TWLV    TWST    TWSO    TAGP   GASST   MREST  HINDEX TRC   WUSE
   39    780.   1767.   2103.   5922.   9792.  20886.   6104.    .60 152.  14.9
   83

                WATER BALANCE WHOLE SYSTEM
            irrigation    .0     evap. water surface    .0
              rainfall  41.8      evap. soil surface  11.5
 final minus initial:                   transpiration  14.9
      -surface storage    .0           surface runoff   5.5
    -water in root zone   8.5       lost to deep soil 10.1  checksum:  .0
  -water in lower zone   -8.6

                  WATER BALANCE ROOT ZONE
 initial water content   2.9     final water content  11.3
          infiltration   36.3      evap. soil surface  11.5
  added by root growth   8.6            transpiration  14.9
                                          percolation   10.1  checksum:  .0

1WATER LIMITED CROP PRODUCTION, Year    2                              Start day 180
 ============================                                        monthly raindata
  CAMAGUEY 1961-1990            Maize                                 fixed fraction
 Loam (B8 + O9)                    RDMso= 40.    no groundwater      NOTinf= .00
   SM0= .401 SMFC= .287 SMW= .099    RDM= 40.       WAV= 10.0         SSmax=  .0

 DAY  ID   WLV    WST    WSO    LAI   RD    RAIN     T  EVAP    SM     SS W+WLOW
 180   0    7.     5.     0.    .03   10.     .0   .00   .37   .287    .0  11.5
 190  10  112.    69.     0.    .36   22.    1.2   .08   .22   .200    .0   9.6
 200  20 1041.   641.     0.   2.89   34.    5.0   .38   .08   .233    .0   9.6
 210  30 2624.  2300.     0.   6.51   40.   12.0   .49   .02   .287    .0  11.5
 219  39 3275.  4348.   138.   7.41   40.   14.8   .50   .01   .243    .0   9.7
 220  40 3302.  4541.   221.   7.41   40.   14.9   .49   .01   .232    .0   9.3
 230  50 3243.  5805.  1800.   6.91   40.   16.5   .34   .00   .152    .0   6.1
 240  60 3012.  5965.  4186.   6.30   40.   20.5   .28   .00   .143    .0   5.7
 250  70 2776.  4973.  5656.   5.70   40.   32.8   .41   .02   .272    .0  10.9
 260  80 2205.  4064.  6642.   4.32   40.   40.8   .36   .04   .262    .0  10.5
 263  83 1711.  3825.  6650.   3.19   40.   42.7   .32   .07   .277    .0  11.1

 SUMMARY :
 DAYS   TWRT    TWLV    TWST    TWSO    TAGP   GASST   MREST  HINDEX TRC   WUSE
   39   1566.   3931.   5965.   6650.  16546.  38889.  13401.    .40 170.  28.1
   83

                WATER BALANCE WHOLE SYSTEM
            irrigation    .0     evap. water surface    .0
              rainfall  42.7      evap. soil surface   6.1
 final minus initial:                   transpiration  28.1
      -surface storage    .0           surface runoff   1.3
    -water in root zone   8.2       lost to deep soil   7.7  checksum:  .0
  -water in lower zone  -8.6

                  WATER BALANCE ROOT ZONE
 initial water content   2.9     final water content  11.1
```

```
        infiltration  41.4      evap. soil surface   6.1
 added by root growth   8.6           transpiration  28.1
                                        percolation   7.7  checksum:  .0
```

