Short Course on

Crop Weather Modeling

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Lecture Notes

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BASIC ASPECTS OF MODELING SOIL-PLANT-ATMOSPHERE CONTINUUM

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What is a Model?

It is a simplified description
(often, a mathematical representation)
of a system to assist
calculations and predictions.

In the present context, ómodelô is expressed as a computer program that can be repeatedly run several times for computing several designed mathematical or statistical expressions (equations) governing crop growth-environment relations, given appropriate input data.

Simulation: This is the reproduction of an observed phenomenon (e.g., growth of biomass with time; water use by a growing crop etc.,) by developing a model and a computer programme written for it. Such a programme usually is comprised of mathematical, statistical, physical, graphical or empirical expressions relating the various parameters given as input information or data.

Model is a concept; simulation helps reproduction of a system in the laboratory using the concept;; could contain measurable or estimated parameter values or both. Most often, the computer programme written for any particular purpose is itself called a model.

Crop-environment interactions are unlimited in number. They can be studied from several points of view (physical, physiological, chemical, biochemical, bio-technological, agronomical, entomological or pathological, economic benefit angles etc.,). We have the roots growing with passage of time and interacting with soil, taking up water and nutrients for transport to the above-ground parts of a plant. The stem, branches, leaves as they grow interact with environment (both individually and together), under the influence of solar radiation to produce flowers and pods / oils, grainsð ultimately yield. Evapotranspiration, Leaf-air interactions, Photosynthesis, respiration, carbon dioxide assimilation, are the other processes involved in crop growth. Crop is also affected by pest/disease incidence. Thus crop growth is usually viewed as a ñcomplex systemò which comprises of ñsub-systemsò in which several processes take place. One process leads to the other and so, individual processes (water or nutrient uptake by roots, biomass accumulation, grain growth etc.,) are considered as ñsub-systemsò. All the processes which interact among themselves (since the start of growth of plant from seeding to final yield) and put together are considered as a ñsystemò. Thus one can have ñsub-modelsò as part of a ñmodelò, ñsub-systemsò and a ñSystemò. One can simulate water uptake, branching pattern and growth, leaf development, pod growth, etc. and their interaction with soil and aerial environment, as ***individual models***. The point to note is that there is no limit to the items that can be taken up to develop a simulation model.

Systems analysis models:

Modeling several of the soil-plant-atmosphere-water interactions which are mutually dependent on each other resulting in crop growth, popularly known as the ***SPAW-system,*** is a ***linked single entity*** of sub-systems. System models could also include economic factors such as operating costs, cost-benefit ratios from the time land is prepared, till transport and marketing of the produce. Examples of systems-model are the Oryza model for rice, CERES maize model, DISSAT models etc., which have several component sub-systems.

Subsystems: These are parts of a complex ówholeô which themselves could be viewed independently where needed. Rainfall-yield model, Soil moisture distribution model, rainfall-run off model, root growth model etc., are all sub-systems. Interaction among leaf-atmospheric vapour, stomatal resistance, air stream adjoining the leaf surface, net radiation could be the parameters of a theoretical (mechanistic) subsystem model development. Each such objective can become a sub-model material. In modeling crop-weather interactions, possibilities are immense and limitless. Ultimately, such subsystems can be appropriately connected to evolve them into a single óSystem-modelô.

Mechanistic process models:

A *process model* is an elaborate and practically complete description of the ***mechanism*** involved in a processð e.g., photosynthesis, green or dry matter production, partitioning of photosynthates, soil water uptake and transport by the root system etc., Such models for crop growth usually are designed to compute the products daily to simulate growth of a plant including all known processes (the underlying mechanisms) in the soil-plant-water-environment system. These could include water-fertilizer uptake and their transport, effect of flood and water logging, effect of pest-disease incidence etc., popularly known as the **dynamic crop growth simulation models,** since, given the relevant data input, they are designed to compute day-to-day expected crop growth as a result of several growth related phenomena that ultimately influence the yield. .

Operational models:

On the other hand, operational models(for day-to-day field operations) in relation to the SPAW system can be developed to simulate crop growth using known relations (statistical, empirical, mathematical or graphical models) depending on data availability, regional and local crop-environmental conditions for growth, ***including or bypassing some of the mechanistic details involved in the system.*** Also, different models need to be developed for space and time variations involved. In this exercise, area of operation (could start with a village), time-duration of individual crop growth phases and seasonal factors characteristic of crop species are involved. After gaining experience with such operational models at a few diverse locations, they can be modified or integrated to extend them from local (a village) to a district or agroclimatic regional level. In this process, several modifications may be needed. They can be **"user targeted"** to find an answer to several day-to-day crop-weather related problems encountered in the field. For example, an operational model can be developed to answer a question such as: How many days would it take for the field to be free from water logging after a heavy rainfall for a couple of days? How much reduction in yield could one expect due to continuous high temperature period for four to five days at pod formation stage? Is the crop suffering from agricultural drought or atmospheric drought? What would be expected reduction in yield? Such individual models not forming a systems model, ultimately lead to development of ñEXPERTò systems.

It should be recognized that unforeseen contingencies cannot be modeled and local on-the-spot decision has to be taken. Flooding due to breeches in bunds, water logging due to very heavy local rainfall, gale strength winds, thunderbolts are some of the examples. After immediate remedial action is taken against these calamities, if the crop gets destroyed, crop-weather contingency models can then be used for alternate contingency crop planning for the remaining part of the season.

Statistical models and dynamic simulation models

Crop-weather modeling has two approaches (i) statistical (ii) dynamic simulation modeling. Statistical approach has found wide application since the early 20th century but it has several limitations for application in operational agriculture at the present time. Dynamic simulation approach similarly has both advantages and disadvantages. Process oriented approaches are considered desirable for establishing rate-processes and linkages in the soil-plant-atmosphere-water flow system. They have their own role to play more as research tools and for yield forecasting rather than for field operations.

Statistical models are developed using long term (say 20-30 year series) average values over a long period between two or more parametersð say rainfall and crop yield. Statistical functions like linear, curvilinear, multiple regression, orthogonal polynomials (depending on the number of parameters and data availability) etc., are developed between these two or a few more parameters. Their variability and significance are tested using rigorous procedures and ultimately a regression function is finalized. These could assist in making long-term assessment of crop performance on an average over a couple of decades but given the vagaries of monsoon rainfall, such regressions, more often than not, fail in an individual year. As an example, in semi-arid regions, rainfall variability being high (>100%), applicability of such regressions may fail in an individual season. So, in practice, it becomes unusable except to understand the extent of association between rainfall, temperature etc., and yield ***in general*** in a locality ***over a long period***. This is a limitation of such regression models in the tropical or sub-tropical region like ours. Often the experience in the All India Coordinated field trials, is that one year the crop-weather parameter association comes out as significant while the very next year it could be non-significant association leading to erroneous interpretation.

Dynamic simulation models:

On the other hand, dynamic simulation models seek to compute such growth values on a day to day basis using the relations between crop growth parameters and weather parameters. It seeks to rebuild the day to day crop growth in mathematical or mechanistic terms (simulation) depending on the magnitude of rainfall (or any other parameters) on a particular day and magnitude of a crop parameter (or other parameters like physiological, soil, biological parameters) representing crop growth till that day. i.e., daily simulation is done depending on the parameter values obtaining on a day and cumulated over the growth period.. Such simulation is continued till harvest time. ***“Growing the crop on the computer”*** is a popular expression.

It is not essential to run a mechanistic model for all purposes. In subsystems of such models, several assumptions are made with boundary conditions. One need not always look to full-scale mechanistic models and systems approach for finding solutions to day-to-day problems arising in agriculture operations imposed by short-period adverse weather conditions. Individual subroutines can be utilized profitably.

Development of a model:

Objective: ***Clarity of objective or purpose is significant and essential.***

Objective of developing a particular model is the first step. It should be derived from intended end-use of any model and clearly identified. The objective could be (i) for academic understanding(research purpose) of crop growth dynamics (ii) for monitoring crop growth for any possible field action including prediction of crop growth and yield (iii) for solving field level (extension) problems (iv) for crop planning in relation to climate change or climate variation, for introduction and assessment of new varieties etc.,. Parameters used may remain same but depending on the purpose of developing a model, the ***structure of the model*** differs. After the objective is decided, it is customary to prepare a ***flow chart***. It is a framework depicting the different steps to be followed like reading the data, computing different components, repetition of calculations if any, print format desired etc., in achieving the objective of the model. Sample flow chart is shown in fig.1.

Field level problems need an immediate answer for decision-making where both time and space scales are involved. It could range from a single village to a region, or a single day to a week or even a season, depending on the nature of the dayӧs weather (a heavy shower of rain) or movement of a weather system (depression, cyclone, heat wave etc.,) over a period of time. So, models need to cater to several such widely varying specific objectives. A thermometer developed for macro scale use (Stevenson screen) obviously is not suitable for measurement of micro-climate. Similar is the case with crop-weather models. Models cannot be expected to have universal application.

To illustrate, one can ask the question: Do we know how the crop growth in its various facets (water redistribution in the cropped soil, pest/disease development, nutrient distribution, biomass accumulation, partitioning of dry matter etc.), is affected by say a rainfall of 20mm received on a single day at different growth stages of the crop? Or if the same rain occurs in three or four consecutive days or falls intermittently, what would be the effect on crop growth or agricultural operations? If there is a rise or fall of temperature during a heat or cold wave at a particular growth stage how is crop growth rate affected and when would the temperatures return to the normal? These questions look simple. Linear equations built in a model do not serve such purpose. More ñifò ñgo toò statements are needed in the computer programme. As yet we do not have immediate answer in quantitative terms for these contingencies as to their effect on crop growth. These are of immediate practical utility. Models can be developed for finding solution to such problems. They would be different from the models developed for research / academic purposes.

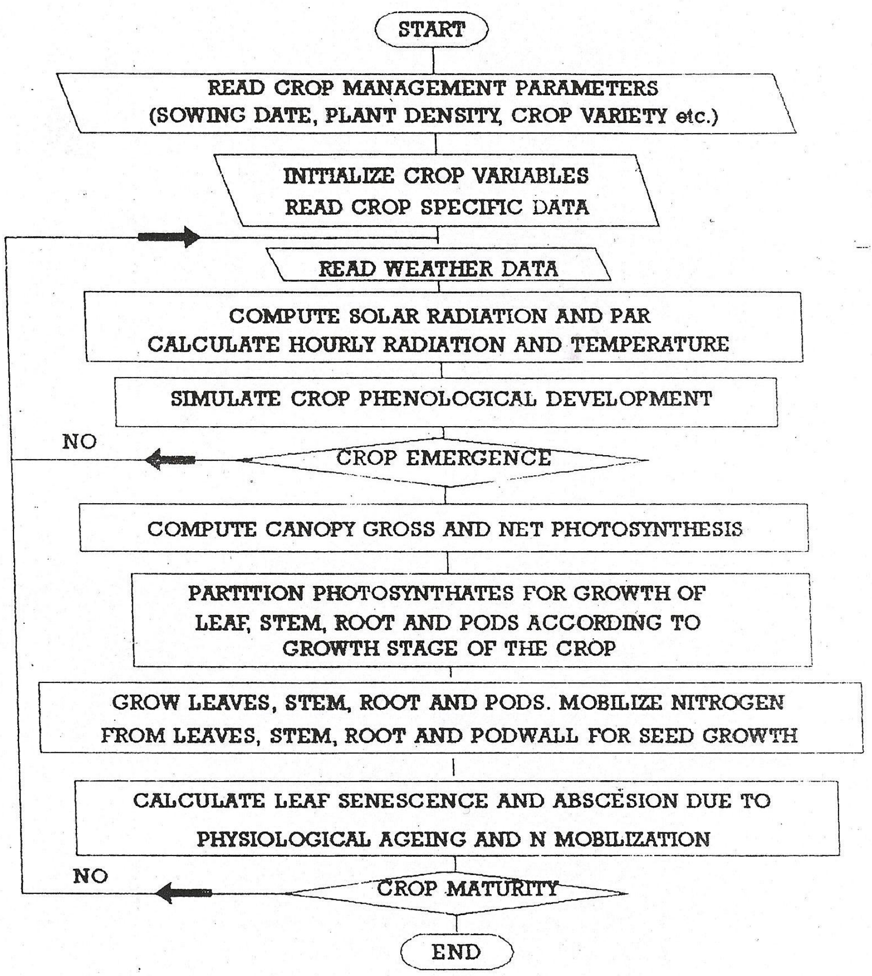

Fig.1. A simplified flowchart of ‘BRASSICA’ model

Sub-models:

Each sub-model is geared to provide quantitative relationship between the parameters involved. For example, root growth subroutine provides information on root growth rates with time, soil depth and moisture for a particular crop and soil type, which are of practical utility in working out water balance or irrigation depth and needs of a growing crop. Rainfall-runoff sub-model can provide information on how much of the rain received on a day (a heavy shower) would infiltrate into the soil and get redistributed depending on the rainfall intensity, antecedent soil wetness and root growth.

