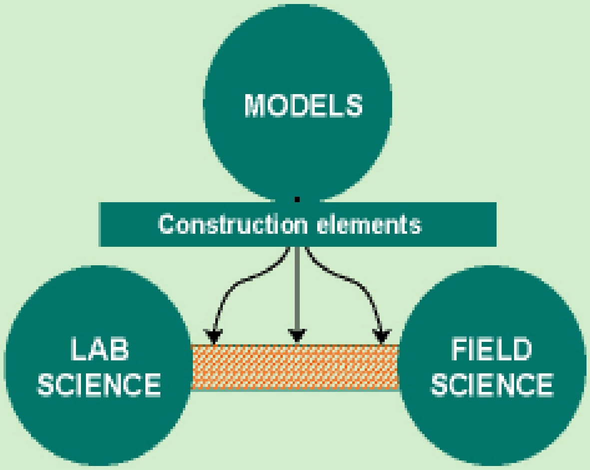
Basics of Crop Modelling



Moin Us Salam

Agro-Meteorological Information
Systems Development Project
Department of Agricultural Extension (DAE)
Khamarbari, Farmgate, Dhaka 1215
Bangladesh

THE WORLD BANK

May 2019

Basics of Crop Modelling

Moin Us Salam

A training manual prepared for
Agro-Meteorological Information Systems
Development Project (Component “C”: Bangladesh
Weather and Climate Services Regional Project)

Department of Agricultural Extension (DAE)
Khamarbari, Farmgate, Dhaka 1215
Bangladesh

May 2019

First edition 2019

Published by
Agro-Meteorological Information Systems Development Project
(Component “C”: Bangladesh Weather and Climate Services
Regional Project), Department of Agricultural Extension (DAE)
Khamarbari, Farmgate, Dhaka-1215, Bangladesh

Correct citation
M. U. Salam. 2019. Basics of Crop Modelling. Agro-Meteorological Information Systems Development Project. Department of Agricultural Extension (DAE), Khamarbari, Farmgate, Dhaka-1215, Bangladesh.

Printed by
College Gate Binding & Printing
1/7, College gate, Mohammadpur,
Dhaka 1207, Bangladesh

Author’ note

‘Basics of Crop Modelling’ was developed as a training material for the selected scientists of Bangladesh Agricultural Research Institute (BARI), Bangladesh Rice Research Institute (BRRI), Bangladesh Jute Research Institute (BJRI), Bangladesh Sugarcrop Research Institute (BSRI) and Department of Agricultural Extension (DAE). This training, a part of the Agro-Meteorological Information Systems Development Project of DAE, was conducted at BRRI Headquarters at Gazipur, Bangladesh, in three phases during January through May 2019; each phase comprised of four full days. It covered understanding and applying modelling techniques to five crops – ‘Aus’ rice, Jute, Maize, Potato and Sugarcane.

The Author gratefully acknowledges the help and cooperation of Dr. Mazharul Aziz, Project Director, and Mr. Sabuj Roy, Technical Officer, of the Agro-Meteorological Information Systems Development Project of DAE in conducting the training. Thanks to Mohammad Abu Sayeed for assisting in compilation of the book.

The materials compiled in this book derived mostly from the author’s PhD thesis entitled “A Systems Approach to the Study of Potential Production of *Boro* Rice in the *Haor* Region of Bangladesh” (University of Reading, 1992).

Moin Us Salam
Freelance International Consultant
(Agricultural Systems)

Contents

Contents (continued)

1. WHAT IS CROP MODELLING?

Crop modelling is the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers, is a technology used to construct a relatively transparent surrogate (or substitute) for a real crop, one that can be analyzed and manipulated with far greater ease than the complex and cumbersome original. Crop modelling is analogous to biological life cycles (Sinclair and Seligman, 1996). This discipline is based on systems approach.

2. WHY A SYSTEMS APPROACH

The conventional method of tackling problems related to crop production is to carry out the field experimentation. This approach has several drawbacks:

i. To draw a resilience conclusion, long term experimentation is necessary which is time consuming and costly (Dent and Blackie, 1979);
ii. It can only explain the response to the specific treatment levels used, extrapolation cannot be fully justified and may lead to mistaken conclusions (Biscoe and Willington, 1985);
iii. Weather also influences the process, complicating interpretation of the responses and often make it almost impossible to determine the precise effect of the treatment (Patterson et al., 1977).

The general approach in real life experimentation is to study the components of the whole process separately. The questions about the performance of the whole system cannot be answered (Baker and Curry, 1976). It must be studied holistically, the items must be treated as a whole.

The nature of the problem encountered in many field studies cannot be properly dealt with by conventional physical experiments. Weather variables are an essential consideration in management decisions (Fischer, 1985) and in such situations the systems approach seems to be the most appropriate method of study. This is not only a quick way to solve the problem but it considers the whole production process and can show how the management decisions interact with one another and how performance can be manipulated through these variables. It has been established now that the systems approach is an efficient technique of the studying the agricultural environments (Spedding, 1975a; Baker and Curry, 1976; Dent and Blackie, 1979; Conway, 1985). Such an approach can provide very good guidance for tackling problems we face in crop management (Stapper et al., 1983; Fischer, 1985; Penning de Vries, 1990).

Spedding (1975a) defines the approach as the study of how component parts of a system interact and contribute to behavior of the whole system. The interlinks between the components cannot easily be seen or touched in biological systems; but their existence has attracted scientists (Brockington, 1979). Since 1960s, there has been tremendous growth of interest in this discipline (Day, 1985). The approach permitting integration of the valuable information generated from isolated experiments related to the physical, physiological and chemical properties of the plants and thereby the whole production system can be studied in the holistic way. Therefore, a system approach seems to be an appropriate way to analyze the crop production systems.

3. SYSTEM, MODEL AND SIMULATION

The approach of systems analysis can be characterized by the terms systems, models and simulation (Rabbinge and de Wit, 1989). These have been briefly explained below.

3.1 System

A system has been defined and explained by a number of authors (Spedding, 1975a; Baker and Curry, 1976; Brockington, 1979; Dent and Blackie, 1979; Jones et al., 1987). Conway (1985) defines a system as 'an assemblage of elements contained within a boundary such that the elements within the boundary have strong functional relation with each other, but limited, week or non-existent relationships with elements in the other assemblages; the combined outcome of the strong functional relationships within the boundary is to produce a distinctive behavior of the assemblage such that it tends to respond to stimuli as a whole, even if the stimulus is only applied to one part'. The definition itself is self-explanatory. The essential conditions in designing a system have been given by Spedding (1975a; 1975b). In the system structure, a boundary is drawn although in reality it does not occur (Dent and Blackie, 1979). Within the boundary the components, as the crop systems, photosynthesis, translocation and respiration exist and interact with each other. The system is run by inputs - both controllable (management decisions) and uncontrollable (weather variables such as temperature and radiation) which produce output, e.g. the grain yield.

3.2 Model

In the systems approach, the system under study is represented by some forms; the representation is termed a model. So, models are imitations (Moorby, 1985) or analogues (Bell, 1987) of the real system while the process of developing the representation is called modeling (Jones et al., 1987). Reality is always simplified in a model, partly because our understanding of basic process is limited, partly because this enables us to handle the model (van Keulen et al., 1975).

Models are basically of two types - physical or iconic (Churchman, 1971) models, and symbolic or conceptual (Churchman, 1971; Brockington,

1979) models. There are symbolic models of different kinds but mathematical models are generally used in agriculture (Brockington, 1979). These models may be empirical or mechanistic. Empirical models are also be termed as input-out or block-box model where they produce output only without referring to underlying physical or biological structure between the variables (Chanter, 1981), e.g. statistical models. On the other hand, mechanistic or explanatory or white-box models (Brockington, 1979) explicitly represent causality between variables. Mechanistic models are the interest in the systems approach. These models may be divided into two types – simulation type and optimization type. Optimization type is used to get best or optimal solution to a practical problem in the system whereas the general behavior of the system is studied by simulation (Brockington, 1979).

3.3 Simulation

Simulation means that the model acts like the real system, for example, a real crop by gradually growing roots, stems, etc., during the season. It does not just predict some final state such as biomass or yield (Whisler et al., 1986). A formal mathematical statement of assumptions is made in simulation about the cropping system being studied (Charles-Edwards and Vanderlip, 1985) which represents the behavior of the system (van Keulen et al., 1975). Finally experimentation is conducted using the model to obtain approximate solutions (Stern, 1975) in a way that represents the behavior of the real system under different circumstances (Charles-Edwards, 1982). Simulation models are dynamics in nature, i.e. predicting changes in crop status with time. A deterministic model makes definite predictions for quantities such as crop yield, without any associated probability distribution while stochastic models contain some explicitly random elements which allow study of variance (France and Thornley, 1984).

4. HIERARCHY

Model building must be consider the level of detail at which the model should be considered (Whisler et al., 1986). Jones and his associates (1987) state that the fundamental goals and objectives of a model should guide one to determine the hierarchical level to use. Conway (1985) has listed the hierarchy of natural systems as: organism – population – community – ecosystem – biome - biosphere. Eight levels of hierarchy for production systems have been specified by Whisler et al. (1986). The levels range from molecule to biome and the time frame is considered from seconds to years according to the level. Peart and Barrett (1979) indicate that models in agriculture are based on 7 levels: world – region - farming areas - crop ecosystems (corn, pasture etc) - elements (individual plants) - components (leaves, roots, stems etc) - micro-components (stomata, biochemical pathways etc). Of these, the first three levels are considered as management oriented and the rest as research oriented.

The crop production level has further been stratified into four levels by Prof. C.T. de Wit as listed by Penning de Vries, 1982). A brief summery has been given below.

> Production level I: Ample water and nutrients; growth rate depends only on the current state of the crop and on current weather, particularly radiation and temperature.
>
> Production level II: Growth rate is limited only by the availability of water, for at least part of the growing season.
>
> Production level III: Growth rate is restricted by N shortage for at least part of the growing season and by water shortage.
>
> Production level IV: Growth rate is restricted by P and others minerals.

In reality, crop production systems really fit into one of these levels. However, the simplification has been directed towards the dynamics of the major constraint and its relationship with crop production. Disease, pests, and weeds exert influence at any one of the levels causing further constraint to production (Penning de Vries et al, 1989).

5. PROCEDURE OF SIMULATION MODEL BUILDING

A number of well-defined and interlinked steps are followed in the building simulation models. Details of the steps have been thoroughly described by (Dent and Blackie, 1979) and (Jones et al., 1987). The procedures to follow in constructing a crop model is presented in Figure 1.

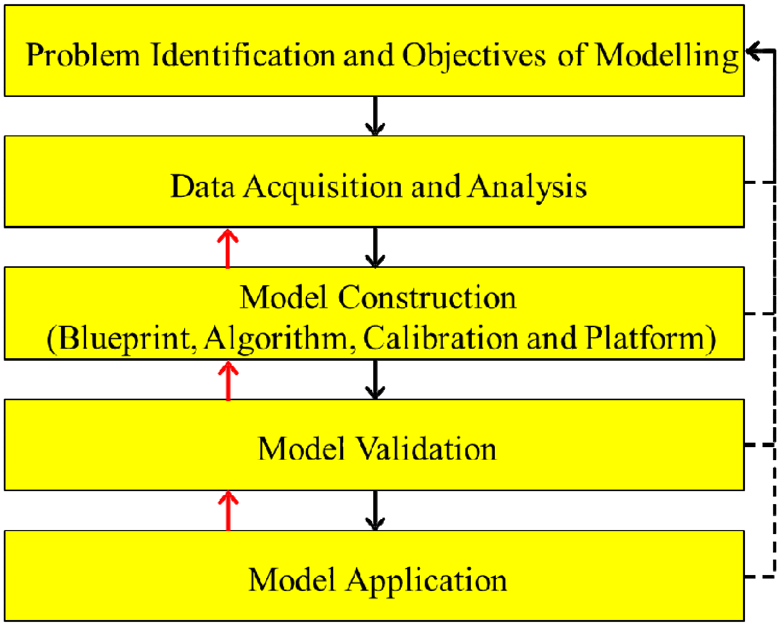


Figure 1. Steps in building a crop model

The steps as mentioned in the figure should not be viewed as strict sequential process. The steps are repeated in an interactive fashion as information is gained (Jones et al., 1987).

After the preliminary analyses the model is structured in diagrammatic form by symbolic representation (Figure 2); later it is converted into a flow diagram showing the components and their interactions. The interactions are then converted into mathematical statements. The statement of assumptions may be entirely empirical, based on observations of the field performances, or they may be based on an underlying, or knowledge of physiological mechanisms underlying crop growth and production (Charles-Edwards and Vanderlip, 1985). The model, thus considered, may not predict correct behavior of the crop growing in the field because the assumptions are wrong, or put together in the wrong way. Equally, it may predict the correct behavior fortuitously even though some of the assumptions are wrong because it is insensitive to them under these circumstances or because in-built errors cancel out (Charles-Edwards and Vanderlip, 1985). Thus one needs to shuffle between the steps and thus it makes the whole process tedious.