```
1WATER LIMITED CROP PRODUCTION, Year    3                           Start day 180
 ============================                                   monthly raindata
  CAMAGUEY 1961-1990          Maize                               fixed fraction
 Loam (B8 + O9)                     RDMso= 40.    no groundwater      NOTinf= .00
   SM0= .401 SMFC= .287 SMW= .099    RDM= 40.       WAV= 10.0         SSmax=  .0
```

DAY	ID	WLV	WST	WSO	LAI	RD	RAIN	T	EVAP	SM	SS	W+WLOW
180	0	7.	5.	0.	.03	10.	.0	.00	.37	.287	.0	11.5
190	10	107.	66.	0.	.34	22.	2.0	.07	.25	.222	.0	10.1
200	20	835.	525.	0.	2.33	34.	8.3	.34	.13	.273	.0	11.0
210	30	2390.	2146.	0.	5.90	40.	9.7	.48	.02	.190	.0	7.6
219	39	2690.	3309.	27.	6.18	40.	11.3	.36	.01	.155	.0	6.2
220	40	2715.	3444.	85.	6.19	40.	11.3	.30	.01	.145	.0	5.8
230	50	2412.	3877.	579.	5.25	40.	12.7	.13	.01	.120	.0	4.8
240	60	2176.	3933.	2242.	4.65	40.	18.3	.42	.03	.186	.0	7.4
250	70	2116.	3279.	4697.	4.50	40.	29.8	.18	.05	.328	.0	13.1
260	80	1649.	2679.	6119.	3.37	40.	34.4	.33	.07	.286	.0	11.4
263	83	1167.	2521.	6143.	2.28	40.	36.1	.27	.12	.299	.0	11.9

SUMMARY :

DAYS	TWRT	TWLV	TWST	TWSO	TAGP	GASST	MREST	HINDEX	TRC	WUSE
39 83	1345.	3139.	3933.	6143.	13214.	31039.	10609.	.46	170.	22.5

```
               WATER BALANCE WHOLE SYSTEM
           irrigation    .0     evap. water surface    .0
             rainfall  36.1      evap. soil surface   7.3
 final minus initial:                 transpiration  22.5
     -surface storage    .0          surface runoff    .0
   -water in root zone   9.1       lost to deep soil   5.8  checksum:  .0
  -water in lower zone  -8.6

                 WATER BALANCE ROOT ZONE
 initial water content   2.9     final water content  11.9
         infiltration  36.1      evap. soil surface   7.3
  added by root growth   8.6           transpiration  22.5
                                         percolation   5.8  checksum:  .0
```

```
1WATER LIMITED CROP PRODUCTION, Year    4                           Start day 180
 ============================                                   monthly raindata
  CAMAGUEY 1961-1990          Maize                               fixed fraction
 Loam (B8 + O9)                     RDMso= 40.    no groundwater      NOTinf= .00
   SM0= .401 SMFC= .287 SMW= .099    RDM= 40.       WAV= 10.0         SSmax=  .0
```

DAY	ID	WLV	WST	WSO	LAI	RD	RAIN	T	EVAP	SM	SS	W+WLOW
180	0	7.	5.	0.	.03	10.	.0	.00	.37	.287	.0	11.5
190	10	112.	69.	0.	.36	22.	.2	.07	.18	.169	.0	8.9
200	20	802.	501.	0.	2.23	34.	1.4	.27	.07	.160	.0	7.2
210	30	1759.	1583.	0.	4.35	40.	3.2	.23	.02	.138	.0	5.5
219	39	1599.	1910.	0.	3.74	40.	3.2	.04	.02	.107	.0	4.3
220	40	1556.	1910.	0.	3.63	40.	3.2	.03	.02	.105	.0	4.2
230	50	1422.	2405.	938.	3.20	40.	9.4	.38	.06	.197	.0	7.9
240	60	1415.	2600.	3707.	3.18	40.	11.8	.28	.04	.153	.0	6.1
250	70	1328.	2168.	5595.	2.96	40.	24.4	.23	.10	.316	.0	12.7
260	80	898.	1771.	6994.	1.90	40.	25.0	.24	.10	.214	.0	8.6
263	83	486.	1667.	6994.	.96	40.	25.0	.15	.13	.192	.0	7.7

SUMMARY :

DAYS	TWRT	TWLV	TWST	TWSO	TAGP	GASST	MREST	HINDEX	TRC	WUSE
39 83	974.	2122.	2600.	6994.	11716.	25189.	7436.	.60	154.	18.1

```
               WATER BALANCE WHOLE SYSTEM
           irrigation    .0     evap. water surface    .0
             rainfall  25.0      evap. soil surface   7.3
 final minus initial:                 transpiration  18.1
     -surface storage    .0          surface runoff    .0
   -water in root zone   4.8       lost to deep soil   3.5  checksum:  .0
  -water in lower zone  -8.6