Most of the time our concentration is on testing readymade models using single plot approach without nutrient or moisture constraint.. While this is essential to generate data under controlled conditions, to date, we do not know how to translate these plot level results to regional level even if it is as small as a taluk / mandal. Hence one cannot expect homogeneity in any parameter and one has to deal with applying results derived under homogeneity to a heterogeneous larger region with high spatial variability. This heterogeneity cannot be avoided as farmerô practices and capabilities vary widely and exhibited both in time and space. It is also not practicable to generate data from every plot in the region.

Graphical and Checklist models:

Besides simulation models, graphical, parametric or checklist models are also useful in day-to-day work in field operational decisions. These are developed from thumb rules from past experience and simple relations between crop growth and related environmental parameters For example, at a particular growth stage of crop, afternoon humidity more than 60percent, a brief rainfall of 3mm or more, temperature between 25 to 30°C is known to initiate a pest/disease development, Such information can be displayed in a graphical form ***everyday*** and marked ófavourableô or óunfavourableô using weather data. Normally three or four such favourable days would be needed for the pest/disease symptoms to appear on the crop. Since organisms are viable, even when one or two days are not favourable in-between, such favourable days can be counted to make a prediction about the onset of pest/disease over the crop. ***A mere glance at the chart*** would reveal the situation. No computer model need be run. The country needs such simple models, easy to develop into ñEXPERTò systems without much sophistication.

CROP-ENVIRONMENT MODELS.

A pertinent question in the above context is: Is it always essential to use mechanistic models? The answer is ñNOò. Mechanistic models are more geared towards research and need several data inputs which are always not measurable or experimented at every location. This is a physiological approach, and such models also involve several approximations and estimates often resulting in deviations from the actual. Crop-weather models should preferably be designed as operational models needing weather and agronomic data with no genetic coefficients involved, or not always requiring potential conditions of moisture or nutrients etc., Rainfed agriculture being a dominant practice in the country, with potential conditions being absent in several seasons, rainfall driven models are our need. A few models are listed below that can be written as statistical or dynamic simulation models or both and are depicted in fig.2.which shows different pathways to design a crop-weather model. These are only a few examples and not an exhaustive list.

Rainfall- yield model (atmospheric drought, flood)
ET-biomass-yield model ---(Yield potential)
Rainfall-soil moisture distribution model ï (ET, Water balance)
Rainfall-soil water balance-yield model.
Solar radiation interception, LAI, green/dry matter production (Remote sensing)
Rainfall intensity / surface run-off model ----- (water harvesting)
Root zone moisture linked to growth phase ---- water availability to crop
Yield potential models without any constraints (for water, soil, pest disease, nutrient etc.,)
Water ï nutrient uptake ---yield models
Yield potential models with constraints like drought, water logging, pest/disease etc.,
Yield correction models for catastrophic or disastrous events linked to growth phase
Storms and cyclones
Heat and cold waves

Advection effects

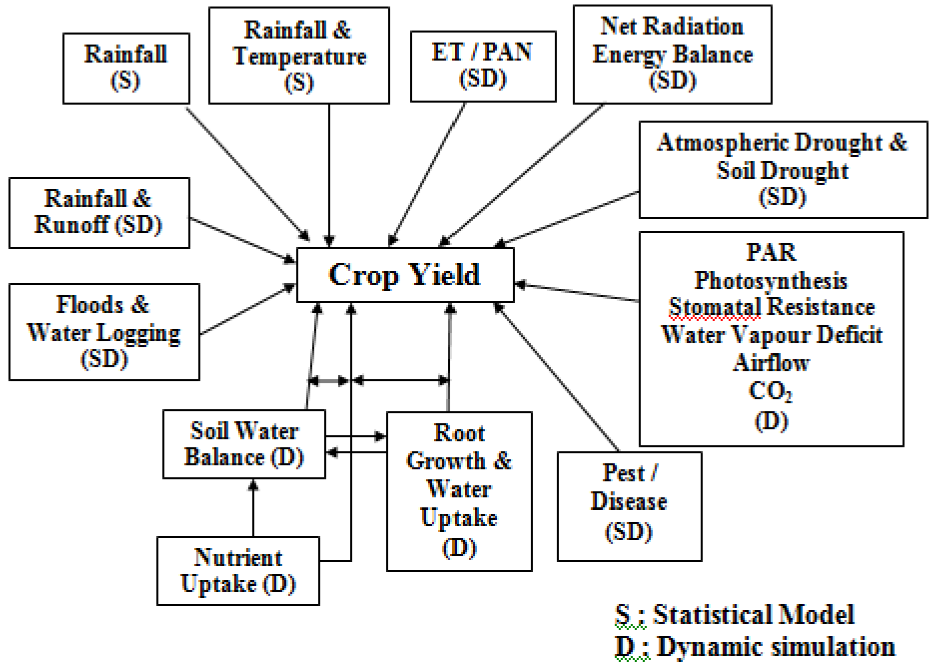

Fig.2. Crop – Environment Models

Concentration should be on

Models relevant to weather based agro-advisories

User targeted models

Phenology as driverð phenology based models

Minimal mechanistic processesð more crop-weather parameters

If you get to successfully write a flow chart and computer software for ñHow to make teaò or ñHow to cook riceò, you would have learnt the logic of programming and model development. Training should provide capacity to write computer programmes ourselves and not be a slave to readymade programs that we may not care to thoroughly scrutinize and understand before applying them.

Phenology, Biomass and its partitioning in crops

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1. Introduction:

Estimation of the timing of the Phenological stages and partitioning of biomass are two important components of any crop simulation model. Accurate representation of phenology is essential when using crop simulation models to study the effect of changes in climate or management practices (e.g. planting date, cultivar selection or irrigation scheduling) on crop yield. Unfortunately, the timing of phenologiocal stages is not always well simulated when models are used in environment or management conditions differing significantly from those for which they were developed (White et al., 2003). Allocation (Partitioning) of total drymatter to different organs of a plant is of great importance in crop growth, development and yield. There is a great diversity in the way crops partition assimilates and simulation models developed so far are speciesï specific. Within species, genotype, development stages of plant, growth conditions and internal regulations by the plant may also affect drymatter allocation (Marcelis 1996).The simulation of biomass partitioning is one of the weakest features of current crop growth models.

Phenology or stages of crop development, crop growth rate, partitioning of biomass in to growing plant organs accomplish the state of a crop at any time. All these processes are dynamic and are affected by weather, soil and cultivar specific factors. The objective of the presentation is to describe the processes, their estimation and importance to crop simulation modeling.

2.Basic principle of crop simulation:

In simplest form, total biomass (Bt) of a crop can be written as the product of average growth rate (g) and growth duration (d) i.e

$$Bt = g \times d$$

Simulation of yield in process based models must predict these two important variables. The duration of plant growth also has two district features viz., phasic and morphological development. Phasic development involves changes in the stage of growth and is always associated with major changes in biomass partitioning. Phasic development of crop in the models quantifies the physiological age of the plant and describes duration of various growth phases.

3.Phenology:

Phenology is the study of periodic biological phenomena. It qualitatively describes the successive stages in the development of plants, from seed germination to flowering to maturity. The crop growth stages, also known as phenophases differ from crop to crop. Only main stages viz., germination, differentiation of flower, flowering seed formation, seed filling and maturity are common to almost all flowering plants.

Phenology can be modeled based on vernalization, photoperiod, thermal response and intrinsic earliness (Cao and Moss 1997), most of which are plant specific. The environmental and cultural factors directly or indirectly influencing crop phenology are : Atmospheric Carbon dioxide (indirect), Solar radiation (indirect) , photo period (direct on flowering), Temperature (direct) , water (Indirect) ,wind (indirect), nutrients(N,P,K) (both direct and indirect) and growth regulators (indirect).

Temperature and photoperiod are the two main environmental factors that determine flowering in young and established plants.

3.1. Effect of temperature on phenology:

Temperature plays an observable effect on rate of development of plants and the effect is significant not only in temperate countries but also in tropical countries (Malhood, 1997)

Growing degree-day Concept;

Heat units, expressed in growing degree days (GDD) are widely used to describe the timing of biological process. Growing degree-days (GDD), also called heat units, effective heat units, or growth units, are a simple means of relating plant growth, development, and maturity to air temperature. The concept is widely accepted as a basis for building phenology and population dynamic models. Degree-day units are often used in agronomy, essentially to estimate or predict the lengths of the different phases of development in crop plants (Bonhomme, 2000).

The GDD concept assumes a direct and linear relationship between growth and temperature. It starts with the assumption that the growth of a plant is dependent on the total amount of heat to which it is subjected during its lifetime. A degree-day, or a heat unit, is the departure from the mean daily temperature above the minimum threshold (base) temperature. This minimum threshold is the temperature below which no growth takes place. The threshold varies with different plants, and for the majority of plants it ranges from 4. 5 to 12.5°C, with higher values for tropical plants and lower values for temperate plants.

3.2 Methods of Degree-Day Estimation

Many methods for estimating degree-days are available in the literature (Perry et al., 1997; Vittume et al., 1995). The three most dependable and commonly used methods are the standard method, the maximum instead of mean method, and the reduced ceiling method. Numerous other methods have been proposed, majority of them are modifications of one of these three. An exhaustive review of degree-day methods was reported by Zalom et al. (1993).

1. Standard degree-day method:

$$GDD = \times \; [(Tmax + Tmin)/2] \text{ ï } Tbase \qquad (1)$$

where (Tmax + Tmin)/2 is the average daily temperature and Tbase is the minimum threshold temperature for a crop.

2. Maximum instead of means method:

$$GDD = \times \; (Tmax \text{ ï } Tbase) \qquad (2)$$

3. Reduced ceiling method: where Tmax Ò$T_{ceiling}$, then

$$GDD = \times \; (Tmax \text{ ï } Tbase), \text{ or} \qquad (3)$$

where Tmax > $T_{ceiling}$, then

$$GDD = \times [(T_{ceiling} - (Tmax - T_{ceiling})) - Tbase] \qquad (4)$$

If maximum temperature (Tmax) is greater than the ceiling temperature ($T_{ceiling}$), then set Tmax equal to $T_{ceiling}$ minus the difference between Tmax and $T_{ceiling}$.

Over the years, many equations have been proposed to substitute the GDD method.

The equation below, recently published by Xinyou Yin et al. (1995) seems to give reasonable results under field conditions (which does not mean that it would yield useful results at a regional scale).

The graph below (figure 1) illustrates the behaviour of a more sophisticated model proposed by Xinyou Yin et al. (1995), based on the beta distribution. The development rate DR is given by

$$DR = ȷ^{µ} (Tï T_b)^{Ŭ} (Tu - T)^{ϭ} \qquad (5)$$

where T_b and T_u are the base and upper values. µ is a size parameter, while Ŭ and ϭ are shape parameters.