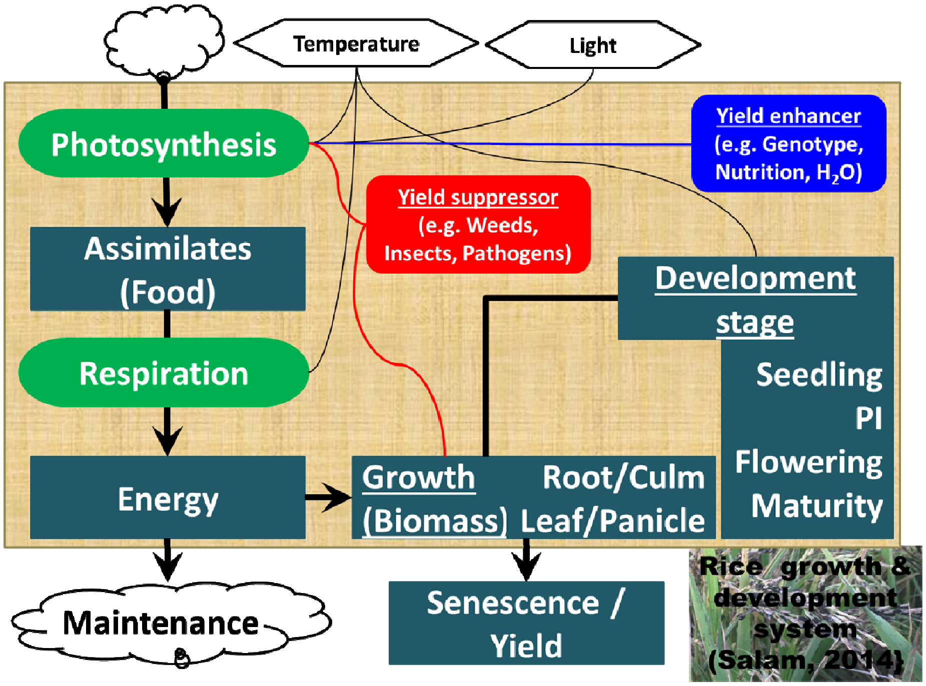


Figure 2. Relational diagram of a rice model.

In a dynamic simulation model, systems are approximated to first order difference equations and defined in terms of state variables (levels) and rate of change (Jones et al., 1987; Penning de Vries et al, 1989). The state variables include biomass in different plant parts whereas the photosynthesis rate is an example of a rate variable. The system is governed by inputs or forcing or driving variables like radiation and temperature, as in the present case; their variations are of course independent of the state of the system (Driessen, 1986). Constants and parameters, the characteristics of the components of the model, usually remain unaltered throughout the simulated time (Driessen, 1986; Jones et al., 1987).

6. MODELING GROWTH AND THE DEVELOPMENT PROCESS TAKING RICE AS AN EXAMPLE

There are two broad parts of the rice growing process, that which occurs in the nursery and that in the main paddy field. Principles involved regarding growth and developmental process in these two parts are almost same. This is why they have been described in general. However, special processes and /or consideration(s) necessary to model each of the parts are mentioned accordingly.

6.1 Photosynthesis

In agriculture, solar energy is conserved for future use via its fixation in biomass; the process is called photosynthesis (van Heemst, 1986a). Photosynthesis comprises a very complex processes by which plants reduce carbon dioxide (CO_2) using absorbed radiation energy in the presence of water (H_2O) and form organic molecules, conventionally represented by the molecule glucose or carbohydrate ($C_6H_{12}O_6$ or CH_2O). The process is also called CO_2 assimilation and hence the products are often termed assimilates (van Heemst, 1986a).

Photosynthesis or CO_2 assimilation can be calculated based on the procedure of Goudriaan and van Laar (1978). The biomechanical mechanism of CO_2 assimilation is not the same for all plants (Bidwell, 1983). Although a few exceptions have been reported (Hedge and Joshi, 1974), rice plants generally possess the C_3 type of photosynthetic pathway. Photorespiration, an intensive process in C_3 plants, is intimately coupled with photosynthesis itself (Penning de Vries et al. 1989). Photosynthesis is expressed in the calculation as gross photosynthesis of the leaf canopy (Goudriaan and van Laar, 1978). There are three important steps in the calculation of photosynthesis.

6.1.1 Light absorption by leaves

In the leaves, the photo synthetically active radiation (PAR) is absorbed by green chlorophyll and others pigments and is used for the reduction of $CO_{2.}$ PAR belongs to the visible radiation in the wavelength of 400-700 nm, representing about 50% of the total global radiation (Monteith, 1973). This is true for both tropical and temperate regions (Monteith, 1972). In the crop, 10% of the incoming radiation is reflected, 10 % is absorbed by the pigments not contributing to photosynthesis, 10% is transmitted through the leaves and the remaining 70% is absorbed by chloroplast (van Heemst, 1986a). So, the first layer of the leaves utilizes 70% of PAR and the second layer only 10% whereas the rest do substantially nothing. Thus PAR absorbed by the leaves is assumed to be 80% (Penning de Vries et al, 1989).

6.1.2 The initial light use efficiency

About 15 quanta of PAR is required by C_3 plants to reduce a single molecule of $CO_{2,}$ mainly due to light absobption by non-photosynthetic pigments, and photorespiration (Penning de Vries et al. 1989). This value can be translated into a measure of light efficiency use rate (EFFE) of 0.48 kg CO_2 per hectare of leaf surface and per hour J $m^{-2}s^{-1}$.

Yoshida (1981) indicates that the EFFE of rice is around 0.40. It may vary according to variety (McDonald, 1971).

A reference value of EFFE should be used in the model because the light use efficiency might be affect by temperature (McDonald, 1971). In fact, photorespiration increase with the rise of temperature (Penning de Vries et al., 1989). In case of rice, as with other C3 plants, EFFE is negatively related to temperature. Penning de Vries and his associates (1989) report that the value of EFFER is not affected when the temperature is 10°C or below, whereas the value becomes about 0.01 at 50°C. The relative effect of temperature on EFFER (EFFET) to be accounted for in the model.

Thus the EFFE for a day is calculated by:

EFFE=EFFER*EFFET

EFFE is initial light use efficiency expressed as kg CO_2 $ha^{-1}h^{-1}$ per J $m^{-2}s^{-1}$ of absorbed PAR

EFFER is the reference value of EFFE

EFFET is the relative factor on EFFER due to temperature variation

Environment factors others than the temperature have little effect on EFFE (Penning de Vries et al., 1989; Dingkuhn et al. (1990) reported that nitrogen management might affect the EFFE, which may be considered in the model.

6.1.3 Maximum rate of light photosynthesis

The value of the maximum rate of leaf photosynthesis (AMAX) at high light intensities and normal CO_2 concentration (340 ppm by volume) usually ranges from 25 to 80 kg CO_2 $ha^{-1}h^{-1}$ (Penning de Vries et al., 1989). Higher values apply to C_4 plants, the net assimilation rate usually varies from 15 to 50 kg CO_2 ha^{-1} h^{-1} (van Heemst, 1986a). For rice plants, leaf photosynthesis ranges from 40 to 50 kg CO_2 ha^{-1} h^{-1} (Yoshida, 1981). In the case of the modern varieties, Yoshida (1981) found that the leaf photosynthesis rate to be 47 kg CO_2 $ha^{-1}h^{-1}$ at 25°C. Temperature and leaf thickness are the most important factors of AMAX (Penning de Vries et al., 1989). The variation in AMAX within a species is due to the differences in the leaf thickness (Charles-Edwards, 1982).

6.1.4 Temperature effect on leaf photosynthesis

Horie (1979) reported net photosynthesis of rice varied by less than 10% for leaf temperatures between 20° and 35°C. Indicating similar views, Venkateswarlu et al. (1977) suggest that temperature may be considered as limiting factor for photosynthesis of rice in the tropics. When the temperature is low it restricts the growth more than limiting photosynthesis (Evans, 1975b). Cooper (1975) also indicated that for a wide range of temperature, the photosynthesis varies little. Considering these views, RICEMOD was built (McMennany and O'Toole, 1983) without considering any effect of temperature on photosynthesis.

The situation as reviewed above is not, however, a true picture of the tropics and sub-tropics as a whole. Even between cropping seasons within a year the situation varies widely. For example, for part of the 'Boro' rice growing season in Haor region the temperature drops below 20°C. Photosynthesis in such a situation may be limited, with the interference in chlorophyll synthesis, leaf development and the reaction rates of chemical reactions (Troughton, 1975). In extreme situations, temperature not only reduces photosynthesis, but the effect may prevail even when the temperature becomes favourable (Bauer et al., 1975; Fukai et al., 1976; Marcellos,1977; Legg, 1981); in some cases total destruction of plants has been reported (Larcher, 1973). At the temperature level of 15° to 19°C, the rice crop has been reported to suffer stress (Terao et al., 1941; Nishiyama et al., 1969; Kabaki et al., 1982; Wilson, 1984; Setter and Greenway, 1988), and in such situations the loss of photosynthetic capacity cannot be ignored (Kishitani and Tsunoda, 1974; Makino et al., 1984; Moll and Steinback, 1986).

6.1.5 Leaf-N content and photosynthesis

As has stated earlier, that thickness of the leaves has an effect on photosynthesis; the thickness-photosynthesis relationship, on the other hand, depends strongly on the nitrogen content of the leaves (Penning de Vries et al., 1989). The Leaf-N content falls with the aging of the crop, besides new leaves have less N content than older ones (Raymond et al., 1960; Greenwood et al., 1965; Thompson et al., 1976; Greenwood and Barnes, 1978). This causes a change in the value of AMAX (Takano and Tsunoda, 1971; Yoshida and Coronel, 1976). The relationship of the N-fraction of leaves and that of the maximum rate of leaf photosynthesis has been quantitatively presented by Penning de Vries et al. (1990). However, the estimation can be made by relating plant age (days) with that of the leaf-N content (Murata, 1975a; McMennamy and O'Toole, 1983). Penning de Vries et al. (1990) have presented typical leaf-N fraction curve of rice throughout its growth period under two situations: at high level of soil N, and at low level of soil N. A relationship is based on development stage (DVS) of the crop rather than simply age of the plant (day) can be more appropriate.

The relationship between leaf-N content and AMAX has been given by Dinguhn et al. (1990). The value of AMAXG, the maximum gross photosynthetic rate, can be taken as 66 kg CO_2 $ha^{-1}h^{-1}$ at a leaf-N content of 4. The AMAXG decreases almost linearly below the value 4, and increase slowly up to 6. Finally, AMAX can be obtained as a function of leaf-N, the AMAXN and then as a function of temperature, AMAXT.

AMAX=AMAXG*AMAXN

AMAX=AMAX*AMAXT

AMAX is the maximum rate of single leaf photosynthesis expressed as kg CO_2 $ha^{-1}h^{-1}$

AMAXG is gross AMAX at leaf-N content of 4 AMAXN is the relative effect of leaf-N on AMAXG.

AMAXT is the relative effect of temperature on AMAX at particular leaf-N level.

6.1.6 Canopy photosynthesis

Canopy photosynthesis is the sum of the rates of photosynthesis of all the leaves. If the photo synthetic rate was proportional to the light intensity and if all leaves had identical properties, then canopy photosynthesis would simply be equal to the multiple of the quantity of light absorbed and the light use efficiency (Penning de Vries et al., 1989). However, reality is complicated by the influence of direct and diffused light, total leaf area, leaf angle distribution, leaf optical properties and solar height on the distribution within the canopy, each of which have to be taken into account (van Heemst, 1986a). Models have been developed which make these complicated processes easy to tackle. Calculation of canopy photosynthesis can be made in the model according to the mechanisms developed by Goudriaan and van Laar (1978). Using this model, the assimilation rate of a canopy can be calculated at any moment of a day in response to the incoming PAR and depend on solar height and the degree of cloudiness of the sky. Two extreme situations are considered:

a) a completely clear day, and
b) a completely cloudy day.

The assumptions made in the calculation are:

a) the respiration (except the photorespiration) is zero, and
b) the leaf area index is 5, so that the canopy is practically closed.

The overall equation is:

FGC = FO*FOV+ (1-FO)*FCL

FGC is the gross CO_2 assimilation rate expressed as kg CO_2 $ha^{-1}h^{-1}$

FO is the fraction of a day which is overcast (FO is 0 for a completely clear day, and FO is 1 for completely overcast day)

FOV is the gross CO_2 assimilation rate (kg CO_2 $ha^{-1}h^{-1}$) on a completely overcast day.

FCL is the gross CO_2 assimilation rate (kg CO_2 $ha^{-1}h^{-1}$) on a completely clear day.

The fraction of the day the sky is overcast (FO) can be obtained from the actual daily global irradiation and the daily global irradiation of a completely clear day. The global irradiation of a completely overcast day may be calculated by multiplying the value for a perfect day by 0.2 (de Wit, 1965).

FO = (HG-HA)/(HG-0.2*HG)

FO is the fraction of a day is overcast

HG is the total global irradiation on a completely clear day expressed as J m^{-2} d^{-1}.

HA is the measured total global irradiation of a given location ($Jm^{-2}d^{-1}$).

The value of HG has been listed by Goudriaan and van Laar (1978) for different geographical locations. The values represent the middle day of each month. The measured actual global irradiation, HA, is not measured in all meteorological stations of Bangladesh. Berkhout and van Keulen (1986) state that in such a situation it is possible to estimate the value of HA by means of an empirical relation, using the measured duration of bright sunshine hours (Black et al., 1954). The relation is known as the Angstrom formula (Angstrom, 1924).

HA=RA*(A+(B*SUN(J)/N)

HA is the measured total global irradiation expressed as J m^{-2} d^{-1}.

RA is Angot's value or the theoretical amount of radiation that should reach the earth's surface in the absence of an atmosphere expressed as J m^{-2} d^{-1} (List, 1951)

SUN (J) is the actual duration of bright sunshine hours in the Jth day

N is the maximum possible length of a cloudiness' day expressed as hours

A and B are the empirical constants.

The values of RA and N have been listed by Berkhout and van Keulen (1986) for different geographical locations and have been extrapolated for the study area. Within the ranges of the values, it has been assumed that they would be same in between the periods. The numerical values of the constants A and B depend on latitude (Glover and McCulloch, 1958), and the climate (Rietveld, 1978). Black et al. (1954) show that the value of A equals 0.023 and that of B equals 0.048. They also report that B remains more or less constant whereas A shows marked variation. Explaining the reasons, Glover and McCulloch (1958) believe that A depend upon optical air mass, and hence the latitude of an area. In the range of O to 60^0 latitude, they established that B=0.052, and A=0.29*cos X, where X is the latitude of the area. The Food and Agricultural Organization, on the other hand, indicated the values of A and B under broad climatic regions.