                 WATER BALANCE ROOT ZONE
 initial water content   2.9     final water content   7.7
         infiltration  25.0      evap. soil surface   7.3
  added by root growth   8.6           transpiration  18.1
                                         percolation   3.5  checksum:  .0
```

Nutrient limited yield simulation

The last section of WOFOST.OUT gives us a final SUMMARY of results including nutrient limited crop production. This last information appears here as output. In the upper right part of this table the values of Nbase, Pbase and Kbase for this case in WOFOST as well as the default values for the recovery fractions of N, P and K can be accessed. The reader should know that the Nbase, Pbase and Kbase values that were entered in the corresponding program questions were taken by it as corresponding to some "standard crop" with a 120 days growth cycle. As in this case the crop reached maturity at day 83 after emergence, those entered values were multiplied by 83/120 before being printed in WOFOST.OUT.

In the first column the first three rows give us results for plant organs (no roots included). In the fourth row is introduced an important and useful parameter first mentioned in this workbook. That is the Storage organ/straw Ratio, a sort of analogue of the Harvest Index especially useful for cereals. The Harvest Index itself comes below. The interpretation of the next three rows is not so direct.

Fertilizer N is the amount of nitrogen that should be applied to the soil, with chosen recovery fraction, to obtain the given potential and water limited yields. This same concept applies to **Fertilizer P** and **Fertilizer K**.

If the user does not apply this amount of N, P and K fertilizers, introducing corresponding values in questions about Nbase, Pbase and Kbase made by the program in the Third Interactive Mode, the only attainable yield for this case will be that one reported in the second central column. That is why there are no values for these fertilizers in this column, the only available N, P, K nutrients for the crop were those specified in Nbase, Pbase and Kbase.

Observe that the reported water limited yield corresponds not to a particular year, but to the mean of the four years that the weather generator was used. It may also be seen that mean Harvest Index for the water limited yields was higher than the potential yield one. This is interpreted as meaning that some water stress at some phenological stages could be beneficial for some crops and may lead to the confusing fact that sometimes simulated water limited yields can be higher than potential ones. That possibility was not included in the original definition of potential yields.

As water limited yields in this table are mean values, no measure of dispersion is given by the model and that must be done by the user if he wants to assess the risk of obtaining a very low water limited yield. To do that he should take each particular yield at the end of each run made by the weather generator. These particular yields are reported in the screen at the end of each run, but are not written on disk. In using the written file on disk the user should take, in most crops but not in sugarcane where **TWST** values should be used. The value **TWSO** should be used for final dry matter yield and make an independent statistical analysis of results.

For the case shown here it can be shown that:

Mean value of water limited yields: 6427.25 kg DM / ha
Standard deviation of water limited yields: 485.42 kg DM / ha
Maximum expected water limited yield: 6994 kg DM / ha
Minimum expected water limited yield: 5922 kg DM / ha

The number of simulations needed to obtain stable mean values that can be used as approximation of the population values cannot be specified "a priori". It will depend on crop and environmental conditions during the growth cycle. In some cases it could be in the range 50 – 100 years.

1SUMMARY CROP PRODUCTION AND NUTRIENT REQUIREMENTS Nbas= 36. Pbas= 43. Kbas= 29.
== Nrec= .50 Prec= .10 Krec= .50

	Potential Crop production	Nutrient limited Crop production	Water limited Crop production
Leaves	3944.	1096.	2740.
Stems	6051.	1682.	3650.
Storage organ	8427.	2088.	6427.
Ratio SO/straw	.84	.75	1.14
Harvest index	.46	.43	.52
Fertilizer N	358.1	-	235.6
Fertilizer P	124.1	-	.0
Fertilizer K	259.5	-	153.4

1

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APPENDIX C

CARIBBEAN REGIONAL TRAINING WORKSHOP ON

BIOPHYSICAL MODELS AND CLIMATE CHANGE IMPACT ASSESSMENT ON AGRICULTURE

April 14th – 25th, 2008

WORKSHOP PROGRAMME

Day 1

Morning Session: 8:00 - 12:00:

1. Opening
2. Presentation of the workshop and objectives to be attained
3. General outlook of assessments procedures in agriculture and forests, including livestock
4. Climate change scenarios. Recommended procedures
5. The use of climatic and bioclimatic indexes
6. Simulation models

Afternoon Session: 13:00 - 17:00

1. Preliminary climate change scenarios for the region
2. The radiation and energy balances
3. The simple water balance equation
4. Discussion