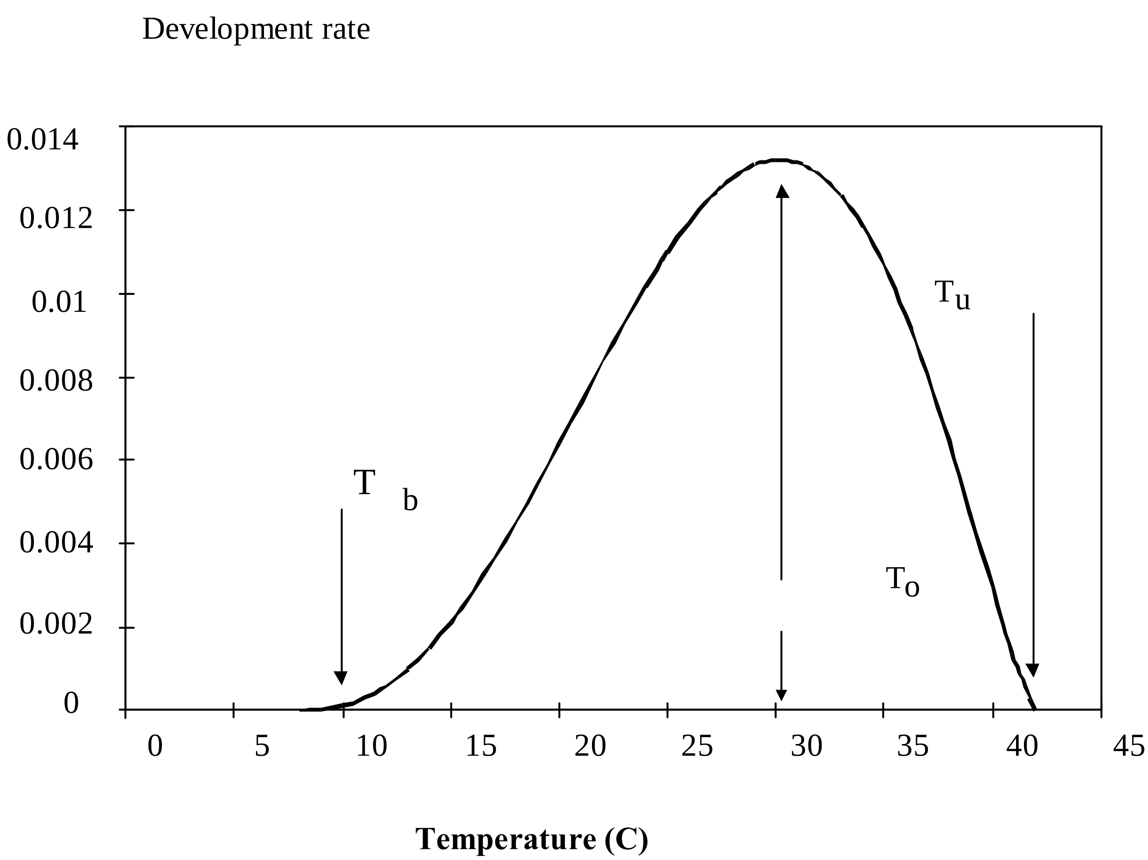
For a given phenological interval (planting to emergence, of heading to maturity, etc.), the development rate is the reciprocal of the time in days to complete the phase.

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

$$T_o = (ŬT_u + ϭ\, T_b) / (Ŭ + ϭ) \qquad (6)$$

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

figure 1 : Variation of development rate (Rice 1R8, from sowing to flowering) as a function of temperature using the Beta model of Xinyou Yin et al. (1995). T_b is taken as 8 C and T_c is 42 C. The other parameters are µ= -15.6721; Ŭ= 2.5670; ϭ= 1.3726.



4. Photoperiod

Plants can be categorized as long-day plants, short-day plants and day-neutral plants. Flower differentiation is initiated in long-day plants by a threshold of day length below which the plants will not flower. Above the threshold, there is an optimum daylength. Similarly, short-day plants will not flower if the day exceeds a threshold. To some extent, the photoperiodic response is independent of growth: if plants are grown outside the optimum time of the year, they may flower in very early stages (millet) or never flower at all if the proper daylength is not available.

Duration of the life cycle and, therefore, rate of development, may be influenced by photoperiod during one or more phases of development (Fig. 2). Duration of the life cycle in short-day plants can be increased when plants are growing in environments with a day length longer than 12 hours (or when the duration of the dark period is less than 12 hours).

Effects of photoperiod on duration of the life cycle vary with phase of development, i.e., at least three phases can be distinguished:

Phase 1: A photoperiod-insensitive phase. Photoperiod does not influence time to flower initiation during the juvenile phase, a phase that starts at sowing.

Phase 2: A photoperiod-sensitive inductive phase. This phase extends from the end of the juvenile phase to flower initiation. Flower initiation is advanced or postponed by the photoperiod during this phase.

Phase 3: A photoperiod post-inductive phase. This phase may comprise photoperiod sensitive and/or photoperiod insensitive phases; photoperiod during this phase may influence the duration from flower initiation to physiological maturity.

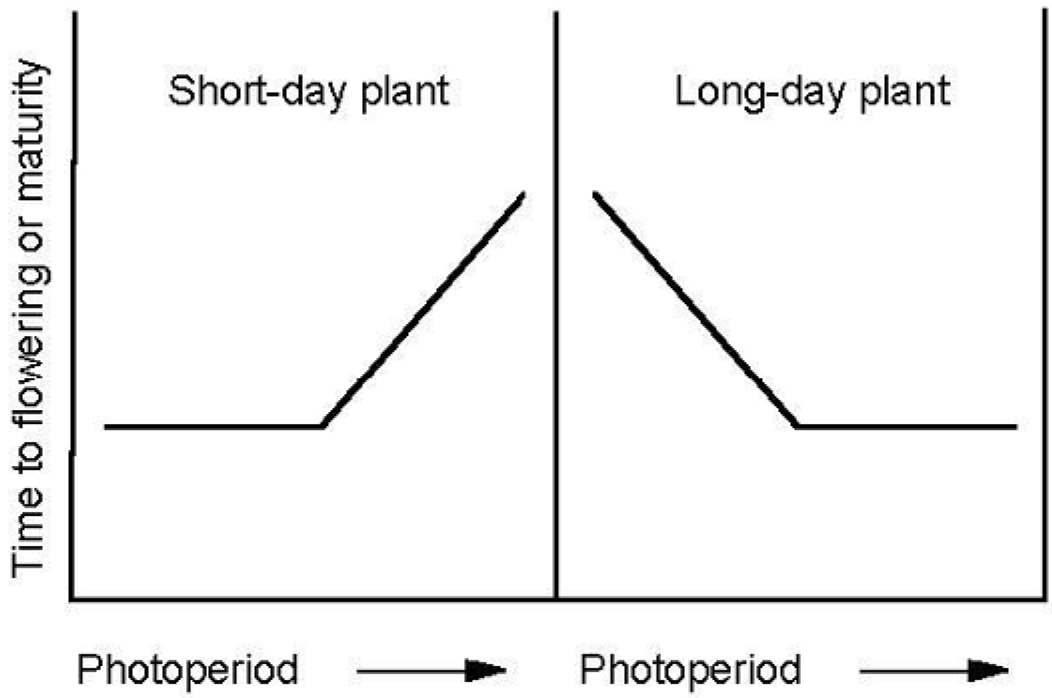


Fig 2. Duration of time to flowering or maturity in response to photoperiod in a short-day or long-day plant

5 Vernalization.

Vernalization can be seen as the need for seeds or plants to be exposed to a cold threshold between T_1 and T_2 ($T_1 < T_2$). It also constitutes a mechanism to avoid frost damage. Temperatures below T_1 will kill the plant, while if temperature stays above T_2, plants will not develop. This may be combined with the duration of exposure: a shorter exposure is sometimes sufficient close to T1, while the vernalization duration is much longer close to T_2.

Other environmental factors can have a "photoperiod like" trigger response in plants. For instance, some cereal crops (e.g., winter wheat and barley cultivars originating in northern Europe and Canada) have a specific requirement for a period of low temperature for floral initiation (the vernalization requirement). In other crop species (such as tulip), seeds, bulbs, seedlings, and/or plants have to be exposed to a specific temperature regime for floral initiation to occur. Temperature, solar irradiance, soil nitrogen, and soil moisture can also have a small effect on final leaf number in maize, thereby changing time to flowering and maturity. The photoperiod and photoperiod like responses appear to influence the duration of the life cycle by affecting translation and/or transcription of the genetic code that triggers differentiation.

Wheat and barley varieties usually require relatively low temperatures before spikelet formation can begin. This low temperature requirement for flowering, called vernalization , begins at germination . The optimum temperature for vernilization is assumed to be in the range of O to 7^0 C ,with temperatures between 7 and 18^0 C having decreasing influence on the process.

6.Biomas growth

There are several approaches to the estimation of biomass production, which range from the estimations of photosynthesis and respiration to direct estimation of biomass production from radiation interception or transpiration of crops. Simple and most common method is the estimation of biomass from radiation interception and radiation use. In CERES models biomass production is estimated as follows.

$$\text{Potential biomass production (PCARB)=RUE} \times \text{IPAR}$$

Where RUE is the radiation use efficiency and IPAR is the fraction of PAR intercepted by plants. The actual daily biomass production (CARBO) may be less than PCARB because of non-optimal temperature or deficits of water or nitrogen. The equation to calculate CARBO uses the law of limiting concept to reduce PCARB.

$$\text{CARBO=PCARB}\times\text{MIN (PRFT, SWDF1, NDEF1,1)}$$

Where PRFT, SWDF1 and NDEF1 are the temperature, water deficit, and nitrogen deficit factors, respectively, varying between 0 and 1, and min indicates the minimum value of the parenthesis is used. Another approach used in the APSIM suit of models is the estimation of biomass production by two methods each day, one limited by available water for transpiration, and the other limited by radiant energy. The minimum of these is the actual biomass production for the day.

$$\text{Biomass production = transpiration} \times \text{transpiration efficiency}$$

$$\text{Biomoss production = RUE} \times \text{radiation interception}$$

RUE incorporates the temperature, water-logging (oxygen deficit), and nitrogen stress effects.

7. Biomass partitioning and translocation

On the day of emergence, biomass (and nitrogen) allocation to leaves, stems, and roots is initialized. After this biomass produced is allocated to different plant parts as function of growth stage and evaluates each day the sink capacity of the above ground biomass to determine if the crop is sink-limited or source-limited (or the supply ï demand limited).

The following procedures are followed in the models.

Allocation to roots

Roots are grown as per the root-shoot ratio specified for each growth stage.

Above ground biomass allocation in legumes

Emergence to flowering: A proportion of biomass produced during this phase is partitioned to leaf and stem. If leaf demand for assimilates is less than supply, the residual is partitioned to stems. Likewise, if supply is less than leaf demand, the rate of leaf area increase is reduced.

Flowering to start of grain fill: The same procedure is used for determining leaf biomass as for the emergence to flowering phase. Of the remaining carbon, a proportion goes to stem and pod in the specific ratio.

Start to grain –fill to maturity: The biomass produced during this phase is portioned among pod including grain, and stem. If grain demand is lower than supply, the remaining goes to leaf and stem as per amounts specified for the growth phase.

Above ground biomass allocation in cereals

Emergence to terminal spikelet: Of the daily biomass produced , 65% is portioned to leaves and the rest goes to stems. This may vary among different cereals.

Terminal spikelet to flag leaf: After terminal spikelet leaf biomass fraction is linearly decreased with the fraction of thermal time to zero at flag leaf. On the day the estimates of specific leaf area (SLA) goes below the minimum SLA, the extra biomass is diverted to roots.

Flag leaf to beginning grain fill: Leaf growth ceases and all the above ground biomass increase is assumed to go to the functional stems.

Beginning grain fill to end of grain fill: Biomass increase is used to meet grain demand first and the rest is put in to stems.

Reference

Bonhomme, R. (2000). Beware of comparing RUE values calculated from PAR vs solar radiation or absorbed vs intercepted radiation. *Field Crops Research* 68: 247-252.

Perry, K.B., Wu, Y., Sanders, D.C., Garrett, J.T., Decoteau, D.R., Nagatta, R.T., Dufault, R.J., Batal, K.D., Granberry, D.M., and Mclaurin, W.J. (1997). Heat units to predict tomato harvest in the southeast USA. *Agricultural and Forest Meteorology* 84: 249-254.