Once the HA is calculated, the FO can be obtained. Finally, FOV and FCL are calculated (details are explained by Goudriaan and van Laar (1978), and thus the gross CO_2 assimilation rate (FGC) is obtained for a particular day. The absorbed CO_2 is reduced in the crop plants in the form of sugars.

So, the gross assimilate rate can be expressed as sugar (GASS) by multiplying FGC with the ratio of molecular weights of CH_2O and CO_2.

GASS=FGC*30/44

GASS is the rate of gross assimilation expressed as kg CH_2O ha^{-1} d^{-1}

FGC is the gross CO_2 assimilation rate expressed as kg CO_2 ha^{-1} d^{-1}

For low values of leaf area index (LAI) when the canopy does not form a closed surface, radiation is to the soil and thus photosynthesis is reduced (Goudriaan and van Laar, 1978). This reduction is estimated from the fraction of the incoming radiation intercepted by the crop.

RF=1-EXP(-K*LAI)

RF is the fraction of light intercepted by the crop

K is the extinction coefficient for visible light

LAI is the leaf area index

The K as stated by Chang (1968) is a measure of the space of diminution, or extinction of any transmitted light. According to the physics of light the extinction coefficient, K is the ratio of horizontally projected area of an object to its plane or surface area (Monteith, 1973); therefore, in the case of any crop plant it is the ratio of leaf area when it is projected on to a horizontal surface to the leaf surface area (Catrileo, 1990). Thus, the value of K is related to the leaf angle or orientation (Hayashi and Ito, 1962; Venkateswarlu and Visperas, 1987). Saeki (1960) as quoted by Chang (1968) indicates the value of K for a herbaceous community ranges between 0.3 to 0.5 in stands with upright leaves and between 0.7 to 1.0 in stands with horizontal leaves. For crop plants K usually ranges from 0.6 to 0.8. (Goudriaan, 1977). A list of K values for different crop species has been given by Monteith (1969). Norman (1980), referring to reports of scientists (Hayashi and Ito, 1962; Ito, 1969; Udagawa et al, 1974), find the value of K for rice is between

0.4 and 0.8. Horie (1987) used the value of 0.6 in his model (for *japonica rice*) on the basis of his early research (Horie and Sakuratani, 1985).

6.2 Leaf area development

The amount of incoming radiation that would be intercepted' is governed by the leaf density of the crop. The leaf area index (LAI), developed by Watson (1947), is the common way of charactering the leaf foliage density (Chang, 1968). The LAI is expressed as total surface of live leaves, one sides, per unit of soil surface (Penning de Vries et al., 1989). Generally, specific leaf weight (SLW) or specific leaf area (SLA) is considered in determining the LAI (van Keulen, 1986a; Jones and Boote, 1987). It may be mentioned that the LAI can alternatively be calculated independently of the weight of leaves especially when water and nutrients are not limiting. In such cases LAI is taken as function of daily mean temperature (details are given by Horie, 1987). The SLA is the ration between the area and weight of the leaf blades; the SLA is the inverse of SLS (Hesketh and Jones, 1980). The SLW is considered as the structural dry weight of leaves with no reserves; the petioles and leaf sheaths are not included. It is further assumed that all the leaf area is equally effective in [photosynthesis if exposed to the same conditions (Penning de Vries et al., 1989). The value of SLW is thought to vary little between species (van Keulen et al., 1982) and the range lie between 200 and 800 kg ha^{-1}, although the average for the entire canopy rarely exceeds 600 kg ha^{-1} (Penning de Vries et al., 1989). In the case of rice, Yoshida (1981) gives a range of 222 to 500 kg ha^{-1}. Working with a number of modern varieties, Vinaya Rai and Murty (1979) recorded SLW at maximum tillering stage ranging between 421 and 514 and averaging 455 kg ha^{-1}. Van Keulen (1986b) used the value of 400 kg ha^{-1} in his model in the case of the variety IR8. Murata (1975b) indicated variation of SLW between cultivars. The SLW, in fact, does not remain constant throughout the growth period of a crop. It may vary due to leaf thickness, leaf position, growth stage, nutrition, climatic environment (Murata, 1975b). Considering of all these factors makes the calculation of SLW complex. Therefore, McMennamy and O'Toole (1983), in RICEMOD, used a relationship which increased SLW with the advance of crop age in days. Thus the correlation in SLW(SLN) for a particular development stage can be made by:

SLN=SLC*CLT

SLN is the corrected SLW for a particular DVS

SLC is the specific leaf weight constant expressed as kg ha^{-1}

SLT is the relative effect on DVS on the SLC

The calculation of LAI then can simply be made by dividing the weight of the live leaves by the corrected SLW(SLN) (van Leulen et al., 1982; Jones and Boote, 1987).

LAI=WLV/SLN

LAI is the leaf area index

WLV is the dry weight of live leaves expressed as kg ha^{-1}

SLN is the corrected SLW for a particular DVS

Although non-leaf photosynthesis is although to have a minor role in gross photosynthesis, the contribution of stems to the total green area can be significant especially for small grains (Penning de Vries et al., 1989). The contribution of stem area can be taken into considering in LAI in the same way as that of the leaf area by using a 'specific culm weight constant' (SCC). The SCC value has been indicated for different crop species (Penning de Vries et al., 1989). According, the value of 1000 kg ha^{-1} used in the model. The SCC has been related to DVS due to lack of information. Only half of the stem area has been considered in the calculation because, unlike the leaf, only the upper surface of the stems are active (Penning de Vries et al., 1989). Therefore, final form of the computation of LAI can be:

LAI = (WLV/SLV) + (0.5*(WCU/SCC))

LAI is the leaf area index

WLV is the dry weight of live leaves expressed as kg ha^{-1}

SLN is the corrected SLW for a particular DVS

WCU is the dry weight culm expressed as kg ha^{-1}

SCC is the specific culm weight constant expressed as kg ha^{-1}

6.3 Respiration

Crop plants need energy to maintain cells and to carry out physiological activities. The energy is obtained from the assimilates produced during photosynthesis; the process is called respiration (van Heemst, 1986a). The energy obtained is utilized for two main processes: i) for maintenance of ionic gradients, and re-synthesis of degrading structural proteins; ii) conversion of primary photosynthetic products into structural plant materials. The process involved in the first case is called maintenance respiration, and in the second case is growth respiration.

6.3.1. Maintenance respiration

Maintenance can be considered at different levels of biological organization. In crop growth modeling, it is only considered at cellular levels (Penning de Vries et al., 1989). Three components of maintenance at cellular level are distinguished: maintenance for protein turnover, for the active transport process to maintain certain ion concentrations, and for metabolic activity (Penning de Vries, 1975b; van Heemst, 1986a; Penning de Vries et al., 1989). The proteins in the plant, especially leaves, consist mainly of enzymes, which have only a limited life span. They deteriorate at a relative rate of 0.10 d^{-1}. Energy that is required for turning over of the enzymes come from the maintenance respiration process. The ion concentration in the vacuoles of plant cells is higher than in the surrounding tissue; so it leakage of ions from the vacuoles. To maintain the desired internal concentration, the ions have to be taken up against a concentration gradient. That requires an active transport through the cell membranes which require energy. The biochemical basis of metabolic activity is not well understood. It is assumed that the maintenance cost here is equal to between 10 to 20% of daily photosynthesis (Penning de Vries et al., 1989). The physiological basis of crop maintenance respiration is rather weak (Yoshida, 1981; Spitters et at., 1989). So far it has been only partially quantified and this is why it is a weak part of modeling (Penning de Vries et al., 1989). In early work, scientist used to believe that, apart from temperature, respiration rate was proportional to leaf mass (de Wit et al., 1970; Evans, 1975a). However, later it was proved that maintenance respiration was related to the photosynthetic rate of the crop surface (McCree and Troughton, 1966). Later McCree (1970; 1974) quantified the rate of maintenance respiration as 0.015 kg $ha^{-1}d^{-1}$ of the photosynthesis. He used white clover as experimental crop. McCree's value is thought to be well established and has been used in modeling of a number of species (de Wit et al., 1970; Sheehy et al., 1979; Johnson and Thornley, 1983; Sarti, 1987; Catrileo, 1990). However, relative maintenance rate is likely to vary between species (Lake and Anderson, 1970). Penning de Vries (1972) showed that the value of 0.008 and 0.022 kg $ha^{-1}d^{-1}$ for maize and bean, respectively. Different value (0.026 kg $ha^{-1}d^{-1}$) was also reported for cotton seedlings (Hesketh et al., 1971). It was further revealed that respiration may not only differ for species but also between different plant parts, and for different stages of plant growth (Hesketh et al. 1971; IRRI, 1972; Yamaguchi, 1978). A list of maintenance respiration coefficients for a number of crops has been presented by Hesketh et al. (1980a). Penning de Vries and van Laar

(1982) proposed a quantitative description of maintenance as a function of dry weight depending on type of organ as follows:

$$MAIN=0.003*LEAF+0.015*STEM+0.01*ROOT+0.01*STORAGE$$

The coefficients were derived on the basis that leaves were the most active tissue and highest in protein, with stems being about half as active as leaves, and roots even less active. The maintenance cost of the storage organs is low (Norton, 1963). This is because the stored oil, starch or protein is presumed to be inactively turning over and thus not requiring high maintenance (Boote et al., 1987a). Spitters et al. (1989) suggest that carbohydrate in grain is metabolically inactive and does not require maintenance. So, the maintenance coefficient for storage organs should vary with the species concerned; for other plant parts variation is not significant (Sinclair and de Wit, 1975). Maintenance respiration can be calculated in models by a slightly different method than that proposed by Penning de Vries and van Laar (1982). The respiration rate of leaves can be taken as 0.02 kg CO_2 kg d^{-1}. During day time, the respiration of the leaves is reduced due to excess energy; this is why the fraction 0.75 can be used as a multiplier according to Penning de Vries et al. (1989). The respiration rates of culm and roots can be considered as 0.01 and 0.015 kg CO_2 kg d^{-1}, respectively. The respiration rate of storage organs can be taken as 0.015 kg CO_2 kg d^{-1} according to Penning de Vries et al. (1989). It has been stated that above 1000 kg ha^{-1} of storage dry matter, there is no maintenance cost (Penning de Vries et al., 1989). Therefore, this restriction can be made in the model. Apart from the consideration of different plant organs, the metabolic cost (RMMA)) can be accounted at 20% of the daily gross photosynthesis. The cost of the metabolic process during day time is thought to be reduced by 50% (Penning de Vries et al., 1989); this is why a factor of 0.5 can be used as a multiplier. Penning de Vries (1975b) stated that temperature influences the rate of protein turnover and thus it also influences maintenance respiration. The reference temperature (TR) at which the coefficients can be incorporated is 25°C. The maintenance respiration rate is reported to be doubled for each 10°C rise of temperature (McCRee, 1974; Kase and Catsky, 1984). Amthor (1984) reports lower or higher values. In the models the temperature factor (Q_{10}) can be taken as 2. The factor is increased or decreased in maintenance respiration (TFAC) can then be determined by the formula given by Spitters et al. (1989).

$TFAC= Q_{10}$ ^((TEMP-TR)/10)

TFAC is the relation of maintenance respiration to temperature.

Q_{10} is the factor accounting for increase in maintenance respiration with a 10°C rise in temperature

TEMP is the mean daily temperature in °C

TR is the reference temperature at which maintenance coefficients and considered.

Finally, total maintenance cost of the crop in a day (RMCR) can be calculated by adding the component parts and by multiplying it by 30/44 (the ratio of molecular weight of CH_2O and CO_2), to express the value as kg CH_2O $ha^{-1}d^{-1}$.

It has been argued that, for theoretical consideration, it is preferable to relate maintenance respiration to the protein or nitrogen content of the plant (Barnes and Hole, 1978) because the respiration reduces in vegetative parts as N concentration declines (Boote et al., 1987b). De Wit et al. (1978) in BACROS model show that if information on N and mineral contents are available, the maintenance cost can be estimated. Van Keulen and Seligman (1987) used this procedure in their model. However, this refinement can only be used when N concentrations are encountered in crop models that simulate nutrient uptake (Legg, 1981).

6.3.2 Growth respiration

Growth refers to the accumulation of mass or increase in size of a plant over time (Lowry, 1967). The process involve is the biochemical conversion of primary photosynthesis into dry matter (Yoshida, 1981; van Heemst, 1986a; Penning de Vries et al., 1989). Energy is required for the conversion process and also to translocate the assimilated from the source to the growth size. The energy demand is met by growth respiration. Growth respiration is also termed ‘conversion’ (Penning de Vries, 1972) or ‘constructive’ (Thornley, 1976) respiration.

The respiration cost for growth can be expressed as conversion efficiency. The total amount of maintenance cost (RMCR) is subtracted from the amount of gross carbohydrate assimilated (GASS) which gives the amount of dry matter available for (ASAG). The amount of growth is then determined from the ASAG considering the conversion efficiency.

Semikhatova (1970) indicated that the conversion efficiency of plants might be in between 60 to 80%. For white clover, McCree (1970) found an efficiency of 80%; later (1974) he corrected the value to 75%. For cereals in general and for oil seeds the ranges of conversion efficiency have been mentioned as 51to 78%, and 88 to 96%, respectively (Penning de Vries, 1972; 1975a), whereas for cotton it is 75% (Thornley and Hesketh, 1972) reports on grasses show that the conversion efficiency factor is about 0.75 (Johnson and Thornley, 1983). De Wit and his associates (1970) suggested that a better way of calculation the conversion efficiency was to consider the chemical composition of the end products. Yamaguchi (1978) showed that the conversion efficiency of proteins, lipids and carbohydrate were38, 31 and 84% respectively. Penning de Vries and his co-researchers (1974) related growth respiration with the chemical composition of new biomass. They considered six types tissues: carbohydrates (structural), proteins, lipids (including oils and fats), lignins, organic acids, and minerals. These group of tissues have different energy costs.