Day 2

Morning Session: 8:00 - 12:00

1. Preliminary assessment of water resources in the region
2. Representative climatic and bioclimatic indexes in actual climate
3. Representative future climatic and bioclimatic indexes
4. Terrestrial Ecosystems Impact Model. Preliminary results

Afternoon Session: 13:00 - 17:00

1. Practical exercises
2. Presentations by participants

Day 3

Morning Session: 8:00 - 12:00

1. Agriculture: The meaning of potential and water limited yields
2. Discussion of main physiological processes simulated in biophysical models for the estimation of potential yield
    - Growth and development. Phenological processes. Duration of phenological stages and its dependence of daylength and temperature.
    - Gross photosynthesis. Photosynthesis intensity and its relationship with photosynthetic pathway of crops (C_3 and C_4), available photosynthetic radiation intensity, temperature and atmospheric CO_2 concentration.
    - Respiration rate. Its relationship with type of crop, temperature and phenological stage.
    - Biomass balance equation. Net photosynthesis.
    - Distribution of daily new generated biomass among different plant organs. Its relationship with phenological stage. Harvest Index. Logistic equations.

Afternoon Session: 13:00 - 17:00

1. FAO Agro-ecological Zones Model
2. Theoretical basis of the model. Accompanying Tables
3. Practical model exercises

Day 4

Morning Session: 8:00 - 12:00

1. Water availability in soils and its relationships with irrigated and rain-fed crop yields
2. Potential and actual evapotranspiration. Estimation methods
3. Soil water balance. Calculation procedures
4. Calculation of irrigated and rain-fed yields
    - Method of Doorenbos y Kassam (FAO)
    - Other available methods

Afternoon Session: 13:00 - 17:00

1. Calculation of potential evapotranspiration
    - Temperature based and other simple methods
    - Modified Penman method (FAO)
    - Penman-Monteith method
2. Estimation of terms in the water balance equation
    - Thornthwaite – Mather method
    - Budyko-Sellers method
    - Other methods
3. Practical exercises in the estimation of irrigated and rain-fed yields

Day 5

Morning Session: 8:00 - 12:00

1. Discussion of yesterday sessions
2. Theoretical basis and structure of the WOFOST dynamical crop model (both versions). General description of files.
3. Preparation of climatic data needed for running WOFOST model. CLIM41 data file.
4. Crop specific data used by WOFOST model. CROP41 data file
5. Soil hydro-physical parameters. SOIL41 data file
6. Calculation of crop potential yields
7. Calculation of crop water limited yields with or without groundwater. REALRD data file for daily precipitation data and for taking into account irrigation procedures
8. Crop yields limited by nutrients availability

Afternoon Session: 13:00 - 17:00

1. Introduction to the use of the model: WOFOST 4.1 and WOFOST 7.1.2
2. Practical exercises in calculation of crop potential yields
3. Practical exercises in calculation of water limited yields
4. Practical exercises in calculation of crop yields limited by nutrient availability
5. Adaptation of climate, crops and soil data files for sites, cultivars and soils not included by default in the original version of the model

Day 6

Morning Session: 8:00 - 12:00

1. Presentation and general discussion of the Decision Support System for Agro-technology Transfer (DSSAT)
2. Crops models included in different versions of the DSSAT system. Their evolution through time
3. DSSAT User's Manual

Afternoon Session: 13:00 - 17:00

1. Presentation of the DSSAT system. External management of the system
2. Experimental simulation for crops and models included in the system
3. Interpretation of results and output files
4. Practical exercises

Day 7

Morning Session: 8:00 - 12:00

1. Discussion of yesterday sessions
2. Creation of agricultural experiments to be used in simulations with the DSSAT system
3. Creation of meteorological data files for DSSAT system
4. Seasonal and sequential options to be used with experimental data files

Afternoon Session: 13:00 - 17:00

1. Practical exercises in the creation of meteorological data files for sites not included by default
2. Practical exercise in experiment design
3. Analysis of outputs and discussion of results obtained by workshop participants

<u>Day 8</u>

1. Vulnerability of livestock
2. Pastures and supplementary feeding
3. Bioclimatic indexes. The THI index
4. Expected impact of THI index on livestock

Afternoon Session: 13:00 - 17:00

1. Practical exercises in supplementary feeding assessment in future climate conditions
2. Practical exercises in expected THI behaviour during the 21st century

<u>Day 9</u>

Morning Session: 8:00 - 12:00

1. Integrated water resources/agriculture impact assessments
2. The MIIA 2.0 model
3. Practical examples calculations

Afternoon Session: 13:00 - 17:00

Workshop conclusion

WORKBOOK OF CLIMATE CHANGE IMPACT ASSESSMENT IN AGRICULTURE

BASIC KNOWLEDGE, METHODOLOGIES AND TOOLS

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