Cao, W. And D.N. Moss, 1997. Modelling phasic development in wheat: a conceptual integration of physiological components. J. Agric. Science, 129(2):163-172.

Vittum, M.T., Dethier, B.E., and Lesser, R.C. (1995). Estimating growing degree days. Proceedings of the American Society for Horticultural Science 87: 449-452.

Xiniou Yin, M.J. Kropff, G. McLaren and R.M. Visperas, 1995. A nonlinear model for crop development as a function of temperature. Agric. Eor. Meteorol., 77:1-16.

Zalom, F.G., Goodell, P.B., Wilson, L.T., Barnett, W.W., and Bentley, W.J. (1993). *Degree-Day: The Calculation and Use of Heat Units in Pest Management.* University of California, Division of Agricultural Sciences Leaflet 21373.

Interception of Solar Radiation, Radiation and Water-use Efficiency

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01. Solar Radiation and Solar Constant

Introduction:

Plants are the natureǿs converters of solar energy into useful form of the energy, which is biomass and sustain biological life providing food. fodder, fiber, fuel etc. Solar energy fulfils two essentials need of the plants ï

1. Light for Photosynthesis
2. Thermal Conditions required for all normal physiological functions of the plants

Radiation increases evapotranspiration. Transpiration rate increases almost in proportion to the intensity of the solar radiation, while in many crops, the rate of the photosynthesis increases less rapidly, Crop production in agriculture is basically dependant on quality and quantity of radiation.

Radiation:

The transfer of thermal energy in the form of electromagnetic waves from one place to another through the vacuum with speed of light is called radiation. Every material in our vicinity--soil, water, plant, animal etc. with temperature greater than absolute zero emits characteristics radiation specific to itǿs own body temperature. Thus, all bodies are in interaction with other bodies through radiation process .

ñ*Solar radiation is defined as "The flux of radiant energy from the sun. The variations of the total radiation flux from one site to another on the surface of the earth are enormous and the distribution of plants and animals responds to this variation".*

Solar Constant:

The flux of solar radiation that is received on a unit area of surface held perpendicular to the sunĝs direction at 0

the mean distance between the sun and the earth is referred to as solar constant.

The solar constant is 56 x 10^{26} cal energy min^{-1}.The mean distance of the earth from the sun is

1.496 x 10^{13} cm. The energy per unit area incident on the spherical shell of the earth concentric with the sun with this radius is :

Total radiation = 56 x 1025 cal cm-2min-1

Total area of spherical shell 4π(1.5 x 1013)2

= 1.979 cal cm-2 min -1 OR 2 Langley min -1

02. Important Terms and Definition

Forms of Solar Radiation

Direct Solar Radiation

Sky radiation or diffused radiation

Global radiation

Reflected radiation

Thermal radiation

Net Radiation

Transfer of heat can occur in 3 ways

Conduction: transfer of heat through solids

Convection: transfer of heat by circulation

Radiation: transfer of heat by electromagnetic waves

Electromagnetic Energy: Solar energy is an electromagnetic phenomenon. In terms of electric energy, the radiation from the sun attenuated by atmosphere as incident upon the earth is equivalent to 1390 watts m^{-2} or roughly, 1.4 kilowatt m^{-2}

Electromagnetic Spectrum: It is total range of radiation from short to microwave. In other words, it is the continuous sequence of electromagnetic energy arranged according to wavelength or frequency

Solar Spectrum: A very broad part of the electromagnetic spectrum occupied by wavelength from which the radiant energy received from the sun is spread.

Global Radiation: Sum of the short wave radiation directly from the sun and indirectly from the sky.

Insolation: Incoming solar radiation from the sun that strikes the earthś surface over a finite time period such as day.

Infrared Radiation: Solar radiation higher than visible wavelength segment wavelength between 07 and 50 microns

Ultraviolet radiation: Part of solar spectrum having wavelength shorter than visible segment and range from 0.0005 to 0.4 microns.

Light: Middle part of the solar radiation in the wavelength between 0.4 to 0.7 microns, It is sensitive to human eye and most important for plant life.

Net Solar Radiation: It is the difference between the extra terrestrial radiation received on outer boundaries of atmosphere and actual radiation absorbed by the earth.

Net radiation: It is the balance of the energy after gain of solar radiation and loss of long wave terrestrial radiation flux. The net radiation responses the amount of energy, which is used for various kind of activities of biosphere.

Albedo: The proportion of incident energy that is reflected or the reflection coefficient of incoming solar radiation . A high albedo indicates that much of the incident solar radiation is reflected than absorbed.

Atmospheric Window: This refers to the outgoing long wave radiation from earth in the wave length of 8.5 to 11 microns, which goes into space without absorption.

Radiant Flux : The amount of radiant energy emitted , received or transmitted across a particular area per unit time.

03. Electromagnetic Spectrum

Electromagnetic Radiation

EMR is a dynamic form of energy that propagates as wave motion at a velocity of c = 3×10^{10} cm/sec. The parameters that characterize a wave motion are wavelength (λ), frequency (v) and velocity (c) (Fig. 2). The relationship between the above is

$$c = v\lambda.$$

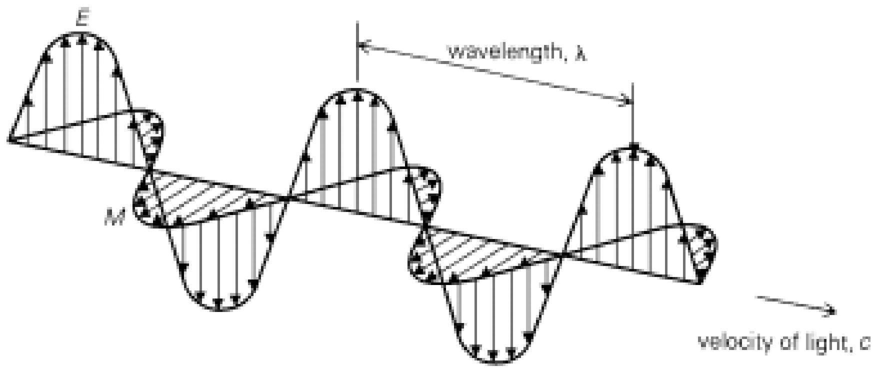


Figure 2: Electromagnetic wave. It has two components, Electric field E and Magnetic field M, both perpendicular to the direction of propagation

Electromagnetic energy radiates in accordance with the basic wave theory. This theory describes the EM energy as travelling in a harmonic sinusoidal fashion at the velocity of light. Although many characteristics of EM energy are easily described by wave theory, another theory known as particle theory offers insight into how electromagnetic energy interacts with matter. It suggests that EMR is composed of many discrete units called photons/quanta. The energy of photon is

$$Q = hc / \lambda = h\,v$$

Where

Q is the energy of quantum,

h = Planck's constant

Electromagnetic Spectrum:

Light forms a small part of a large family of **electromagnetic waves**. We know how light splits into the colors of the rainbow. The scientific term for this is a **spectrum**. You can see that the colours run into each other. There are no distinct boundaries.

The properties of electromagnetic waves are related to their length and frequencies. When arranged according to length, they form a continuous arrangement, known a Electromagnetic Spectrum. Here is a picture that sums up the electromagnetic spectrum

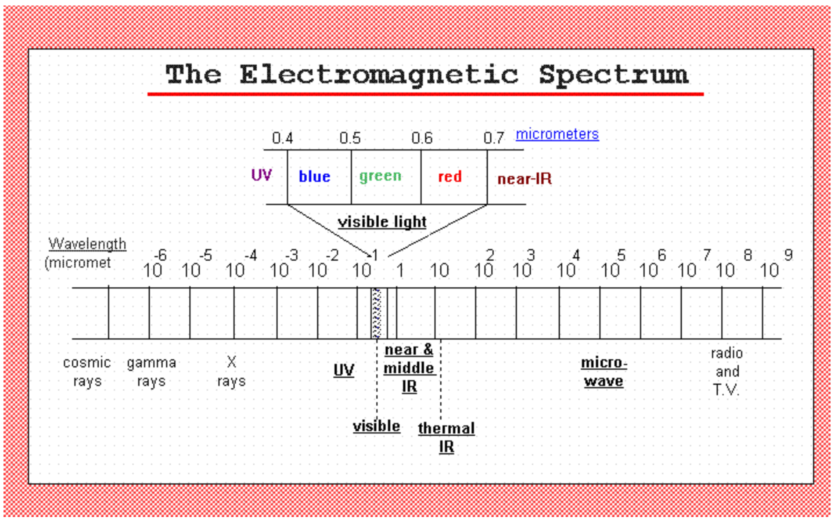


Figure 03. EMR Spectrum

Physiological Response to plant to different band of Incident Radiation:

S. No.	Band No	Spectral region (microns)	Character of absorption	Physiological effect
1.	1st	Infrared >1.000	By water in tissues	Converted into heat; this has no specific effects on photochemical and biochemical processes.
2.	2nd	1.000 to 0.700	slight	Stimulator elongation in plants
3.	3rd	0.700 to 0.610	Very strong by chlorophylls	Large effect on photosynthesis and photoperisodism
4.	4th	0.610 to 0.510	Somewhat less	Small effect on photosynthesis; small morphogenic effect
5.	5th	0.510 to 0.400	Very strong by chlorophylls and carotenoids	Large effect on photosynthesis; large morphogenic effect
5.	5th	0.510 to 0.400	Very strong by chlorophylls and carotenoids	Large effect on photosynthesis; large morphogenic effect
6.	6th	0.400 to 0.315	By chlorophyus and protoplasm	Small effect on photosynthesis. Produces fluorescence in plants
7.	7th	0.315 to 0.280	By protoplasm	Significant germicidal action; Large morphogenic effect; stimulating some biosynthesis; large effect on physiological processes
8.	8th	< 2.80	By protoplasm	Large germicidal effects. Lethal in large doses

04. Light Interception and Crop Growth

Photosynthetically Active Radiation (PAR) is the amount of light available for photosynthesis, which is light in the 400 to 700 nanometer wavelength range. PAR changes seasonally and varies depending on the latitude and time of day.Levels are greatest during the summer at mid-day. Factors that reduce the amount of PAR available to plants include anything that reduces sunlight, such as cloud cover, shading by trees, and buildings. Air pollution also affects PAR by filtering out the amount of sunlight that can reach plants. Usually measured in Einsteins (Einstein = 6.02 x 1023 photons or one mole of photons). At night, PAR is zero. During mid-day in the summer, PAR often reaches 2,000 to 3,000 millimoles per square meter.

How is Photosynthetically Active Radiation measured?

Photosynthetically Active Radiation (PAR) is reported as millimoles of light energy per square meter. Photosynthetically Active Radiation (PAR) is measured by a silicon photovoltaic detector.

This detector measures light in the 400 nanometer to 700 nanometer range. Some PAR sensors measure the PPFD of photosynthetically active radiation.

PAR Spectral Characteristics of the Crop:

Spectral characteristics explains the reflectance , transmittance, absorption of surface under different wavelength . spectral properties of a vegetation or canopy or itôs components like leaves, stems, ear head in the wavelength visible (0.4 -0.7µm) , NIR(0.76-1.0 µm),mid IRC (2.0-4.0 µm) can be measured with spectral radiometer (LICOR-1800-10) with cosine correction.

Diurnal Pattern and Seasonal variation : PAR, albedo increases from PI (panicle initiation) to flag leaf as LAI and chlorophyll concentration increases further till boot stage as LAI becomes highest .PAR albedo at boot to 50% flowering. Green reflectance decreases with senescence. Moisture stress increases blue and red reflectance.

Changes in Spectral Composition in Plant Canopy : The spectral composition of the radiation after transmission changes. This may be partly due to the factor that most of the visible (about 80% in maize) is absorbed by leaf however the leaf allows the transmission of IR radiation. Kyle (1971) found that 30-40% IR transmitted to the ground while only 5-10 % of visible part transmitted to the ground in corn crop.