Once the composition of plants are known, the conversion efficiency can be worked out. The composition may gain vary for different plant organs and thus the conversion efficiency may vary accordingly. Using quantified information from literature, the amount of glucose required for converting assimilates into organs of leaf, culm, root and storage part can be determined as 1.326, 1.326, 1.326 and 1.462 kg kg^{-1} dry matter, or in other words, the inverse values provided the conversion efficiency. In this way, the overall conversion efficiency (CVF) can be calculated to determine the total crop rate (GTW).

GTW=ASAG*CVF

GTW is the total crop growth rate expressed as kg DM d^{-1}

ASAG is the total dry matter available for growth expressed as kg DM ha^{-1} d^{-1}

CVF is the overall conversion efficiency.

Although Robson (1980) indicates that there is a genetic variation in efficiency of respiration, the procedure applied above could well be applicable to all species (Penning de Vries et al., 1974) because the efficiency processes in higher plants are the same for all species (Penning de Vries, 1975a). Conversion efficiency is independent of temperature (McCree, 1974). Experimental evidences show that within the range of 11 to 38^0C there were no variations in growth respiration (Penning de Vries, 1972). Similar reports were found for the rice crop (Tang et al., 1959; Tanaka, 1971). In fact in higher in higher temperature, the conversion process is accelerated, but pathways are identical. Hence, assimilate requirements do not vary with temperature (Spitters et al., 1989). Therefore, no consideration of temperature is needed in calculating the conversion efficiency.

6.3.3 Carbohydrate remobilization

The carbohydrate used for maintenance and growth come from photosynthesis. However, there is another source of carbohydrate which comes from mobilization or redistribution (Penning de Vries at el., 1989). In rice, the growth of vegetative organs more or less slow down, especially after the panicle initiation stage ((Inada, 1967) and as a result, accumulation of available carbohydrate begins in the leaf sheaths and culm bases (Togari et al., 1954; Murayama et al., 1955; Murata and Matsushima, 1975a; Yoshida, 1981). The accumulated carbohydrate sharply increases during the two weeks before heading (Yoshida, 1981) and reaches its highest value at anthesis (Murata and Matsushima, 1975a). After anthesis, the amount rapidly decreases (Yoshida, 1972). The accumulated carbohydrates are mostly sugars and starch (Murata and Matsushima, 1975a). It has experimentally been shown that these carbohydrates are remobilized to the panicle after anthesis (Murata and Matsushima, 1975a; Oshima, 1966; Cock and Yoshida 1972). Quantification of the amount remobilized carbohydrates is a matter of question. Reports indicate that there is small contribution of these reserves to the grain yield in wheat (5-10%, Evans et al., 1975), maize (20%, Duncan, 1975), and barley (20%, Archbold and Mukerjee, 1942), and to tuber yield in potatoes (10%, Moorby and Milthorpe, 1975). Murata and Matsushima (1975) reported that such a contribution in rice yield might be from 0 to 71%. Cultural practices like low level of N and/or high plant density can substantially increase the mobilization (Yoshida and Ahn, 1968; Wada, 1969) as do climatic factors like low light intensity (Soga and Nozaki, 1957). Cock and Yoshida (1972) quantitatively showed that 2 t grain ha^{-1} might come from accumulated carbohydrates when the yield was 7.8 t ha^{-l} indicating a contributing of little over 25%. In the rice models the fraction culm weight at flowering that is remobilzable (FSTR) can be taken as 0.25. The remobilization process starts when the growth of the culms stops and the rate of remobilization is taken as 0.1 d^{-1} of the amount of the weight of the accumulated reserves (WIR) (Penning de Vries at el., 1989). The amount of remobilized carbohydrates (LSTR) has been added to the ASAG, the carbohydrates available for growth. Thus, the final form of calculation of ASAG becomes:

ASAG = GASS-RMCR + (LSTR*1.111*0.947)

ASAG is the amount of carbohydrate available for growth expressed as kg DM ha^{-1} d^{-1}

GASS is the rate of gross photosynthesis expressed as kg DM ha^{-1} d^{-1}

RMCR is the rate of total maintenance respiration expressed as kg DM ha^{-1} d^{-1}

LSTR is the rate of carbohydrate remobilization expressed as kg DM ha^{-1} d^{-1}

During the process of remobilization small amount of energy are required (Penning de Vries at el., 1989).

The fraction 1.111 denotes the yield in glucose from starch hydrolysis. However, not all the glucose is considered to be remobilized. It has been reported that about 5.3% of glucose is sacrificed during intercellular transport to provide energy for this process (Penning de Vries at el., 1989). So, the fraction 0.053 is lost and the remaining 0.947 accounts for the final amount of LSTR.

6.4 Development

Development refers to the progression in the successive phonological phases (van Heemst, 1986b; Spitters et al., 1989), regardless of whether growth is great or small (Lowry, 1967). In the case of rice, the changes from one stages to another in sequence are marked by phenomena such as emergence, tillering, flowering, grain filling and grain maturity.

Crop development is characterized by the order and rate of appearance of vegetative and reproductive organs (van Heemst, 1986b). Although crop phenology is the oldest branch of environmental botany (Legg, 1981), the physiological or biochemical methods of charactering and measuring the developmental processes are still unknown or least well understood (Penning de Vries et al., 1989). This is why explanatory models are not available for this purpose. In a simplified way, development is expressed in the model on a numerically dimensionless scale from 0 to 2; 0 being the emergence, 1 and 2 being anthesis and maturity respectively (van Heemst, 1986b; Penning de Vries et al., 1989). Anthesis here refers to the first date when 50% of fertile tillers carry or have carried open flowers (Penning de Vries et al., 1989). The rate of development (DVR) is the part of the scale that accumulated per unit time expressed as d^{-1} whereas the numerical values adding the DVR constitute development stage (DVR) of the crop. In rice as for others crops, the major environmental factors which affect crop development are temperature and length (van Heemst, 1986b). Other factors like water stress or nutrition deficiency usually have a small effect on development (Penning de Vries et al., 1989). The concept of temperature sum (TSUM) relating development of crops to the temperature dates back over 200 years (Chang, 1968). The TSUM is the summation of daily mean temperatures over a certain period of growth or development; when the temperature drops to a certain level, the threshold temperature, the growth or development can be assumed to have stopped. For example, the rice crop may require a TSUM of 1000 to 3000 from sowing to heading (Toriyama et al., 1969 as cited by Yoshida, 1981) and a further 800 for ripening (Ishizuka et al., 1973 as cited by Yoshida, 1981). TSUM is expressed as degree-days (°d). The threshold temperature for rice given as 10^0C for *japonica* and 12°C for *indica* type (Liangzhi et al., 1987). The concept of TSUM is also known as heat sum (Lowry, 1967; Chang, 1968). Using this concept, the growth and development of corn have been predicted successfully (Cross and Zuber, 1972; Brown, 1975; Phipps et al, 1975; Bunting, 1976, Tollenaar et al., 1979; Coelho and Dele, 1980). It has been used in wheat (Vos et al., 1982; Vos, 1985) and other models (Biscoe and Willington, 1985). The application of the TSUM concept has been advocated (Gallagher et al., 1979; Warrington and Kanemasu, 1983; Moorby, 1985) due to its simplicity. Hesketh et al. (1980b) found that accounting for photoperiod, TSUM could adequately be used in the field situation. The essential basis of TSUM is linearity between development rate and temperature (Yoshida, 1981) and this is the main drawback of the concept (Jones and Hesketh, 1980). For example, in the whole growth process of rice, from germination to maturity, some process may be temperature insensitive, some process may be linearly related to temperature, some logarithmically dependent (Yoshida, 1981).Thus the TSUM approach is an oversimplification (Yoshida, 1981) and effort to develop a TSUM function for the rice growth period have not been successful (Liangzhi et al., 1987). Alternatively, the temperature effect on the development rate (DVR) of rice has been used in a non-linear fashion. Temperature has different effect in the vegetative and reproductive stages. The DVRs in the vegetative stage (emergence to anthesis) and during the reproductive phase have been calculated as the inverse of the duration of the period between the stages at a constant temperature. At 25^{o}C, the constant DVR for the vegetative phase (DVRVC) and that for the reproductive phase (DVRRC) can be calculated according to the information on the variety used in the model (Penning de Vries et al., 1989). The relative effect on DVR due to various temperatures at the vegetative (DVRVT) and reproductive (DVRRT) stages can be related using the information from literature. Once DVRVT and DVRRT are calculated, the development arte at the vegetative (DVRV) and reproductive (DVRR) stages can be estimated by:

DVRV=DVRVC*DVRVT

DVRR=DVRRC*DVRRT

DVRV and DVRR are the development at vegetative and reproductive stages, respectively. DVRVC and DVRRC are the development rate constants at vegetative and reproductive stages, respectively. DVRVT and DVRRT are the development rates relative to temperature at vegetative and reproductive stages, respectively.

When the development stage (DVS) is 1 or below, the crop development rate (DVR) takes the value of the DVRV and when the DVS is more than 1, it assumes the value of the DVRR. Finally, the DVS is the updated each day by adding initial DVS with that of the DVR of that day. When the DVS reaches 2, the crop attains maturity and model stops running. Apart from the temperature, the day length can influence the DVR of rice (Vergara, 1976; Vergara and Chang, 1976).

6.5 Assimilate partitioning and growth of individual organs

6.5.1 Assimilate partitioning

Assimilates that are available for growth (ASAG) are allotted to different organs; the process is called assimilate partitioning (Penning de Vries et al., 1989). In the present model, four plant organs have been considered –roots, culms, leaves and storage organs. Culms are defined in a functional rather than morphological manner which includes true culm, leaf sheaths, and petioles (van Heemst, 1986c). Leaves consists of only leaf blades whereas the storage organs comprise the whole panicles that contain grains, the important economic part of rice. The distribution pattern of assimilates is a function of physiological age (Penning de Vries et al., 1989), which has been expressed in the model as development stage (DVS). The pattern is independent of the amount of assimilate available. Van Heemst (1986c) showed in the potato crop that management practices, like shifting sowing dates, had a small effect on distribution pattern. Moderate nutritional shortage has a small effect on the allocation pattern of assimilates of rice whereas significant differences may exist between cultivars (Penning de Vries et al., 1989). (Penning de Vries and his associates also indicate that low temperatures may cause abnormal shoot-root balance. The distribution pattern of assimilates used in the model is such that initially the major share goes to roots and leaves, and then to culms and finally, after flowering all go to the storage organs. The allocation is first made for the shoot (FSH) and thus the rest remain for the roots. From the shoot fraction, distribution is made to the leaves (FL), and culm (FC) and the rest to storage organs.

6.5.2 Growth of different organs

Once assimilates are ready and the distribution pattern has been allocated, the growth of different organs can take place. However, there are two additional aspects to be considered in the growth process of some of the organs of rice. They senescence and accumulation of carbohydrates.

6.5.2.1 Senescence

Senescence refers to the loss of the capacity to carry out essential physiological process and to loss of biomass (Penning de Vries et al., 1989). Quantitatively, two types of senescence have been reported (Thornley, 1981), one is triggered by the environment and the other endogenously. Environmental factors such as severe water shortage, nutritional deficiency (Fisher and Charles-Edwards, 1982; Boote et al., 1987b) or high temperatures (Throne et al., 1967; 1968) can cause loss and death of plant materials. On the other hand, physiological aging, protein breakdown, canopy self-shading (Charles-Edwards and Vanderlip, 1985; Boote et al., 1987b; Penning de Vries et al., 1989) are the major causes of senescence under non-stress conditions of plant growth. In such a situation, the component of the plant most liable to be affected is the leaf tissue. In rice, leaf senescence in *indica* type is faster than *japonica* (Yoshida, 1981). Quantification of senescence is not very easy as the process is not well understood (Fisher and Charles-Edwards, 1982). In the models, a simple descriptive approach can be taken. In rice, van Keulen (1986c) assumed in his model that leaf biomass declined at a constant rate of 0.02 kg kg^{-1} d^{-1}. Earlier, van Keulen and his associates (1982) reported that a rate of 0.03 kg kg^{-1} d^{-1} could be used for a wide range of species. Information on root senescence is not widely available; however, Herrera-Reyes and Penning de Vries (1989) reported natural loss of after the flowering of rice.

6.5.2.2 Accumulation of carbohydrates

It was noted earlier that carbohydrates accumulate in the culms, leaf bases and leaf sheaths of rice. The causes of such accumulation and the remobilization process have also been discussed. It was further indicated that the fraction culm weight at flowering that is remobilizable (FSTR) is 0.25. In estimating the accumulation, it is assumed that the FSTR fraction of the culm growth (WCU) will be the gross amount of the assimilates. The accumulated carbohydrates is considered as starch. So, the carbon fraction has been adjusted. 0.431 is the carbon fraction of the culm whereas 0.444 is the carbon fraction of starch. The net amount of accumulates can be obtained by subtracting the remobilization rate (LSTR) from that of the gross amount. Finally, by adding each day’s process, the final weight of the reserves (WIR) can be updated.

6.5.2.3 Root growth

An estimation of carbohydrate available for root growth (CART) can be obtained from:

CART=ASAG-CASH

CART is the carbohydrate available for root growth expressed as kg DM $ha^{-1}d^{-1}$

ASAG is the amount of carbohydrate available for growth expressed as kg DM ha^{-1} d^{-1}

CASH is the carbohydrate available for shoot growth expressed as kg DM ha^{-1} d^{-1}

CASH is determined by multiplying ASAG with the fraction allocated to the shoots (FSH). Now, the root growth (GRT) can be worked out by multiplying the CART with CERT, the conversion efficiency of root. Taking account of the rate of loss of root (LRT), the final weight of roots (WRT) is obtained as initial weight plus GRT minus LRT.

6.5.2.4 Culm growth

Carbohydrates available for culm growth (CACU) is obtained by:

CACU=CASH*FC

CACU is carbohydrate available for culm growth expressed as kg DM ha^{-1} d^{-1}

FC is the fraction of FSH allocated to the culms

The growth rate of culms (GCU) is then calculated considering CECU, the conversion efficiency of the culm. The final culm weight (WCU) considers the initial WCU plus the non-remobilized portion (1-FSTR) of the GCU.

6.5.2.5 Leaf growth

Estimation of the carbohydrates available for growth (CALV) is obtained from:

CALV=CASH*FL

CALV is the carbohydrate available for leaf growth express as kg DM $ha^{-1}d^{-1}$

CASH is the carbohydrate available for growth expressed kg DM $ha^{-1}d^{-1}$

FL is the fraction of FSH allocated to the leaves.

The leaf growth rate (GLV) is then calculated by the leaf conversion efficiency, CELV.

6.5.2.6 Growth of storage organs

Estimation of the carbohydrates available for the growth of storage organs (CASO) is given by:

CASO= CASH-CACU-CALV

CASO is the carbohydrate available for growth of storage organs expressed as kg DM $ha^{-1}d^{-1}$

CASH is the carbohydrate available for shoot growth as kg DM ha^{-1} d^{-1}

CACU is the carbohydrate available for culm growth expressed as kg DM ha^{-1} d^{-1}

CALV is the carbohydrate available for leaf growth expressed as kg DM ha^{-1} d^{-1}

Now, the growth rate of storage organs (GSO) is obtained by multiplying CASO with the conversion efficiency, CESO. The weight of the storage organs (WSO) can be calculated by adding the increments of GSO. Not all of the WSO is economically important for rice. Only 80% of the panicles is thought to be the grain portion of rice (Yoshida, 1981). This is why the weight of grain (WGR) is calculated by multiplying WSO by 0.8.

It has been observed before that an unlimited sink size is considered in the model but in reality may not be possible. Carbohydrate production in cereals can be limited by the capacity of the grains to use them (Cock and Yoshida, 1973; Evans and Wardlaw, 1976). This can be taken into account if morphological features of rice can be modeled. Duration of the integration period is important in modeling the morphology of a crop. Although wheat morphology has been at one-day intervals (van Keulen and Seligman, 1987), the early part of tillering of rice is hard to simulate properly with such an integration period. A quarter-day integration is better. As this is beyond the scope of present study, alternative process were taken. The harvest index (HI) has been restricted to its upper limit of 0.55 in consonance with the present semi-dwarf *indica* types of rice (Yoshida, 1981); this technique was successfully used by Dua et al., (1990). The HI can be obtained from:

HI=WSO/WSS

HI is the harvest index

WSO is the weight of storage organs expressed as kg DM $ha^{-1}d^{-1}$

WSS is the weight of the shoot storage organs expressed as kg DM $ha^{-1}d^{-1}$

When the HI exceeds 0.55, no further growth of the storage organs (GSO) takes place.

6.6 Initialization of rice growing processes in the nursery and main paddy field

6.6.1 Nursery

The rice growing process considered in the study begins in the nursery. The initial weights of the above-ground dry matter and roots are necessary to start the process. Values from the experiments not always available. So, a general approach of mobilization of carbohydrates from seed to structural plant materials can be adopted (van Keulen, 1986b).

Experimenting with a number of species, Penning de Vries et al. (1989) found that about half of the seed reserves (endosperm) are lost due to respiration and the rest is divided equally between shoot and root. Tanaka and Yamaguchi (1968) also found similar findings for rice. However, the efficiency attained in the field situation is different. The fraction of seed reserves mobilized is often incomplete and also some organic components leak into the soil; thus even in a highly favorable germination condition only 25% of the endosperm is thought to be conversion (CVR) is used in the model. Taking account of the seed rate (SEED) and germination percentage (GERM), the amount of available dry matter (ADG) can be calculated. Of this ADG, the root fraction (CR) accounts for 60% and the rate is for the leaf (CL). With these considerations, the weight of the initial roots (WRT) and leaves (WLV) is calculated. In the rice production system, seeds that are placed in the nursery bed are pre-germinated, i.e. the development process has begun. These seedlings usually spend two days in the pre-germination process, and thus (if considering the development rate (DVRVC) as 0.013, the initial DVS can be set as 0.026. Initialization of LAI can also be made accordingly. Other parameter values can be taken as zero. Rice seedlings become autotrophic between two and three weeks of age (Yoshida, 1981). This why it is better to start the simulation when seedlings are about 15 days old. Yoshida (1973) showed contribution of photosynthesis at the early stage of seedling growth of IR8. Such information from the report can be used to estimate the low rate of utilization of photosynthesis during early development stage of rice.

6.6.2 Main paddy field

6.6.2.1 Reduction in population density

Only a portion of biomass is transferred from a hectare of nursery to a hectare of main paddy field. The programming to be transferred can be done in a straight forward way takings account of the planting density in the main paddy field, the SERQ, capturing line to line, and hill to hill distances, and also the number of seedlings to be used in a hill. Similarly, the expected number of seedling to be produced (SEEX) in the nursery can be calculated by considering the seed rate, germination percentage, and the seed weight. Finally, the inverse of the factors (SEEX/SERQ) gives the proportion of the dry matter to be transferred from the nursery to main paddy field (PNTM) during transplanting. Thus, when the simulated day (J) becomes the transplanting day (F) then provision has been made to take account of PNTM for roots, culm, leaves and culm reserves. Apart from the consideration of normal density reduction (as denoted by PNTM), a loss of dry matter can also occur during pulling the seedlings from the nursery. The stress the seedlings suffer during this time occurs immediately after transplanting and is termed as ‘transplanting shock’, which can also be modelled.

6.6.2.2 Transplanting shock

Immediately after transplanting, rice seedling shows a very slow growth; this is the expression of a shock due to a change in the environment from the nursery to the main paddy field. This phenomenon is known as ‘transplanting shock’. Unfortunately, the process involved in it are not properly understood (SARP, 1987). It is assumed that the shock arises due to root injury and leaf loss at the time of pulling the seedling from the nursery; and the degree of shock depends on a number of Factors like age of seedling, pulling method, handling during transplanting, and environmental factors like water and air temperatures, soil fertility, and also varietal characteristics (SARP, 1987; 1989b). The general assumption is that there will be no shock if seedlings are transplanted properly. It is reported there are differences in initial growth due to the shock but normally it does not affect final yield (SARP, 1987). The duration of shock, depending on the situation, may be as long as three weeks or more. Most of the rice-based simulation models do not consider this situation, mainly due lack of information on the subject and because it has little effect on grain yield. However, attempt can be made to model the phenomenon. In reflecting the shock period, Mekwatanakarn (1991) simply reduced the development stage (DVS) of rice by a certain factor.

7. MODEL EVALUATION

Once the model has been constructed, it needs an evaluation to see how far it can mimic the real world and how confidently it then be used for working out decisions with its assistance (Dent and Blackie, 1979). In other worlds, evaluation is done to judge the accuracy of the model. Jones et al. (91987) define accuracy in terms three progressive stages: verification, calibration and validation.

Verification measures the truthfulness or correctness of the model (Baker and Curry, 1976); the issue of programming logic is questioned here that of the programmer's intentions (Jones et al., 1987). These philosophical issues (as termed by Dent and Blackie, 1979) are hard to quantify in reality, thereby making the process of verification very complex. A typical approach is to run the model with historical input data recorded for the real system, and then to compare the output from the model that of the reality, particularly concerning the model logic and parameter values (Baker and Curry, 1976). Statically tools can be used to see the level of significance. If the model does not behave as anticipated, corrections are made to the model structure, called 'debugging' (Baker and Curry, 1976; Dent and Blackie, 1979). It should be that a verified model does not mean that it will correctly simulate a crop (Whisler et al., 1986).

Model calibration is often carried out with the verification (Baker and Curry, 1976). It refers to the adjustments made to model parameters so as to give the 'most accurate' comparison between simulated results and results obtained from field measurements (Jones et al., 1987). In calibration, a statistical view point is taken: some probability distribution of the deviations between model and experimental data is assumed, which tests to probability distribution for the parameters (Klepper, 1988).

When the model is verified and calibrated, the validation process can start (Baker and Curry, 1976; Dent and Blackie, 1979; Whisler et al., 1986; Jones et al. 1987). Validation is a process of assessing the accuracy for a given purpose of a simulation model by comparing model's prediction with the independent results (Spedding, 1975a). Independent results mean data which have not been used previously in the development of the model or calibration process. Validation is mainly concerned with the usefulness of the model rather than its truthfulness (Baker and Curry, 1976).

The procedure of the validation has been well described by Dent and Blackie (1979). Validation can be performed firstly, by comparing the behavior of the model with that of the real situation in a qualitative way. Graphical representation in the conventional way to compare the results. This simple procedure, as Dent and Blackie (1979) mention, provides a 'feel' for the situation and a good basis for further analysis. Once the qualitative behavior of the model explains the reality sufficiently, the quantitative comparison can be made. Statistical techniques such as simple linear can be applied to measure relationships between the mean model outputs and real systems measures. Such quantification alone, however, cannot explain all the discrepancies precisely (Dent and Blackie, 1979); therefore, the model cannot be proved to be correct or incorrect (Penning de Vries, 1977). Thus subjective interpretation and assessment are often necessary as well. This is why it is argued that model evaluation is essentially a subjective procedure (Anderson, 1972 quoted by de Castro, 1988).

The test of validity in any crop simulation model should not be performed only at the level of its final prediction such as grain yield. It may so happens that the model is predicting the behavior fortuitously even when some of the underlying assumptions are wrong because it is insensitive to them or because the in-built errors cancel out (Charles-Edwards and Vanderlip, 1985). So, information on intermediate levels may also be crucial for model testing. Validation of a crop model is a continuous process. On one hand, crop models are just working hypotheses and it is never possible to prove a hypothesis absolutely correct in science (Whisler et al., 1986). On the other hand, even for established models, update is made such as by incorporating more management variables which needs further assessment (Dent and Blackie, 1979).

8. SENSITIVITY ANALYSIS

Sensitivity tests how responsive the model is to changes in certain variables and parameters (Whisler et al., 1986). The purpose is to study the behavior of the model (Jones et al. 1987). Through the test, sensitivity parameters are identified. A sensitive parameter is one which causes major change in the model output (Dent and Blackie, 1979). It is also helps to identify the priorities for conventional research program associated with the system. This is why the sensitivity analysis is called ‘a tool for agricultural research guidance’ (de Castro, 1988). It also justified the logic of consideration of the input and parameters in the study of the system. Sensitivity analysis is performed with the model that has been fully or partially validated. Sensitivity analysis is depends on the objective of the study. In some cases there is little need to carry out the test if a given parameter is not important as far as the use of a given model is concerned (Dent and Blackie, 1979). When the analysis consists of examining the effect of the uncertainty in model parameters it is called ‘fine sensitivity analyses and of the uncertainty in the model structure then it is called ‘coarse sensitivity analysis’ (Rossing et al., 1989).

The process of the analysis starts with the selection of the model outputs that are considered to be crucial the study (Jones et al. 1987). Then an individual input variable or parameter is changed to a certain degree, holding the others constant (Whisler et al., 1986). The certain degree is the ‘range of the values’ selected representing the extreme conditions associated with each parameter to be evaluated (Jones et al. 1987). The model is then run and the results are obtained. Results obtained from the analysis can be represented by graphs showing the changes in the output over the range of values of parameters or inputs. Expression of the results in terms of relative sensitivity is often used to show the sensitivity (Jones et al. 1987; Rossing et al., 1989). Jones and his associates (1987) indicate the possibility of another approach by using regression analysis or response surface techniques in which the simulation results are regressed against one or more parameters over the range of interest.

9. BASIC DATA TO BE REQUIRED FOR MODEL DEVELOPMENT AND VALIDATION

Weather data (daily) closer to experimental fields

- Maximum and minimum air temperatures
- Rainfall
- Relative humidity
- Solar radiation / Sunshine hours

Crop phenology

- Identification of crop development stages and their durations (in calendar day) – variety by variety. Most of the crops have pre-defined stages, such as for rice, beginning of tillering, maximum tillering, panicle initiation, flowering and maturity. For some crops like jute, stages of vegetative phase are not well defined. In such cases, one needs to define the stages in consultation with fellow scientists; data collection can be done accordingly.

Crop growth

- Dry matter of plant parts (roots, stem, leaves etc); economic organs preferably every 14 days – panicles, grains, bark (jute), stick (jute), tuber (potato), cob (maize) etc.
- Leaf are index (LAI) preferably every 14 days.
- Final weight of harvest organs panicles, grains, bark (jute), stick (jute), tuber (potato), cob (maize) etc with record of moisture content.

10. LITERATURE CITED AND ADDITIONAL LITERATURE FOR FURTHER CONSULTATION

Amthor, J.S. (1984). The role of maintenance respiration in plant growth. Plant, Cell and Environment, 7: 561-569.

Anderson, J.R. (1972). Economic models and agricultural production systems. Proc. Aust. Soc. Anim. Prod., 9: 77-83.

Angstrom, A. (1924). Solar and terrestrial radiation. Quarterly Journal of the Royal Meteorological Society, 50: 121-1*26.*

Angus, J.F. and Zandstra, H.G. (1979). Climatic factors and the modeling of rice growth and yield. Pages: 189-199. In: Agro meteorology of the rice crop. Philippines, Los Banos: World Meteorological Organization and International Rice Research Institute.

Archbold, H.K. and Mukerjee, B.N. (1942). Physiological studies in plant nutrition. Annals of Botany, 6: 1-41.