Light Distribution in canopy: There is a exponential relationship between light intensity and height in the canopy which is know as Beerôs Law. In double plant density of a crop, less incident radiations travel to the ground as compare to single planting. In closer spacing also, less penetration of radiation takes place.

Let F be the average cumulative leaf area index, F is zero at the top of the canopy and is maximum at ground level. PAR (Q) in the horizontal plane immediately above the top of the canopy is defined by Q_0. At any level F within the canopy, the rate of change of Q is

$$dQ/dF = -kQ_F$$

where dimensionless parameter k represents the fraction of incident photons absorbed per unit area and is referred to as foliar absorption coefficient or extinction coefficient

After integration, Q at level F (Q_F) is $Q_F=Q_0 \; e^{-kF}$ which upon taking logarithms and rearranging becomes

$$kF = \ln (Q_0/Q_F)$$

The foliar absorption coefficient ranges from 0.3 to 1.3 for the majority of leaf canopies. In canopies where the leaves are nearly vertical e.g many grasses, light penetrating in the lower layers, k often low, typically 0.4. For such a canopy the cumulative F needed to absorb 95% of PAR incident at the top of the canopy may be determined using the above equation. Then

$$F = \ln (Q_0/Q_F)/k$$

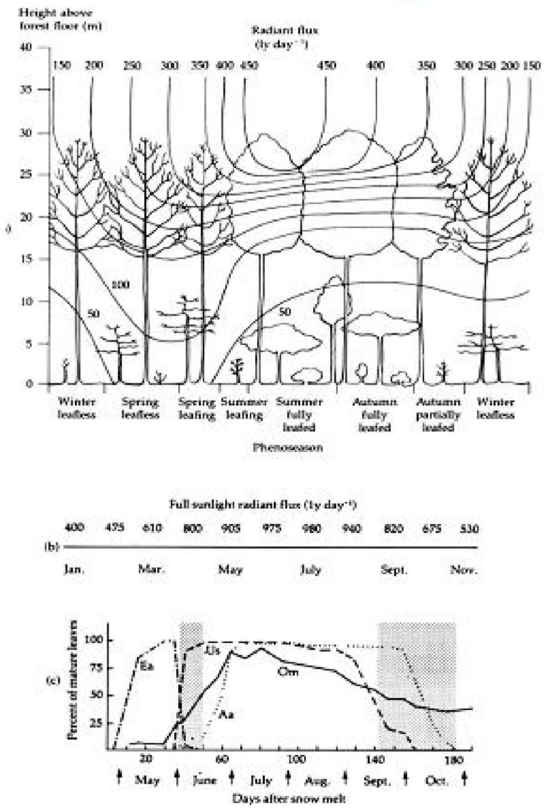
$$= \ln [Q_0/(0.05Q_0]/0.4$$

$$= 7.5$$

The value of k becomes 1 for a high foliar absorption coefficient having horizontal leaves with high chlorophyll levels e.g 0.5 g chlorophyll/m^2 which can be found in crop plants such as potato, soybean, sunflower etc. Canopies with most leaves in horizontal plane are termed planophile, whereas canopies in which leaves are close to vertical are termed erectophile.

At solar noon, vertical leaves absorb less Q per unit leaf area than do horizontal leaves. This accounts for low values of k for grasses, because their leaves are generally erect. Moreover, leaves tend to be vertical near the top of certain plants e.g sugar beat, pineapple having more horizontal leaves towards ground. This canopy architecture reduces the foliar absorption coefficient of the upper layer leaves. In fact, optimal Q utilization for canopy photosynthesis generally occurs when the incident Q is distributed as uniformly as possible over the leaves, because the fraction of the leaves that are exposed to Q levels above light saturation or below light compensation is then minimized.

Effects of vegetation canopy on light regimes



A. The highest radiant flux reaches the forest floor between the spring leafless phenoseason and early summer, when the canopy is in full leaf. It is during this period that sufficient light and adequate temperature allow the spring bloom of geophytes and herbaceous plants on the forest floor.

B. Approximate daily total of un-depleted solar radiation received on a horizontal surface at 35°N.

C. A comparison of the percentage of leaves in the mature leaf stages of four taxa at various times of the the year. Stippled band indicate expanding or falling leaves in the canopy.

From Hutchison and Matt. 1977. The distribution of solar radiation within a deciduous forest. *Ecological Monographs* 47: 185-207 and Mahall and Bormann. 1978. *Botanical Gazette* 139: 467-481.

05. Duration of Light or Photoperiodism

Photosynthesis : Photosynthesis is the process by which plant convert light energy into chemical energy in the form of reducing power as NADPH and ATP . This reducing power used to fix Carbon dioxide as carbohydrates . In oxygenic photosynthetic organisms, inducing higher plants, the source of reducing equivalents is H_2O , releasing O_2 as a by product.

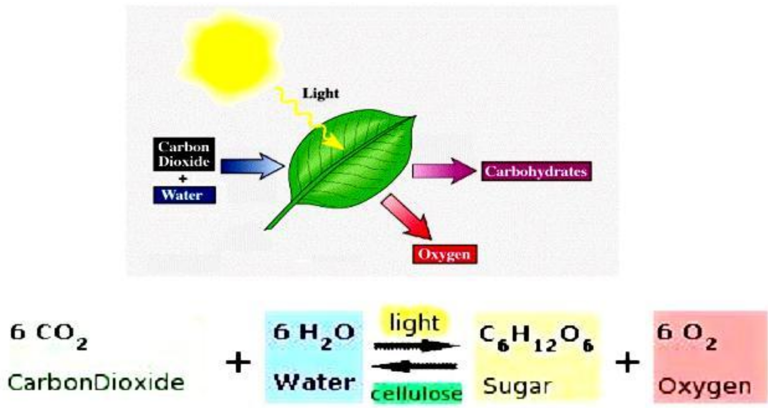


Figure 04. Process of Photosynthesis

Duration of Light : Duration of light (photoperiod) influence time of flowering of many crops . Response of plants to day light period is known as photoperiodism. Based on flowering behaviour to photoperiod , plants are grouped in to four broad type ï

No.	Plant Type	Characteristics
01	**Short Day** **Strict Short day** **Short Day /long day**	Photoperiod < 10 hr flowering does not occur if the day length is above or below a critical value as the case may be short ï day plants requiring an induction period of ling days
02	**Long day** **Facultative** **Long day/Short day**	Photoperiod < 14 hr, effects of photoperiod additive . long day plants will flower in a subsequently unfavorable period , long day plant requiring short day induction
03	**Intermediate day** **Day Neutral**	Photoperiod of 12-14 hours with inhibition of reproduction either below or above these levels unaffected by variation in day.

Importance of intensity of light : light intensity measures itǿs quantity or brightness.

Light intensity is indispensable for photosynthesis

It controls leaf growth

It influence sturdiness of stem and duration of vegetation growth specially of bulbous and tuberous crops.

Nodulation of legumes

Light intensity yield attributes and yield.

Day Degree Days or Heat Units

Heat Unit = days or hours of accumulated temperature above some threshold (but below max. limits)

Measured in degree-days or degree hours

Lower temperature is called the threshold or base temperature

Heat Unit Calculation :

$$DD = \sum_{i=1}^{d} T_{mean} - T_{base}$$

Minimum temp for Plant

Sum over no. of days

Degree above base temp

06. Radiation use efficiency of crops

Crop growth results from photosynthesis and is subject to modification by both abiotic and biotic factors. Early in the growing season the rate of dry matter production by a crop is proportional to the amount of radiation intercepted, a function of leaf area index. Crop growth depends on the quantity of incident light (Q_0), the proportion of that light intercepted (Qt) by the photosynthesizing organs of the plant, its efficiency of conversion of light into dry matter (e) and respiratory losses. The amount of light intercepted at any height z within the canopy is obtained by the difference between the incident radiation and that transmitted and may be calculated from the equation

$$Qi = Qt/Q_0 = e^{-kL}$$

where Qi is the radiation transmitted at a height z in the canopy and L is the leaf area index between the points of measurement of Q_0 and Qt. Efficiency of conversion of light into dry matter is also termed as radiation use efficiency or crop growth efficiency. Crop growth efficiency tends to be higher in crops grown with adequate light, water and nutrients and disease and pest free environment. For most field crops e tends to be high during the vegetative phase when the photosynthetic rate is high and decreases when the area decreases because of age and physiological maturity. The values of e is often calculated as the slope of the best fit line on a plot of cumulative dry matter against cumulative intercepted radiation or absorbed PAR. The values of e for a range of species and environments are given in the following Table. The crop growth efficiency e varies with several factors that affect cro growth such as air and soil temperatures, radiation levels, soil moisture levels, nutrition etc.,.

Shoot dry matter production per unit of intercepted PAR

Crop	Site	e (g/MJ)
Maize(Zea mays)	Davis, CA, USA	3.0
Sorghum (S. bicolor) Pearl	ICRISAT, India	2.4
millet (P. glaucum) Pearl	ICRISAT, India	3.0
millet (P. glaucum)	Niamey, Niger	2.4
Groundnut (A. hypogen)	ICRISAT, India	0.8
Pegionpea (Ciamus cajan)	Trinidad, West indies	1.2
Chickpea (Cicer arietinum)	ICRISAT, India	1.36
Chickpea (Cicer arietinum)	ICRISAT, Inida	1.24

07. Water Use Efficiency in Agriculture

The Food and Agriculture Organization (FAO) predicts a net expansion of irrigated land of some 45 million hectares in 93 developing countries (for a total of 242 million hectares in

2030) and project that agricultural water withdrawals will increase by approximately 14% during

2000-2030 to meet food demand. of the water used to grow crops. Rainfed non-irrigated agriculture accounts for some 60% of production in developing countries. Although irrigation provides only 10% of agricultural water use and covers just around 20% of the cropland, it can vastly increase crop yields, improve food security and contribute 40% of total food production since the productivity of irrigated land is three times higher than that of rainfed land.

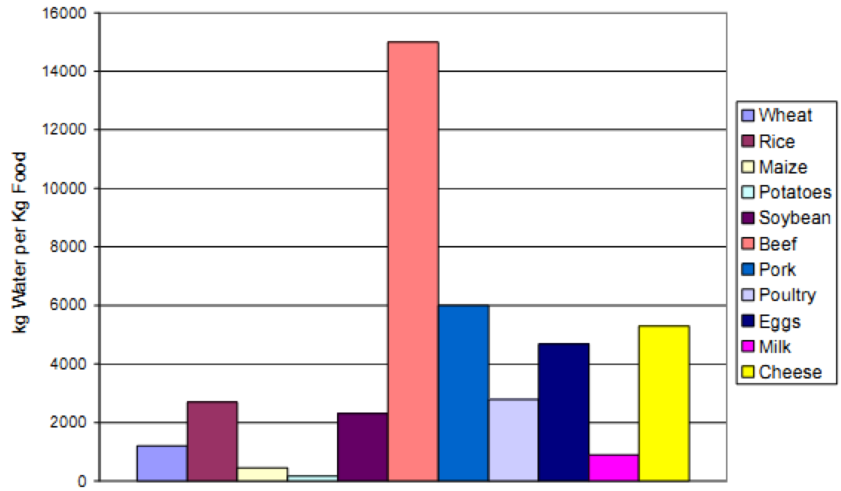


Figure 05. Water needed for food production

Competition among different sectors for scarce water resources and increasing public concern on water quality for human, animal and industrial consumption and recreational activities have focused more attention on water management in agriculture. As water resources shrink and competition from other sectors grows, agriculture faces a dual challenge: to produce more food with less water and to prevent the deterioration of water quality through contamination with soil runoff, nutrients and agrochemicals. Current response measures, including policies and regulations, consist of a combination of ways to ensure adequate and more equitable allocation of water for different sectors. Measures include improving water use efficiency, pricing policies and privatization. Similarly there is an emphasis on integrated water resources management, which takes into account all the potential stakeholders in the planning, development and management.

Water use efficiency (WUE) is a broad concept that can be defined in many ways. For farmers and land managers, WUE is the yield of harvested crop product achieved from the water available to the crop through rainfall, irrigation and the contribution of soil water storage. Improving WUE in agriculture will require an increase in crop water productivity (an increase in marketable crop yield per unit of water removed by plant) and a reduction in water losses from the plant rooting zone, a critical zone where adequate storage of moisture and nutrients are required for optimizing crop production.

The amount of water required for food production depends on the agricultural commodities produced. Improving WUE by 40% on rainfed and irrigated lands would be needed to counterbalance the need for additional withdrawals for irrigation over the next 25 years from additional demand for food. However, this is a big challenge for many countries. Increasing WUE is a paramount objective, particularly in arid and semi-arid areas with erratic rainfall patterns. Under rainfed conditions, soil water can be lost from the soil surface through evaporation (termed soil evaporation) or through plant uptake and subsequently lost via openings on plant leaves (termed plant transpiration). It can also be lost through runoff and deep infiltration through the soil. Total amount of soil water losses associated with both soil evaporation and plant transpiration is referred to as evapotranspiration.

Evapotranspiration, grain yield and water use efficiency of crops

Crop	Evapotranspiration (mm)	Grain yield (kg/ha)	Water-use efficiency (kg/ha/mm)
Pearl millet	362	2049	5.66
Greengram	310	672	217
Mustard	552	2557	4.64

(Source: CAZRI, Jodhpur)

Many promising strategies for raising WUE are available. These include appropriate integrated land-water management practices such as ï

(i) Adequate soil fertility to remove nutrient constraints on crop production for every drop of water available through either rainfall or irrigation,

(ii) Efficient recycling of agricultural wastewater,

(iii) Soil-water conservation measures through crop residue incorporation,

adequate land preparation for crop establishment and rainwater harvesting

(iv) Conservation tillage to increase water infiltration, reduce runoff and improve soil moisture storage.

(v) Fertigation, which combines irrigation and fertilization, maximizes the synergy between these two agricultural inputs increasing their efficiencies. Overall, improving irrigation WUE

(vi) Novel irrigation technologies such as supplementary irrigation (some irrigation inputs to supplement inadequate rainfall), deficit irrigation (eliminating irrigation at times that have little impact on yield) and drip irrigation (targeting irrigation water to plant rooting zones) can also minimize soil evaporation thus making more water available for plant transpiration.

Related literature:

1. Monteith, J.L. and M.H. Unsworth. 1990. Principles of Environmental Physics. Edward Arnold (Publishers) Ltd., London UK.
2. Rao, A.S. and Vamadevan, V.K. 1985. Insolation in monsoonal wet tropics and transmission/reflection coefficients of leaves of some plantation crops. *Mausam*, 36(3):347-350.
3. Subramaniam, A.R. and Rao, A.S. 1985. Prediction of ET of some crops under semi-arid and dry sub-humid climates of Maharashtra. *Mausam*, 36(1):67-70.
4. Rao, A.S. and Alexander, D.1988. Prediction of evapotranspiration and grain yield of rice. *Intl. J. Biometeorology*, 32 (2):81-86.
5. Rao, A.S. 1989. Water requirements of young coconut palms in a humid tropical climate. *Irrigation Science*, 10:245-249
6. Singh, R.S., Rao, A.S. and Ramakrishna, Y.S. 1991. Growth characteristics of mustard crop in response to thermal environment under arid conditions. *Mausam*. 42(4): 409-410.
7. Rao, A.S., Ramakrishna, Y.S. and Singh, R.S. and Chopra, N.K.1993. Water and energy use efficiencies of sorghum inter-cropped with *Accacia nilotica*. *Annals of Arid Zone*. 32(2): 99-101.
8. Rao, A.S., Singh, K.C. and Ross weight, J.R. 1996. Productivity of *Cenchrus ciliaris* in relation to rainfall and fertilization. J. *Range Management*. 49(2):145-146.9. Singh, R.S.,

Rao, A.S., Joshi, N.L. and Ramakrishna, Y.S.2000. Evapotranspiration, water and radiation-utilization in mothbean under two moisture conditions. *Annals of Arid* Zone, 39(1):21-28.

10. Rao, A.S, Singh, R.S, Joshi, N.L. and Ramakrishna, Y.S.2000. Evapotranspiration, water and radiation-utilization of clusterbean (*Cyamopsis tetragonolaba*). *Indian Journal of Agricultural Sciences*, 70(3):149-153.
11. Rao, A.S and Singh, R.S.2003. Evapotranspiration, water-use efficiency and thermal time requirements of greengram (*Phaseolus radiatus)*. *Indian Journal of Agricultural Sciences,* 73(1):18-22.
12. Rao, A.S and Singh, R.S.2004. Water and thermal characteristics of cowpea (*Vigna unguiculata* L. Walp.). *J. of Agrometeorology*,6(1):39-46.
13. Rao, A.S. and Singh, R.S.2004. 2004. Evapotranspiration rates, growing degree days and water-use efficiency of some arid legumes. *J. Arid Legumes* 1(2): 166-170.
14. Singh, R.S. and Rao, A.S. 2007.Water and heat-use efficiency of mustard (*Brassica juncea* L. Czern. & Coss) and its yield response to evapotranspiration rates under arid conditions. *J. of Agrometeorology*. 9(2): 236-241.
15. Rao, A.S. and Singh, R.S. 2007.Evapotranspiration rates and water-use efficiency of Pearl millet (*Pennisetum glaucum* L cv. HHB 67) under arid climatic conditions. *Indian J. Agril. Sciences* 77(12): 810-813
16. Rao, A.S. 2008. Micro-meteorological variations and Rain water-use efficiency of a Silvi-pastoral system. *J. of Agrometeorology* 10(2):137-140
17. Rao, A.S. and Poonia, S. 2011. Climate change impact on crop water requirement in arid Rajasthan. *Journal of Agrometeorology*, 13(1):17-24.
18. Rao, A.S. 2011. Growing degree days, evapotranspiration and water-use-efficiency of *chilli* crop in arid environment. *J. of Agrometeorology* 13(2) 128-130..
19. 64 Rao. A.S. 2011. Evapotranspiration and Water-use efficiency of Sesame crop (*Sesamum indicum* L. cv. RT-127). *Annals of Arid Zone*. Accepted.

Crop Specific Water balance models-SPAW (Soil-Plant-Air-Water) Model

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Simulation of crop growth/forage production from drylands had several difficulties due to temporal and spatial variability in rainfall, high evapotranspiration rates and heterogeneity in land use or crop acreage. Because of our limited knowledge in understanding the assimilation of carbon by various dryland crops, trees or grasses and proceeds to allocate this material to other organs which will undergo respiration, by and large, we have to depend on regression models or soil moisture simulation models for explaining the crop/forage yield. Studies on finding quantitative relationships between growth of crop/tree/grasses in relation to environmental variables will help to know in advance about crop yield/forage production through continuous monitoring of environmental variables. Some of the earlier studies were based on rainfall relating crop production using regression equations. Later studies involved use of dynamic simulation models for simulation of soil moisture and estimation of production.

Soil water and its role in agriculture:

The availability of moisture in the soil is a prerequisite for the survival and growth of plants. The capacity of soil for storing available water can be expressed conveniently in terms of maximum available soil moisture in the root zone. Soil acts as a store-house for moisture, where moisture accumulates upto a certain value, which is called field capacity during periods of excess precipitation. The water contained in the soil above field capacity is not available to crops due to quick drainage to lower layers. The water contained below permanent wilting point (WP) is also not available to crops as it is tightly held by the soil particles. Thus, it is generally considered that the amount of water held in the soil, between field capacity and permanent wilting point is water available for crop use. This is a widely accepted view and is followed by most of the workers for irrigation purposes.

The rate of availability of moisture to crops within field capacity and permanent WP and its effect on crop growth is an important factor in determining crop growth. Veihmeyer and Hendrickson (1955) have made extensive field tests on perennial fruit crop and stated that water is equally available for plant growth at all levels, between field capacity and permanent WP. Their experiments show that favorable conditions of soil moisture extend from the field capacity to about the permanent WP. This view is still being accepted and adopted by agricultural scientists and in irrigation scheduling.

Soil moisture retention

The moisture content of a sample of soil is usually defined as the amount of water lost when dried at 105^{O}C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit volume of bilk soil. Although such information may not give a clear indication of the availability of water for the plants, differences exist because the water retention characteristics are generally different for different soils.

The forces that keep soil and water together are based on the attraction between the individual molecules, both between water and soil molecules (adhesion) and among water forces, while in the dry range absorption is the main factor. The factors influencing the relations of plants and thus their growth and yield response may be grouped into the following;

1. Soil-factor-Soil moisture content, texture, structure, density, salinity, minerate processes, fertility, aeration, temperature and drainage
2. Plant factors-Type of crop, density and depth of rooting, rate of root growth, aerodynamics, roughness of the crop, drought tolerance and varietal effects
3. Weather factors-Sunshine, temperature, humidity, wind and rainfall
4. Miscellaneous factors-Soil volume and plant spacing, soil fertility and crop water, soil and agronomic practices management

Water stress and plant development:

Plant growth and development depends

1. Upon a continuous process of cell division
2. On the progressive initiation of tissue and organ primordial and
3. On the differentiation and expansion of the component cells.

Along with this is an inter-connected chain of metabolic events which involves the uptake of nutrients from both soil and air, the synthesis of metabolites and structural materials and also from the flow of substances within the plant body. Because all these plants processes take place in the aqueous medium and water being a transporting agent as well as a reactant in the majority of these processes, any shortfall in water uptake and dehydration results in negative effects on most of the physiological processes.

Stress affects those tissues most which are in rapid stages of development. Primordial initiation and cell enlargement are inhibited by moisture stress.. After moisture stress is over, developing tissues are rejuvenated and growth rates of many plants are more rapid than those which remained unstressed. This is due to the continued but slow cell division as well as the availability of nutrients released by the old tissues.

Soil moisture stress and grain yield:

There are three key stages when moisture stress affects the grain yield in cereals and these are

1. Stage of floral initiation and inflorescence development
2. Stage of anthesis and fertilization
3. Grain filling stage

Soil-Plant-Air Model:

The SPAW model is a daily hydrologic budget model for agricultural fields. It also includes a second routine for daily water budgets of ponds and wetlands, which utilizes the field hydrology as the watershed. The field budget utilizes a one-dimensional vertical system beginning above the plant canopy and proceeding downward into the soil profile a sufficient depth to represent the complete root penetration and subsurface hydrologic processes. The following schematics describe the field and pond hydrologic systems and each major hydrologic process impacting water movement across the system boundaries and within the systems.

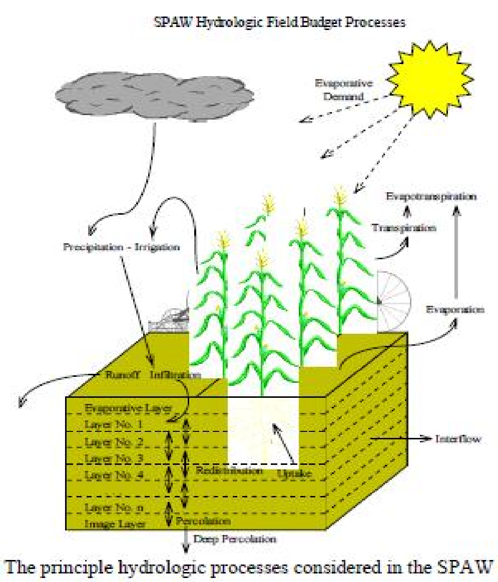


Figure 1: The principle hydrologic processes considered in the SPAW field model

For drought and crop surveillance over the region, the SPAW (Soil-Plant-Air-Water) was tested and modified for Indian region by Rao and Saxton (1995) and Rao *et al*., (2000). They used the SPAW model for assessment of soil moisture and crop stress conditions under pearl millet which explained 89% of pearl millet yields of Jodhpur district. The relationship between pearl millet grain yield (kg/ha) and the water stress index (WSI) of SPAW model was Y = -45.38 W
SI + 526.18 (r=0.9427; Figures 2&3).