Baker, C.H. and Curry, R.B. (1976). Structure of agricultural simulation: a philosophical view. Agricultural Systems, 1: 201-218.

Barnes, A. and Hole, C.C. (1978). A theoretical basis of growth and maintenance respiration. Annals of Botany, 42: 1217-1221.

Bauer, H., Larcher, W. and Walker, R.B. (1975). Influence of temperature stress on CO_2-gas exchange. Pages 557-586. In: Cooper, J.P. (ed), Photosynthesis and productivity in different environment. Cambridge: Cambridge University Press.

Bell, C.J. (1987). The testing and validation of the models. Pages 299-309.In: Rose, D.A. and Charless-Edwards, D.A. (eds), Mathematics and plant physiology. London: Academic Press.

Berkhuot, J.A.A. and Keulen, H. van (1986). Potential evapotranspiration. Pages 63-75. In: Keulen, H. van and Wolf, J. (eds), Modeling of agricultural production: weather, soil and crops. Wageningen: Pudoc.

Biscoe, P.V. and Willington, V.B.A. (1985). Crop physiological studies in relation to mathematical models. Pages 257-269. In: Day, W. and Atkin, R.K (eds), Wheat growth and modeling. NATO ASI Series A86. New York and London: Plenum Press.

Black, J.N., Bonython, C.W. and Presscott, G.A. (1954). Solar radiation and the duration of sunshine. Quarterly Journal of the Royal Meteorological Society, 80: 231-235.

Boote, K.J., Wilkerson, G.G., Jones, J.W. and Mishe, J.W. (1987a). Modeling dry weight gain. Pages 8-15. In: Simulation models for soybeans and other crops. FFTC TB 106. Taiwan, Taipei City: Food and Fertilizer Technology Center.

Boote, K.J., Wilkerson, G.G. and Jones, J.W. (1987b). Modeling pod addition, shell growth, and seed growth. Pages 16-24. In: Simulation models for soybeans and other crops. FFTC TB 106. Taiwan, Taipei City: Food and Fertilizer Technology Center.

Brockington, N.R. (1979). Computer modeling in agriculture. Oxford: Oxford University Press.156 pp

Brown, D.M. (1975). Heat units for corn in Southern Ontario. Fact sheet AGDEX 111/31, Order No.75-007. Canada: Ontario Ministry of Agriculture and Food.

Bunting, E.S. (1976). Accumulated temperature and maize development in England. J. Agric. Sci. Camb., 87: 577-583.

Castro, A.M.G de (1988). A system approach to determining priorities for natural rubber research in Brazil. Ph.D Thesis. Department of Agriculture, University of Reading, UK. 290 pp.

Catrileo, A.R. (1990). Beef production systems from grassland-arable farms in South Chile. Ph.D. Thesis. Department of Agriculture, University of Reading, U.K. 213 pp.

Chang, J.H. (1968).Climate and agriculture. An ecological survey. Illinois, Chicago: Aldine Publishing Company. 304 pp.

Chanter, D.O. (1981). The use and misuse of linear regression methods in crop modeling. Pages 253-267. In: Rose, D.A. and Charles-Edwards, D.A. (eds), Mathematics and plant physiology. London: Academic Press.

Charles-Edwards, D.A. (1982). Physiological determinants of crop growth. Australia, New York, London: Academic Press. 161 pp.

Charles-Edwards, D.A. and Vanderlip, R.L. (1985). Interfacing the analysis and synthesis of crop growth performance. Pages 275-291. In: Day, W. and Atkin, R.K (eds), Wheat growth and modeling. NATO ASI Series A86. New York and London: Plenum Press.

Churchman, C.W. (1971). The design of inquiry systems: basic concepts of systems and organization. New York: Basic Books.

Cock, J. H. and Yoshida A. S. (1972). Accumulation of ^{14}C-labelled carbohydrate before flowering and the subsequent redistribution and respiration in the rice plant Proc. Crop Sci. Soc. Jpn., 41: 226-234.

Cock, J.H. and Yoshida A.S. (1973). Changing sink and source relations in rice (*Oryza sativa* L.) using carbondioxyde enrichment in the respiration in the rice plant. Proc. Crop. Sci. Jpn., 41: 226-234

Coelho, D.T. and Dale, R.F. (1980). An energy-crop growth variable and temperature function for predicting corn growth development-planting to silking. Agronomy Journal, 72: 503-510.

Conway, G.R. (1985). Agro ecosystem analysis. Agricultural Administration, 20: 31-55.

Cooper, J.P. (1975). Control of photosynthetic production in terrestrial systems. Pages 593-621. In COOPER, J.P. (ed), Photosynthesis and productivity in different environment. Cambridge: Cambridge University Press.

Cross, H.Z. and Zuber, M.S. (1972).Predicting flowering dates in maize based on different methods of estimating thermal units. Agronomy Journal, 64: 351-355.

Day, W. (1985). Wheat growth and modeling: an introduction.Pages1-5. In: Day, W. and Atkin, R.K (eds), Wheat growth and modeling. NATO ASI Series A86.New York and London: Plenum Press.

Dent, J.B. and Blackie, M.J. (1979). System simulation in agriculture. London: Applied Science Publishers Ltd. 180 pp.

Dingkuhn, M., Penning de Vries, F.W.T., De Datta, S.K. and Laar, H.H. van (1990). New plant type concepts for seeded flooded tropical rice. Paper presented at the International Rice Research Institute Conference. August 1990, Seoul, South Korea.

Driessen, P.M. (1986). The collection and treatment of basic data: Introduction. Pages 203-207. In: Keulen, H. van and OWLF, J. (eds), Modeling of agricultural production: weather, soil and crops. Wageningen: Pudoc.

Dua, A.B., Penning de Vries, F.W.T. and Seshu, D.V. (1990). Simulation to support evaluation of the production potential of rice varieties in tropical climates. Transaction of the ASAE, 33(4): 1145-1194.

Duncan, W.G. (1975). Maize. Pages 23-25. In: Evans, L.T. (ed), Crop physiology. Cambridge: Cambridge University Press.

Evans, L.T. (1975a). The physiological basis of crop yield. Pages 327-355. In: Evans, L.T. (ed), crop physiology. Cambridge: Cambridge University Press.

Evans, L.T. (1975b). Beyond photosynthesis - the role of respiration, translocation and growth potential in determining productivity. Pages 501-507. In: Cooper, J.P. (ed), Photosynthesis and productivity in different environment. Cambridge: Cambridge University Press.

Evans, L.T. and Wardlaw, I.F. (1976). Aspects of comparative physiology of grain yield in cereals. Advances in Agronomy, 28: 301-359.

Evans, L.T., Wardlaw, I.F. and Fischer, R.A. (1975). Wheat. Pages 101-149. In: Evans, L.T. (ed), Crop physiology. Cambridge: Cambridge University Press.

Fischer, R.A. (1985). The role of crop simulation models in wheat agronomy. Pages 237-255. In: Day, W. and Atkin, R.K (eds), Wheat growth and modeling. NATO ASI Series A86.New York and London: Plenum Press.

Fisher, M.J. and Charles-Edwards, D.A. (1982). A physiological approach to the analysis of crop growth data. III. The effects of repeated short-term soil water deficits on the growth of spaced plants of the legume *Macroptilium atropurpureum cv*. Sratro. Annals of Botany, 49: 341-346.

France, J. and Thornley, J.H.M. (1984). Mathematical Models in Agriculture. London: Butterworths. 335 pp.

Fukai, S., Koh, S. and Kumura, A. (1976). Dry matter production and photosynthesis of *Hordeum vulgare* L. in the field. J. Appl. Ecol., 13: 877-887.

Gallagher, J.N., Biscoe, P.V. and Wallace, J.S. (1979). Field studies of cereal leaf growth. IV. Winter wheat leaf extension in relation to temperature and leaf water status. J. Exp. Bot., 30: 657-668.

Glover, J. and McCulloch, J.S.G. (1958). The empirical relation between solar radiation and hours of sunshine. Quarterly Journal of the Royal Meteorological Society, 84: 172-175.

Glover, P.S. and Shahi, H.N. (1986). Nitrogen use efficiency in relation to seedling age and transplanting time. International Rice Research Newsletter, 11(1): 28.

Goudriaan, J. (1977). Crop micrometeorology: a simulation study. Simulation Monographs. Wageningen: Pudoc. 249 pp.

Gourdiaan, J. and Laar, H.H. van (1978). Calculation of daily totals of the gross CO_2 assimilation of the leaf canopies. Netherlands Journal of Agricultural Science, 26: 373-382.

Graf, B., Dingkuhn, M., Schnier, F., Coronel, V. and Akita, S. (1991). A simulation model for the dynamics of rice growth and development: III. Validation of the model with high-yielding varieties. Agricultural Science, 36: 329-349.

Greenwood, D.J. and Barnes, A. (1978). A theoretical model for decline in the protein contents in plants during growth. J. Agric. Sci. Camb., 91: 461-466.

Greenwood, E.A.N., Goodall, D.W. and Titmanis, Z.V. (1965). The measurement of nitrogen deficiency in grass swards. Plant and Soil, 23: 97-116.

Hayashi, K. and Ito, H. (1962). Studies on the form of plant in rice varieties with particular reference to the efficiency in utilizing sunlight. I. The significance of extinction coefficient in rice plant communities. Proc. Crop Sci. Jpn., 30: 329-333.

Hedge, B.A. and Joshi, G.V. (1974). Pattern of photosynthesis in a saline indica var. of rice kala rata. Pages 755-763.In: The Proceeding of the symposium on use of radiations and radioisotopes in studies of plant productivity. India: Pantnagar.

Heemst, H.D.J. van (1986a). Potential crop production: physiological principles. Pages 13-26.In: Keulen, H. van and Wolf, J. (eds), Modeling of agricultural production: weather, soil and crops. Wageningen: Pudoc.

Heemst, H.D.J. van (1986b). Crop phenology and dry matter distribution. Pages 27-40. In: Keulen, H. van and Wolf, J. (eds), Modeling of agricultural production: weather, soil and crops. Wageningen: Pudoc.

Heemst, H.D.J. van (1986c). The distribution of dry matter during growth of a potato crop. Potato Research, 29: 55-66.

Herrera-Reyes, C.G. (1991). History of modeling at IRRI. Pages 5-9. In Penning de Vries, F.W.T., Kropff, M.J., Teng, P.S. and Kirk, J.D. (eds), Systems Simulation at IRRI Research Paper Series No. 151. Philippines, Los Banos: International Rice Research Institute.

Herrera-Reyes, C.G. and Penning de Vries, F.W.T. (1989). Evaluation of a model for simulation the potential production of rice. Philippine Journal of Crop Science, 14 (1): 21-32.

Hesketh, J.D. and Jones, J.W. (1980). Integrating traditional growth analysis techniques with recent modeling of carbon and nitrogen metabolism. Pages 51-92. In: Hesketh, J.D. and Jones, J.W eds), predicting photosynthesis for ecosystem models, I. Florida, Boca Raton: CRC Press.

Hesketh, J.D., Baker, D.N., and Duncan, W.G. (1971). Simulation of growth and yield in cotton: respiration and carbon balance. Crop Science, 9: 483-486.

Hesketh, J.D., Alberre, R.S. and Jones, J.W. (1980a). Prediction dark respiration in the soil-plant system. Pages 69-84.In: Hesketh, J.D. and Jones, J.W. (eds), Predicting photosynthesis for ecosystem models, II. Florida, Boca Raton: CRC Press.

Hesketh, J.D., Rlmore, J.D. and Jones, J.W. (1980b). Predicting flowering and subsequent leaf expansion. Pages 123-131.In: Hesketh, J.D. and Jones, J.W. (eds), Predicting phosynthesis for ecosystem models, II. Florida, Boca Raton: CRC Press.

Horie, T. (1979). The loess and the origin of Chinese agriculture. Am. Hist. Rev., 75: 1-36.

Horie, T. (1987). Dynamic models for evaluating and predicting the growth and yield of rice and sunflower crops from weather. FFTC TB 99. Taiwan, Tapei City. Food and Fertilizer Technology Center. 13 pp.

Horie, T. and Sakuratani, T. (1985). Studies on crop-weather relationship model in rice. (1) Relationship between absorbed solar radiation by the crop and the dry matter production. Journal of Agricultural Meteorology, Tokyo, 40: 331-342.

Inada, K. (1967). Physiological characteristics of rice roots, especially with the view-point of plant growth stage and root age. Bull. Nat. Inst. Agr. Sci. Japan, Ser.D.16: 19-156.

IRRI (1972). Annual Report for 1971.Philippines, Loss Banos: International Rice Research Institute.

IRRI (1980). Agro meteorology of the Rice Crop. Philippines, Los Banos: World Meteorological Organization and International Rice Research Institute. 254 pp.

Ishizuka, Y., Shimazki, Y., tanaka, A., Satake, T. and Nakayama, T. (1973). Rice growing in a cool environment. Taiwan, Taipei City: Food and Fertilizer Technology Center, Asian and South Pacific Council. 98 pp.

Ito, A. (1969). Geometrical structure of rice canopy and penetration of direct solar radiation. Proc. Crop Sci. Soc. Jpn., 38: 355-363.

Johnson, I.R. and Thornley, J.H.M. (1983). Vegetative crop growth model incorporation leaf area expansion and senescence, and applied to grass. Plant, Cell and Environment.6: 721-729.

Jones, J.W and Hesketh, J.D. (1980). Predicting leaf expansion. Pages 85-122.In: Hesketh, J.D and Jones, J.W. (eds), Predicting photosynthesis for ecosystem models. II. Florida, Boca Raton: CRC Press.

Jones, J.W., Mishoe, J.W. and Boote, K.J. (1987). Introduction to simulation and modeling. FFTC TB 100. Taiwan, Taipei City: Food and fertilizer Technology Center.