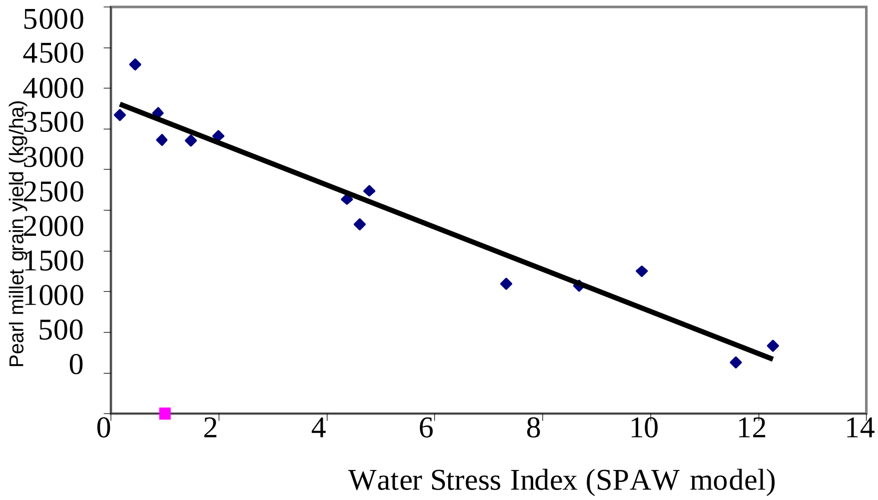
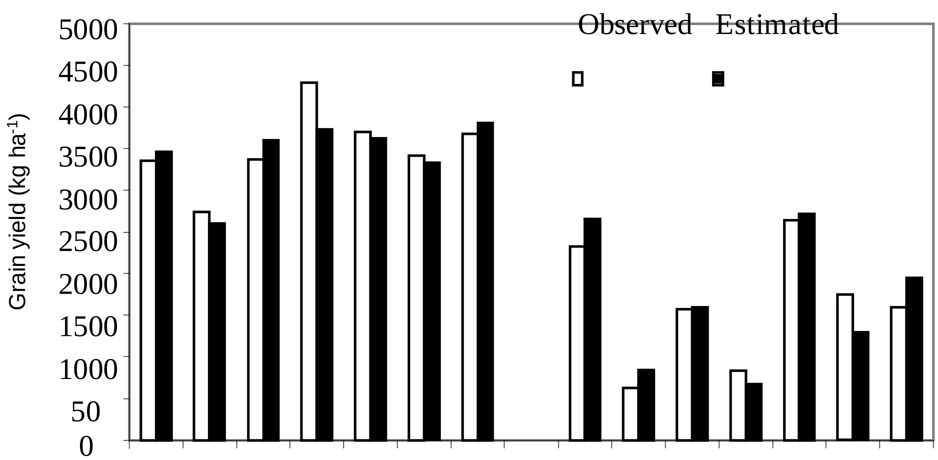


Fig. 2. Relationships between Water Stress Index and Pearl millet yield (Source: Rao and Saxton, 1995)



1990 1991 1992 1993 1994 1995 1996 1990 1991 1992 1993 1994
1995 1996

Year

Irrigated Rainfed

Fig.3 Observed and estimated pearl millet grain yield using the Soil-Plant-Air Water Model (Source: Rao *et al.*, 2000)

References:

1. Rao, A.S., Joshi, N.L. and Saxton, K.E.2000.Monitoring of productivity and crop water stress in pearl millet using the SPAW model. *Annals of Arid Zone*, 39(2):151-161.
2. Rao, A.S. and Saxton, K.E. 1995. Analysis of soil water and water stress under pearl millet in an Indian arid region using the SPAW model. *J. Arid Environments*, 29(2):155-167.

Modeling the effect of weather or weather based indices on performance of crops

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Introduction:

Crop weather modeling refers to the techniques that are used to determine the effect of weather on yield.Although influence of weather conditions on yield is well established, the quantitative assessment is not always straight forward and simple.Inter-annual variability,in a long time series yield data can be due to either or all of these components:Trend,Direct weather effect and Indirect weather effects viz.,pest,diseases,weed competition etc.In developed weather countries,trend due to improved technology and management accounts for 80% of variability while in developing countries trend is substantially less or negligible.The quantitative assessment of the effect of weather on crops is no doubt is a most important application of agrometeorology in both developed and developing countries.The application of crop weather modeling extends from the scale of farmers field to entire countries or continents.The aim of developing crop weather models is to ensure better utilization of resources and hence a more environmental friendly and sustainable agriculture.

Importance of weather:

Weather directly or indirectly influences the crops in their growth cycle. The growth, development and productivity of crops are the resultant of many physical and physiological processes, each of which are affected individually or jointly by weather parameters. Though weather or climate is the least manageable natural resource, understanding of its interaction with agricultural parameters was found to be a powerful tool to develop weather based management strategies in agriculture that will enhance benefits from positive interactions and minimize the losses from negative interactions (Virmani, 1994).

The principal weather parameters which affect crop growth and yield are: Precipitation (amount and distribution), air temperature (Maximum and Minimum), moisture content of the air (Relative humidity, SVPD), solar radiation or sunshine hours and wind speed.

Developments in crop-weather relationship studies

A great deal of research on crop-weather relationships in respect of important rainfed crops was reported in India and elsewhere. Pioneering crop-weather relationship studies can be traced back to Fisher (1924). In India, research on the crop-weather relationships was initiated by Prof. L.A. Ramdas, considered the ôFather of Agrometeorology in Indiaô in 1926. These efforts led to the initiation of research on crop-weather relationship by IMD in 1932 and later by ICAR in 1948 through a Coordinated Crop Weather Scheme. Later, some Agricultural Universities and Agricultural Research Institutes started conducting crop-weather relationship studies. Considerable work on crop-weather relationships was carried out over years by Sarkar (1965) from IMD and Bhargava *et al* (1978) and Agarwal *et al* (1986) from IASRI. The multi-location crop-weather relationships in various crops were geared up after launching of the All India Coordinated Research Project on Agricultural Meteorology in 1983. A review on crop-weather relationship studies in important crops in India and other countries till the late sixties was made earlier by Venkataraman (1972) and on rice by Rao and Das (1971). A brief review of crop-weather regression models in dryland agricultural research was also made later (Rao and Rao, 1992).

Changes in concept of crop-weather relationship studies

Over the years, a lot of changes in the concepts of crop-weather relationships have been evolved. The crop-weather relationship studies in earlier years were based on statistical techniques like correlation, simple and multiple regression, step-wise regression, etc. It was believed by Agrometeorologists working on dryland agriculture earlier that rainfall is main factor for variation in yields of dryland crops. Crop yields were related with rainfall during different stages of the crop growth to identify the critical stages of the crop. Experience and logic prompted them to look for some more parameters other than rainfall for accurate prediction of crop yields. Though total amount of seasonal rainfall showed some amount of relation with final yield, it was not representing the actual water available for plant growth as it does not account the losses through drainage, runoff and also the influence of the water holding capacity of the soil. The proposition of potential Evapotranspiration concept simultaneously by Penman (1948) and Thornthwaite (1948) and the introduction of water budgeting by Thornthwaite (1948) and the modification of the same by Thornthwaite and Mather (1955) brought in an appropriate independent variable, i.e., water use or Evapotranspiration for prediction of crop yields. Later, de Wit (1958) developed an equation to relate dry matter yield (Y) to transpiration as:

$$Y = m\,T/E_o$$

Where T is transpiration in cm, E_o is average free water evaporation rate (cm/day) and m is a crop factor.

The ratio of actual evapotranspiration to potential Evapotranspiration (AE/PE) known as Index of Moisture Adequacy (IMA) has found its use, later, in crop-weather relationship studies. The non-accountancy of crop factor in water balance models was corrected by introduction of models by researchers like Frere and Popov (1979), Ritchie (1972), etc. The simple (FAO) water balance model developed by Frere and Popov (1979) introduced an index called Water Requirement Satisfaction Index (WRSI) for predicting crop yields.

Although water supply plays a dominant role in agriculture, other climatic factors also influence the performance of crops and to understand the effect of more weather parameters, multi-variate crop-weather relationships were developed.

All these statistical models developed with data from a given place though have higher predictability suffer from location-specific bias. To overcome the site-specific problem, concerted scientific effort for development of dynamic crop simulation models which are generic in nature and are applicable universally was initiated across the globe.

Effects of different weather parameters:

Solar radiation:

Crop production is in fact exploitation of solar energy. Solar energy(solar radiation) is the driving force and only source of energy for photosynthesis(Monteith 1973).It is one of the main factors influencing biomass, yield and its quality. When water and nutrients, diseases and insects are not limiting factors, crop growth is determined by the amount of solar radiation intercepted and carbon dioxide assimilated. Three aspects of solar radiation are important for plant processes: Intensity, duration (i.e., photoperiod or day length), and quality. Low intensity of solar radiation during grain filling phase negatively influences grain yield of cereal crops.

The length of the day or photoperiod determines flowering and has a profound effect on the content of soluble carbohydrates present. A majority of plants flower only when exposed to certain specific photoperiods. It is on the basis of this response that the plants have been classified as short day plants, long day plants and day neutral plants. When any other environmental factors is not limiting, the longer duration of photoperiod increases photosynthesis.

Temperature

Temperature is very important not only to plants but also to all the biological species because of following factors:

- Physical and chemical processes within the plants are governed by temperature.
- The diffusion rate of gases and liquids in soil-plant-atmospheric system changes with temperature.

Temperature affects crops by causing (i) variations in duration of phenological events or crop development. (ii) variation in magnitude and time of occurrence of peak in biomass, (iii) significant increase / decrease in growth rates, (iv) variation in growth pattern deviating from sigmoidal curve and ultimately affecting grain yield or harvest index.

Combined influence of temperature and photo-period

Though development of crops is mainly driven by temperature, some plant species respond to photo-period or day length. The photo thermal effects on phenology in many crops were reported. For all tropical and sub-tropical species, the warmest temperature combined with shortest photo period hastened flowering and fruit maturity (Keating *et al*, 1998). However, all temperate species both flowered and matured sooner at the warmest temperature combined with longest photo period.

Cardinal points or temperature thresholds (°C) for some major crops are listed in Table-3.

Table-3.Temperature thresholds (°C) during growing season for some major crops

Crop	**Minimum**	**Optimum**	**Maximum**
Sugarcane	13	35-37	>40
Wheat	0	17-23	30-35
Rice	7-12	25-30	35-38
Maize	8-13	25-30	32-37
Potato	5-10	15-20	25
Sorghum	8-10	32-35	40

(Rötter and van de Geijn, 1999)

Low temperature affect

Low temperature affects several aspects of crop growth, *viz.*, survival, cell division, photosynthesis, water transport, growth and finally yield.

High temperature affects

High temperature adversely affects mineral nutrition, shoot growth and pollen development resulting in low yield. Adverse effects of high temperature during critical growth stages of some major crops were mentioned in Table-4.

Table-4. High temperature effects on key development stages of five major arable crops

Crop	**Effect**
Wheat	T > 30°C for > 8 hrs can reverse vernalisation
Rice	T > 35°C for > 1 hr at anthesis causes spike let sterility
Maize	T > 36 °C reduces pollen viability
Potato	T > 20°C reduces tuber initiation and bulking
Cotton	T> 40ºC for more than 6 hours causes bolls to abort

Source: Acock and Acock (1993)

Rainfall or water use:

Rainfall is an important parameter in agriculture. All plants need water to survive and rainfall is the main source providing water to plants. While normal rainfall is vital to healthy plants, too much or too little rainfall can be harmful to crops. Plants need varying amounts of rainfall to survive. Desert plants require small amounts of water while tropical plants need much higher rainfall. Water is an essential component in the process of photosynthesis. The movement of water out of the plant stomata, known as transpiration is an inevitable consequence of assimilation of carbon dioxide. As transpiration or water use and photosynthesis are inter related, a linear relation between crop yield and seasonal transpiration was established by Hanks (1974) as follows:

$$Y=m*(T/E_0)$$

Where Y=Yield, T=Seasonal transpiration and E_0 is average seasonal free water evaporation and m is a crop factor. This equation gave very good fit for several crops grown in different years in different locations.

Agroclimatic indices:

Some important agroclimatic indices formed by combining two or more weather parameters, are given below:.