Kabaki, N., Yoneyama, T. and Tajima, K. (1982). Physiological mechanism of growth retardation in rice seedlings as affected by low temperature. Japan. Jour. Crop Sci., 51(1): 82-88.

Kase, M. and Catsky, J. (1984). Maintenance and growth components of dark respiration rate in leaves of C_3 and C_4 plants as affected by leaf temperature. Biologia Plantarum, 26: 461-470.

Keulen, H. van (1976). A calculation method for potential rice production. Contributions of the Central Research Institute for Agriculture.NO.21.Indonesia, Bogor: Central Research Institute for Agriculture. 26 pp.

Keulen, H. van (1986a). A simple model of potential crop production. Pages 41-60. In: Keulen, H. van and Wolf, J. (eds), Modeling of Agricultural production: weather, soil and crops. Wageningen: Pudoc.

Keulen, H. van (1986b). The collection and treatment of basic data: Plant data. Pages 235-247.In: Keuken, H. van and Wolf, J. (eds), Modeling of agricultural production: weather, soil and crops. Wageningen: Pudoc.

Keulen, H. van and Seligman, N.G. (1987). Simulation of water use, nitrogen nutrition and growth of spring wheat crop. Wageningen: Pudoc. 310 pp.

Keulen, H. van, Louwerse, W., Simba, L. and Alberda, T.H. (1975). Crop simulation and experimental evaluation- a case study. Pages 623-643. In: COOPER, J.P. (ed.), Photosynthesis and productivity in different environment. Cambridge: Cambridge University Press.

Keulen, H. van, Penning de Vries, F.W.T., and Drees, E.M. (1982). A summery model for crop growth. Pages 87-97.In: PENNING de Vries, F.W.T. and Laar, H.H. van (eds), Simulation of plant growth and crop production. Simulation monographs. Wageningen: Pudoc.

Kishitani, S. and Tsunoda, S. (1974). Effect of low and high temperature pretreatment on leaf photosynthesis and transpiration in cultivars of *Oryza sativa.* Photosynthetica, 8(3): 161-167.

Klepper, O. (1988). A model of carbon flows in relation to macrobenthic food supply in the Oosterschedle estuary (S.W. Netherlands). Ph.D. Thesis, Wageningen Agricultural University: 270 pp.

Lake, J.V. and Anderson, M.C. (1970). Discussion: Dynamics of development of photosynthetic systems. Pages 131-136. In: Prediction and measurement of photosynthetic productivity. Wageningen: Pudoc.

Larcher, W. (1973).Limiting temperatures for life function. Pages 195-231. In: Precht, H. Christopherson, J., Hensel, H. and Larcher, W. (eds), Temperature and life. Berlin: Springer-Verlag.

Lee, M.H. and Shin, J.C. (1989). Simulation of potential production of rice plant under low temperature conditions. In: van Laar, H.H. ten Berge, H.F.M., Jansen, D.M., de Jong, P.D. and Penning de Vries, F.W.T. (eds), Case studies in crop growth Simulation, February 1988-January 1989. Philippines, Los Banos: International Rice Research Institute, The Netherlands, Wageningen: Centre for Agro biological Research and Department of Theoretical Production Ecology of Wageningen Agricultural University.

Legg, B.J. (1981).Aerial environment and crop growth. Pages 129-149.In: Rose, D.A and Charles-Edwards, D.A (eds), Mathematics and Plant physiology. London: Academic Press.

Liangzhi, G., Zhiqing, J. and Lin, L. (1987). Photothermal models of rice growth duration for three varietal types in china. Pages 301-

308.In: Weather and rice. Philippines, Los Banos: International Rice Research Institute.

Lowry, W.P. (1967). Weather and life: an introduction to biometeorology. New York and London: Academic Press. 305 pp.

Makino, A., Mae, T. and Ohira, K. (1984). Changes in photosynthetic capacity in rice leaves from emergence through senescence. Analysis from Ribulose-1, 5 biphoshape carboxylase and leaf conductance. Plant and Cell Physiol., 25(3): 511-521.

Marcellos, H. (1977). Wheat frost injury-freezing stress and photosynthesis. Aust. J. Agric. Res., 28: 557-564.

McCree, K.J. (1970).An equation for the rate of respiration of white clover plants grown under controlled conditions. Pages 221-229. In: Prediction and measurement of photosynthetic productivity. Wageningen: Pudoc.

McCree, K.J. (1974). Equations for the rate of dark respiration of white clover and grain sorghum as function of weight, photosynthetic rate, and temperature. Crop Science, 14: 506-514.

McCree, K.J. and Troughton, J.H. (1966).Non-existence of an optimum leaf area index for the production rate of white clover grown under constant conditions. Plant Physiology, 41: 1615-1622.

McDonald, D.J. (1971). The effect of temperature and light on the rate of photosynthesis of 20 rice varieties and hybrids. Ph.D. Thesis. Texas A & M University, 129 pp.

McMennamy, J.A. and O'Toole, J.C. (1983). Non-existence of an optimum leaf area index for the production rate of white color grown under constant conditions. Plant Physiology, 41: 1615-1622.

Mekwatanakarn, W. (1991). Simulation of potential production of rice variety KDML105 in the northeast of Thailand. In: van Laar, H.H., Bindraban, P.S., Kropff, M.J., ten Berge, H.F.M., Jansen, D.M., de Jong, P.D. and Pennig de Vries, F.W.T. (eds), Case studies in Crop Growth Simulation, February 1990-1991.Philippines, Los Banos: International Rice Research Institute. The Netherlands, Wageningen: Centre for Agrobiological Research and department of Theoretical Ecology of Wageningen Agricultural University.

Moll, B.A. and Steinba, K.E. (1986).Chilling sensitivity in *Oryza sativa*: the role of protein phosphorylation in protection against photoinhibition. Plant Physiology, 80: 420-423.

Monteith, J.L. (1969). Light interception and radiative exchange in crop stands. Pages 89-111.In: Eastin, J.D., Haskins, F.A., Sullivan, C.Y. and Bavel, C.H.M. van (eds), Physiological aspect of crop yield. Wisconsin, Madison: American Society of Agronomy, and Crop Science Society of America.

Monteith, J.L. (1972). Solar radiation and productivity in tropical ecosystems. J. Appl. Ecol., 9: 747-766.

Monteith, J.L. (1973). Principles of environmental physics. London: Edward Arnold (Publishers) Ltd. 241 pp.

Moorby, J. (1985). Wheat growth and modeling: conclusions. Pages 381-386. In: Day, W. and Atkin, R.K (eds), Wheat growth and modeling. NATO ASI Series A86.New York and London: Plenum Press.

Mooby, J. and Milthorpe, F.L. (1975). Potato. Pages 225-257. In: Evans, L.T. (ed), Crop physiology. Cambridge: Cambridge University Press.

Murata, Y. (1975). The effect of solar radiation, temperature, and aging on ne assimilation rate of crop stands- from the analysis of the maximum growth rate experiment of IPB/PP. Proc. Crop Sci. Soc. Jpn., 44(2): 153-159.

Murata, Y. and Matsushima, S. (1975a). Rice. Pages 73-99. In: Evans, L.T. (ed), Crop physiology. Cambridge: Cambridge University Press.

Murata, Y. (eds) (1975b). Crop Productivity and solar energy utilization in various climates in Japan. JIBP Synthesis, vol. II. Tokyo: Japanese Committee for the International Biological program. 244 pp.

Murayama, N., Yoshino, M. Oshima, M., Tsukahara, S. and Kawarazaki, Y. (1955). Studies on the accumulation process of carbohydrates associated with growth of rice. Bull. Natl. Inst. Agric. Sci. (Tokyo), B.4: 123-166.

Nishiyama, Y., Ito, N., Hayase, H. and SATAKE, T. (1969). Protecting effect of temperature and depth of irrigation water from sterility caused by cool treatment at the mitotic stage of rice plants. Proc. Crop Sci. Soc. Jpn., 38: 554-555.

Norman, J.M. (1980). Interfacing leaf and canopy light interception models. Pages 49-67.In: Hesketh, J.D. and jones, J.W. (eds), Predicting Photosynthesis for ecosystem models. II. Florida, Boca Raton: CRC Press.

Norton, G. (1963). The respiratory pathways in potato tubers. Pages 148-159. In: Ivins, J.D. and Milthorpe, F.L. (eds), The growth of the potato. London: Butterworth.

O' Toole, J.C. and Jones, C.A. (1987). Crop modeling: application in directing and optimizing rainfed rice research. Pages 255-269. In: Weather and Rice. Philippines, Los Banos: International Rice Research Institute.

Oshima, M. (1966). On the translocation of ^{14}C assimilated at various growth stages to grains in rice plants. J. Sci. Soil and Manure, Japan, 37: 589-593.

Patterson, H.D., Silvey, V., Tarbot, M. and Weathorp, S.T.C. (1977).Variability in yields of cereal varieties in UK trials. J. Agric. Sci., Camb., 89: 239-245.

Peart, R.M. and Barrett, Jr., J.R. (1979). Future trend in environmental modification: the role of simulation. Pages 476-480.In: Barfield, B.J. and Geber, J.F. (eds), Modification of the Aerial Environment of Crops. MI, St. Joseph: American Society of Agricultural Engineers.

Penning de Vries, F.W.T. (1972). Respiration and growth. Pages 327-347. In: Rees, A.R., Cockshull, K.E.Hand, D.W. and Hurd, R.H. (eds), Crop processes in controlled environments. London, New York: Academic Press.

Penning de Vries, F.W.T. (1975a). The use of assimilates in higher plants. Pages 459-480. : Cooper, J.P. (eds), Photosynthesis and productivity in different environment. Cambridge: Cambridge University Press.

Penning de Vries, F.W.T. (1975b). The cost of maintenance process in plant cell. Annals of Botany, 39: 77-92.

Penning de Vries, F.T.W. (1977). Evaluation of simulation models in agriculture and biology: conclusions of a workshop. Agricultural Systems, 2: 99-107.

Penning de Vries, F.T.W. (1982). Systems analysis and models of crop growth. Pages 9-19. In: Penning de Vries, F.T.W. and Laar, H.H. van (eds). Simulation of plant growth and crop production. Simulation monographs. Wageningen: Pudoc.

Penning de Vries, F.W.T. (1990). Can crop models contain economic factor? Pages 89-103. In: Rabbinge, R, Goudriaan J., Keulen, H. van, Penning de Vries, F.T.W. and Laar, H.H. van (eds). Theoretical Production Ecology: Reflections and Prospects. Simulation monograph 34. Wageningen: Pudoc.

Penning de Vries, F.W.T. (1991). Improving yields: designing and testing VHYVs. Pages 13-19. In: Penning de Vries, F.W.T., Kropff, M.J., Teng, P.S. and Kirk, G.J.D. (eds). System Simulation at IRRI. IRRI research Paper Series No.151. Philippines, Los Banos: International Rice Research Institute.

Penning de Vries, F.W.T. and Laar, H.H. (1982). Simulation of growth process and model BACROS. Pages 114-135. In: Penning de Vries, F.W.T. and Laar, H.H. van (eds), Simulation of plant growth and crop production. Simulation Monographs. Wageningen: Pudoc.

Penning de Vries, F.W.T., Brunsting, A.H.M. and Laar H.H. van (1974). Products, requirements and efficiency of biosynthesis – a quantitative approach. J. Theor. Biol., 45: 339-377.

Penning de Vries, F.W.T., Jansen, D.M., Berge, H.F.M. ten and Bakema, A. (1989). Simulation of ecophysiological process of growth in several annual crops. Wageningen: Pudoc. 271 pp.

Penning de Vries, F.W.T., Keulen, H. van and Alagos, J.C. (1990). Nitrogen redistribution and potential production of rice. Pages 513-520. Sinha, S.K., Lane, P.V., Bhargava, S.C. and Agrawal, R.K. (eds), International Congress of Plant Physiology. India, New Delhi, Indian Institute of Agricultural Research. Water Technology Centre: Society for Plant Physiology and Biochemistry.

Phipps, R.H., Fulford, R.J. and Crofts, F.C. (1975). Relationships between the production of forage maize and accumulated temperature, Ontario heat units and solar radiation. Agricultural Meteorology, 14: 385-397.

Rabbinge, R. and Wit, C.T. de (1989). Systems, models and simulation. Pages 3-15. In: Rabbinge, R., Ward, S.A. and Laar, H.H. van (ed.), Simulation and systems management in crop protection. Wageningen: Pudoc.

Raymond, W.F., Telley, J.M.A., Derias, R.E. and Minson, D.J. (1960). Pages 181-190. In: Production and Uses of Grass.No.9 in the Monograph Series. London: Society of Chemical Industry.

Rietveld, M.R. (1978). A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine. Agricultural Meteorology, 19: 243-252.

Robson, M.J. (1980). A physiologist's approach to raising the potential yield of the grass crop through breeding. Pages 33-49. In: Hurd, R.G., Biscoe, P.V and Dennis, C. (eds), Opportunities for increasing crop yields. London: Pitman Advanced Publishing Program.

Rossing, W.A.H. Groot, J.J.R. and Roermund, H.J.W. van (1989). Simulation of aphid damage in winter wheat: a case study. Pages 240-261. In: Rabbnge, R., Ward, S.A. and Laar, H.H. van (eds), Simulation and systems management in crop protection. Wageningen: Pudoc.

Saeki, T. (1960). Interrelationship between leaf amount, light distribution, and total photosynthesis in a plant community. Botanical Magazine, Tokyo, 73: 404-408.

SARP (1987). Case studies in Crop Growth Simulation, April 1986-January 1987. (Penning de Vries, F.W.T., Jansen, D.M., Bakema, A.K., Rabbinge, R. and Garrity, D.P. (eds)). Philippines, Los Banos: International Rice Research Institute, The Netherlands, Wageningen: Centre for Agro biological Research and Department of Theoretical Production Ecology of Wageningen Agricultural University.

SARP (1989a). Case studies in Crop Growth Smulation, February 1986-January 1989. (van Laar, H.H., ten Berge, H.F.M., Jansen, D.M., de Jong, P.D and Penning de Vries, F.W.T. (eds.)). Philippines, Los Banos: International Rice Research Institute, The Netherlands, Wageningen: Centre for Agro biological Research and Department of Theoretical Production Ecology of Wageningen Agricultural University.

SARP (1989b). Crop Simulation Research in the SARP-Network: Plans, themes and Views. (Penning de Vries, F.W.T. (eds)). Philippines, Los Banos: International Rice Research Institute, The Netherlands, Wageningen: Centre for Agro biological Research and Department of Theoretical Production Ecology of Wageningen Agricultural University.

SARP (1991).Case studies in Crop Growth Simulation. February 1990-1991. (van Laar, H.H., Bindraban, P.S., Kropff, M.J., ten Berge, H.F.M., Jansan, D.M., de Jong, P.D. and Penning de Vries, F.W.T. (eds)). Philippines, Los Banos: International Rice Research Institute, The Netherlands, Wageningen: Centre for Agro biological Research and Department of Theoretical Production Ecology of Wageningen Agricultural University.

Sarti, R.P. (1987). Modeling the soybean agroecosystem in tropical Mexico: production as affected by water supply. Ph.D Thesis. Department of Agriculture, University of Reading, U.K. 169 pp.

Semikhatova, O.A. (1970). Energy efficiency of respiration under unfavorable condition. Pages 247-249. In: Prediction and measurement photosynthetic productivity. Wageningen: Pudoc.

Setter, T.L. and Greenway, H. (1988). Growth reductions of rice at low root temperature: decrease in nutrition uptake and development of chlorosis. J. Exp. Bot., 39: 811-829.

Sheehy, J.E., Cooby, J.M. and Ryle, G.J.A. (1979). The growth of perennial ryegrass: A model. Annals of Botany, 43: 335-354.

Sinclair, T.T and Wit C. T, de (1975). Photosynthate and nitrogen requirement for seed production of various crops. Science, 189: 565-567.

Sinclair, T.T and Seligman, N.G. (1996). Crop modeling: From infancy to maturity. Agron. J., 88: 698-704.

Soga, Y. and Nozaki, M. (1957). Studies on the relation between seasonal changes of carbohydrates accumulated and the ripening at the stage of generative growth in rice plant. Proc. Crop Sci. Jpn., 26: 105-108.

Spedding, C.R.W. (1975a). The biology of agricultural systems. London: Academic Press. 261 pp.

Spedding, C.R.W. (1975b). The study of agricultural systems. Pages 3-19. In: Dalton, G.E. (ed.) Study of Agricultural Systems. London: Applied Science Publishers Ltd.

Spitters, C.J.T., Keulen, H. van and Kraalingen, D.W.G van (1989). A simple and universal crop growth simulator. Pages 147-181.In: Rabbinge, R., Ward, S.A and Laar, H.H. van (eds), Simulation and systems management in crop protection. Wageningen: Pudoc.

Stapper, M., Harries, H.C. and Smith, R.C.G. (1983). Risk analysis of wheat yields in relation to cultivar maturity type and climate adaptability in semi –arid areas, using a crop growth model. In: Need for Climatic and Hydrologic Data in Agriculture if Southeast Asia. Canberra: UN Univ. Workshop, 12-15 December, 1983.

Stern, W.R. (1975). Actual and potential photosynthetic production-conclusions. Pages 661-672. In: Cooper, J.P. (eds), Photosynthesis and productivity in different environment. Cambridge: Cambridge University Press.

Takano, Y. and Tsunoda, S. (1971). Curvilinear regression of leaf photosynthetic rate on leaf nitrogen content among strains of *Oryza sativa* species. Jpn. J.breed., 21(2): 9-17.

Tanaka, A. (1971). Efficiency in respiration. Pages 483-548. In: Proc. Symposium on Rice Breeding. Philippines, Los Banos: International Rice Research Institute.

Tanaka, A. and Yamaguchi, J. (1968). The growth efficiency in relation to the growth of the rice plant. Soil Science Plant Nutrition, 14: 110-116.

Tang, P., Wang, F.C. and Chih, F.C. (1959). Studies on plant respiration. Scient. Sin., 8: 1379-1392.

Terao, H., Otani, Y.Doi and Izumi, S. (1941). Physiological studies on rice plant with special reference to the crop failure caused by the occurrence of unseasonable low temperature. VIII. The effect of various low temperatures on the panicle differentiation, heading and ripening in the different stages after transplanting to heading. Proc. Crop Sci. Soc. Japan, 13: 317-336.

Thompson, A.C., Lane, H.C., Jones, J.W. and Hesketh, J.D. (1976). Nitrogen concentrations of cotton leaves, buds and balls in relation to age and nitrogen fertilization. Agronomy Journal, 68: 17-621.

Thorne, G.N., Ford, M.A. and Watson, D.J. (1967). Growth, development and yield of spring wheat in artificial climates. Annals of Botany, 32: 425-446.

Thorne, G.N., Ford, M.A. and Watson, D.J. (1968). Effects of temperature variation at different times on growth and yield of sugar beet and barley. Annals of Botany, 31: 71-101

Thornley, J.H.M. (1976). Mathematical models in plants physiology. New York: Academic Press. 123 pp.

Thornley, J.H.M. (1981). Organogenesis. Pages 49-65. In: Rose, D.A and Charles-Edwards, D.A. (eds), Mathematics and plant physiology. London: Academic Press.

Thornley, J.H.M. and Hesketh, J.D. (1972). Growth and respiration in cotton bolls. J. Appl. Ecol., 9: 315-317.

Togari, Y., Okamoto, Y. and Kumura, A. (1954). Studies on the production and behavior of carbohydrates in rice plant. I. Porc. Crop Sci. Soc. Jpn., 22: 95-97.

Tollenaar, M., Daynard, T.B. and Hunter, R.B. (1979). Effect of temperature on rate leaf appearance and flowering date in maize. Crop Science, 19: 363-366.

Toriyama, K., Sakamoto, S., Iwashita, T. and Hsu, C.S. (1969). Heading characteristics of japonica varieties planted at the places of different latitudes. Bull. Chugoku Agric. Exp. Stn., Ser., A.17: 1-16.

Troughton, J.H. (1975). Photosynthetic mechanisms in higher plants. Pages 357-391. In: Cooper, J.P. (ed), Photosynthesis and productivity in different environment. Cambridge: Cambridge University Press.

Udagawa, T., Ito, A. and Uchijima, Z. (1974). Phytometrical studies of crop canopies. III. Radiation environment in rice canopies. Proc. Crop Sci. Soc. Jpn., 43: 180-195.

Venkateswarlu, B. and Visperas, R.M. (1987). Solar radiation and rice productivity. IRRI Research Paper Series. In: 129. Philippines, Los Banos: International Rice Research Institute. 22 pp.

Venkateswarlu, B., Prasad, V.V.S.S. and Rao, A.V. (1977). Effect of low light intensity on different growth phases in rice. (*Oryza sativa L.*) Plant Soil. 47: 37-47.

Vergara, B.S. (1976). Physiological and morphological adaptability of rice varieties to climate. Pages 67-75. In: Climate and Rice. Philippines, Los Banos: International Rice Research Institute.

Vergara, B.S. and Chang, T.T. (1976). Flowering response of the rice plants to photoperiod: A Review of literature. Intl. Rice Res. Inst. Tech. Bull. 8. Philippines, Los Banos: International Rice Research Institute. 75 pp.

Versteeg, M.N. and Keulen, H. van (1986). Potential crop production prediction by some simple calculation methods, as compared with computer simulation. Agricultural Systems, 19: 249-272.

Vinay Rai, R.S. and Mutry, K.S. (1979). ^{14}C photosynthesis under reduced light intensity in local and high yielding rice cultivars. J. Nucl. Agric. Biol., 8: 111-112.

Vos, J. (1985). Aspects of modeling post-floral growth of wheat and calculations of the effects of temperature and radiation. Pages 143-148. In: Day, W. and Atkin, R.K. (eds), wheat growth and modeling. NATO ASI Series A86.New York and London: Plenum Press.

Vos, J., Dress, E.M. and Penning de Vries, F.W.T. (1982). Grain formation and assimilate partitioning in wheat. Part II. Modeling post-floral growth of wheat. Pages 144-151. In: Penning de Vries, F.W.T. and Laar, H.H. van (eds), Simulation of plant growth and crop production. Simulation. Monographs. Wageningen: Pudoc.

Wada, G. (1969). The effect of nitrogenous on the yield-determining process of rice plant. Bull. Natl. Inst. Agric. Sci., 16: 27-167.

Warrington, D.J. and Kanemasu, E.T. (1983). Corn growth response to temperature and photoperiod. I. Seedling emergence, tassel initiation and anthesis. Agronomy Journal, 75: 749-754.

Watson, D.J. (1947). Cooperative physiological studies on the growth of field crops. I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. Annals of Botany, 11: 41-76.

Whisler, F.D., Acock, B., Baker, D.N., Fye, R.E., Hodges, H.F., Lambert, J.R., Lemon, H.E., McKinion, J.M. and Reddy, V.R. (1986). Crop simulation models in agronomic system. Advances in Agronomy, 40: 141-208.

Wilson, J.M. (1984). Economic importance of chilling injury. Outlook on Agriculture, 14(4): 197-203.

Wit. C.T. de (1965). Photosynthesis of leaf canopies. Research Report No 663. Wageningen: Pudoc. 57 pp.

Wit, C.T. de, Brouwer, R. and Penning de Vries, F.W.T. (1970). The simulation of photosynthetic systems. Pages 47-70. In: Prediction and measurement of photosynthetic productivity. Wageningen: Pudoc.

Wit, C.T.de, Goudriaan, J., Keulen, H. van, Laar, H.H. van, Louwerse, W., Penning de Vries, F.W.T., Rabbainge, R. and Sibma, L. (1978). Simulation of assimilation, respiration and transpiration of crops. Simulation Monographs. Wageningen: Pudoc.

Wit, C.T. de, Laar, H.H. and Keulen, H. van (1979). Physiological potential of crop production. Pages 47-82. In: Sneep, J. and Hendriksen, A.J.T. (eds). Plant Breeding Perspectives. The Netherlands: Wageningen.

Yamaguchi, J. (1978). Respiration and the growth efficiency in relation to crop productivity. J. Fac. Agric., Hkkaido Univ., 59: 59-129.

Yambao, E.B., Ingram, K.T., Dingkuhn, M. and De Datta, S.K. (1987). Simulation of potential production of rice using Lorice. In: Penning de Vries, F.W.T., Jansen, D.M., Bakema, A.K., Rabbinge, R. and Garrity, D.P. (eds), Case studies in Crop Simulation, April 1986-January 1987. Philippines, Los Banos: International Rice Research Institute, The Netherlands, Wageningen: Centre for Agro biological Research and

Department of Theoretical Production Ecology of Wageningen Agricultural University.

Yoshida, S. (1972). Physiological aspects of grain yield. Ann. Rev. Plant Physiol., 23: 437-464.

Yoshida, S. (1981). Fundamentals of rice crop science. Philippines, Banos: International Rice Research Institute. 269 pp.

Yoshida, S. and Ahn, S.B. (1968). Nitrogen nutrition, leaf resistance and leaf photosynthetic of the rice plant. Soil Science Plant Nutrition, 22(2): 207-211.

Yoshida, S. and Coronel, V. (1976). Nitrogen nutrition, leaf resistance, and leaf photosynthetic rate of rice plants. Soil Science Plant Nutrition, 22(2): 207-211.

About

Agro-Meteorological Information Systems Development Project (AMISDP) and Crop Modelling

AMISDP serves as "Component "C": Bangladesh Weather and Climate Services Regional Project" funded by the World Bank. The overall objective is "to strengthen the capacity of the Government of Bangladesh to deliver reliable weather, water and climate information services and improve access to such services by priority sectors and communities". Activities of the AMISDP, among others, include development of five crop simulation models - 'Aus' rice through Bangladesh Rice Research Institute (BRRI), Jute through Bangladesh Jute Research Institute (BJRI), Maize and Potato through Bangladesh Agricultural Research Institute (BARI) and Sugarcane through Bangladesh Sugarcrop Research Institute (BSRI). Five scientists have been assigned for each of the modelling works from the respective institutes, who had been trained by the AMISDP. This book is a compilation of the training lectures. The AMISDP is also providing research costs in relation to crop-environment-specific field data acquisition aiding development and validation of the models. Details of AMISDP activities and services can be found @ https://www.bamis.gov.bd

---

The Author

Dr. Moin Us Salam (moinsalam1@gmail.com) is an Agricultural Scientist and Crop Systems Modeller, internationally recognized as agro-systems analyst and forecaster of crop diseases. Dr. Salam served the Department of Agriculture and Food Western Australia (DAFWA) of the Government of Western Australia for 17 years and held the position of a Principal Research Officer, the highest level attainable for a practicing scientist in the Department. He was also with the Bangladesh Agricultural University, Mymensingh, Bangladesh, for 10 years as a faculty in the Department of Agronomy. Dr. Salam studied in Reading University, UK, for PhD and University of Florida, Gainesville, USA, for postdoc. His recent work places include the International Maize Wheat Improvement Center (CIMMYT), the United States Agency for International Development (USAID) through Dhaka Ahsania Mission (DAM), Food and Agriculture Organization (FAO) of the United Nations, International Rice Research Institute (IRRI), Practical Action Bangladesh and the University of Western Australia (UWA). He has published 80 refereed papers in reputed journals), 39 papers in conference proceedings, 15 articles in books and delivered 14 Consultancy Reports.