1.Photo thermal units (PTU):

It is the product of Degree days (^{0}C) and Day length (hours) and expressed in units ^{0}C hrs

2. Helio thermal units(HTU):

It is the product of Degree day (^{0}C) and actual bright sunshine hours and it is expressed in units ^{0}C hrs

3.Thermal Interception Rate(TIR):

$$TIR=PARI/n(Tm-Ta)$$

Where PARI=Photosynthetically active radiation intercepted by the crop, n=No. of plants/m^2, Tm=Mean daily temp and Ta is base temp

4.Water Requirement Satisfaction Index(WRSI):

The WRSI is an indicator of crop performance based on the availability of water to the crop during growing season. WRSI for a growing season is calculated as the ratio of seasonal actual evapotranspiration(AET) to the seasonal crop water requirement (WR).The water requirement of the crop at a given time of the growing season is calculated by multiflying the reference(potential) evapotranspiration with a crop coefficient,whose values are published by FAO(FAO,1998).

5. Moisture Availability Index(MAI):

It is defined as the ratio of rainfall at 75% probability (PD) and Potential Evapotranspiration(PET).

MAI=PD/PET

6.Moisture Adequacy Index(MAI):

It is defined as the ratio of actual evapotranspiration and potential evapotranspiration and can be written as MAI=AET/PET

Methods to evaluate Crop-weather Relationship

The three commonly used approaches in crop weather modeling studies are are:

- Correlation techniques
- Crop weather analysis model
- Crop growth simulation models

Correlation analysis provides a measure of the degree of association between variables

Regression analysis describes the effect of one or more variables (independent variables) on a single variable (dependent variable)

Regression and correlation procedures can be classified according to the number of variables involved

- Simple (If only 2 variables, one independent and another dependent)
- Multiple (If more than 2 variables)

The procedure is termed linear, if underlying relationship is linear or non-linear, if otherwise

Regression equations are broadly of four types

- Simple linear regression
- Multiple regression
- Simple non-linear regression
- Multiple non-linear regression

Simple and multiple regressions widely used for crop weather relationship studies can be written as

Y=a+b*X

Y is the dependent variable, example-Yield

X is the independent variable, example-Rainfall, temperature etc

Y=a+b1*X1+b2*X2+……..+bk*Xk

k =Number of independent variables

R^2 is coefficient of determination

There must be enough observations to make n greater than (k+1)

Multi Collinearity:

Multi collinearity in regression equations occurs when predictor variables (independent variables) in the regression model are more highly correlated with other predictor variables than with the dependent variable.

It commonly occurs when a large number of independent variables are incorporated in a regression model.

Searching for best regression

There are two ways in which relationship between dependent variable and k independent variables be specified

- Å Based on accepted biological concepts, secondary data, past experience etc.
- Å Based on the data collected

Four procedures commonly used for specification of appropriate relationship between X and Y are

1. Scatter Diagram(for simple regression)
2. Analysis of variance technique(not relevant for CWR studies)
3. Test of significance technique(for elimination of unnecessary variables)
4. Step-wise regression technique(for identifying the sequence of importance of each variable)

Standardizing variables

The following standardization procedures help to reduce experimental error and biases

- Yields from different varieties to be adjusted to a ñstandardò ñbaseò variety
- Weather variables are to be measured within specific stages of plant development rather than within specified weeks or months
- Yields are to be culled to remove those reduced by disease,hail,pests and other factors
- Reduction in experimental error can be accomplished through use of simulated evapotranspiration amounts rather than precipitation, to measure effects of droughts

Models relating yield with different weather parameters or indices:

Yield and water use:

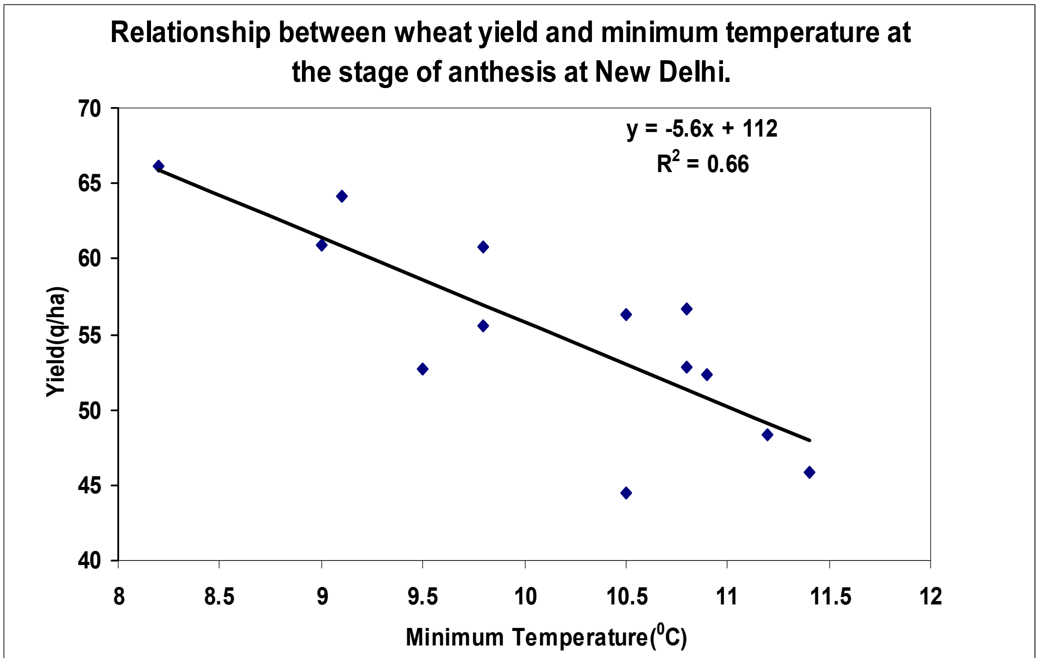
Doorenbos et al.(1979) proposed the following equation relating yield and water use.

$$(1-Y_a/Y_m) = k_y(1-ET_a/ET_m)$$

Where Y_a is actual yield, Y_m is maximum potential yield, k_y is a yield response factor, Et_a is actual crop evapotranspiration and ET_m is maximum or potential evapotranspiration.

Yield response to temperature:

The response of grain yield of wheat to minimum temperature was different under different phenological stages. The linear regression of yield with minimum temperature was positive during crown root initiation stage while it was negative during anthesis stage(Fig- 1 and 2)



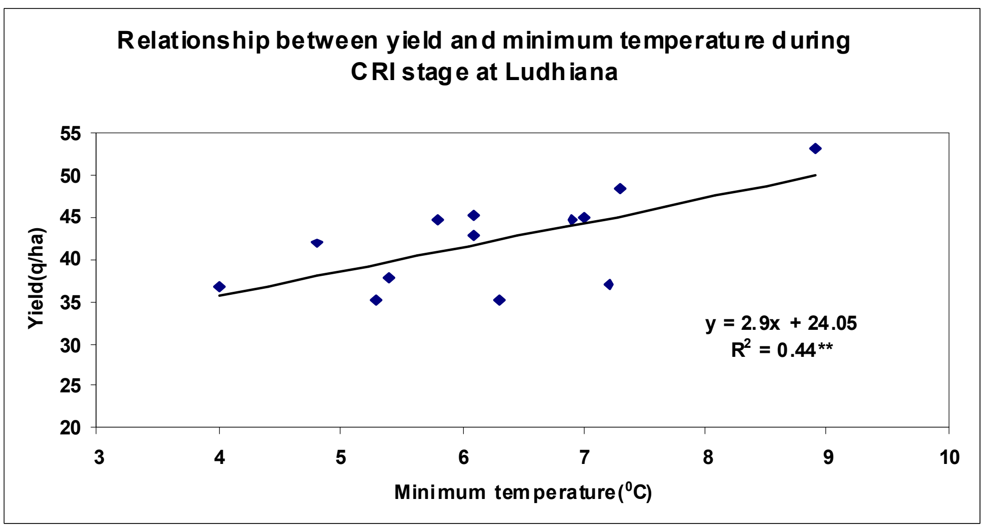


Figure 1 & 2

Yield and rainfall:

Yield usually shows curvilinear relationship with rainfall in most of the crops. The yield response to rainfall varies with the phenological stage of the crop. In most of the field crops rainfall during reproductive stage is critical for the grain yield achieved. The yield and weather relationship of soybean, illustrated below is showing significant curvilinear relationship with rainfall during reproductive period (Fig 3).

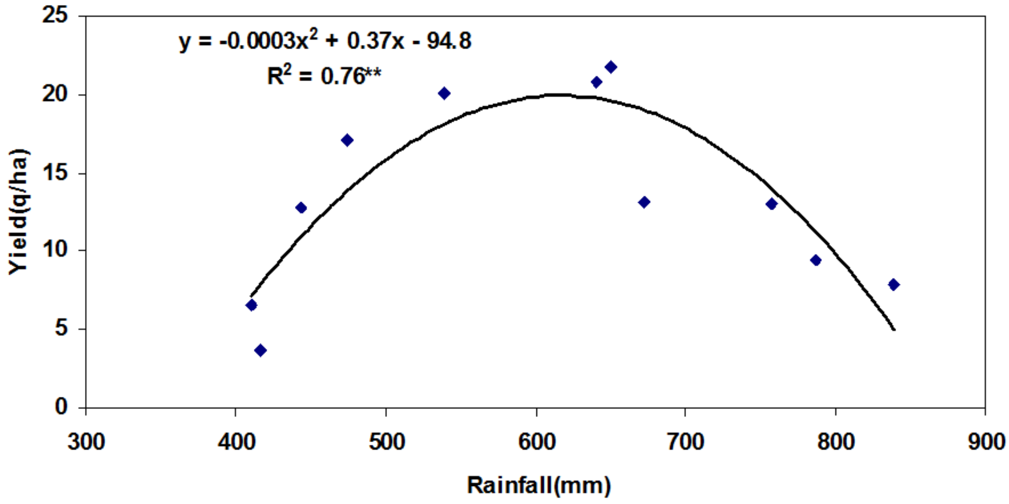


Fig. 3. Relationship between rainfall during reproductive period and yield of soybean at Jabalpur

Yield and canopy temperature:

Yield showed significant inverse linear relationship with canopy temperature in chickpea at Jabalpur(Fig 4).The stress degree day ,which was worked out as the difference between canopy and air temperature also showed highly significant inverse relationship with yield of pearl millet at Solapur (Fig 5)

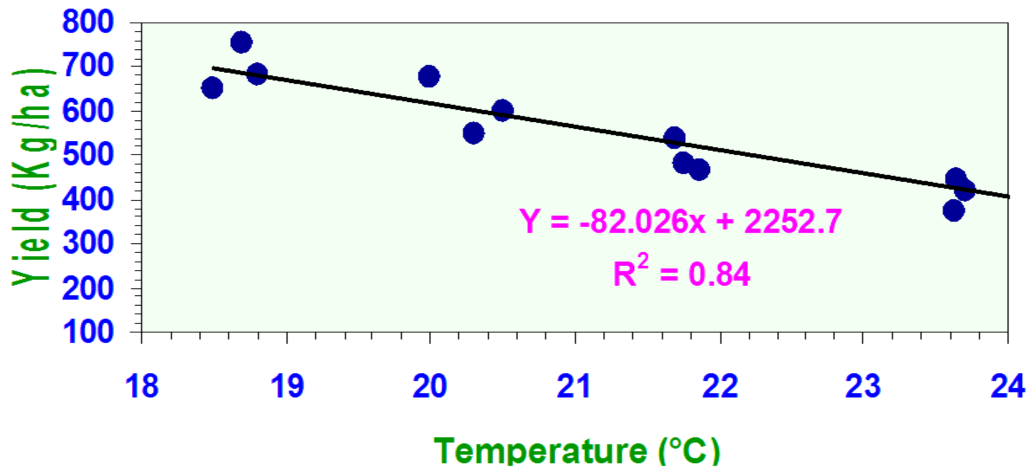


Fig 4. Relationship of canopy temperature and yield in chickpea at Jabalpur

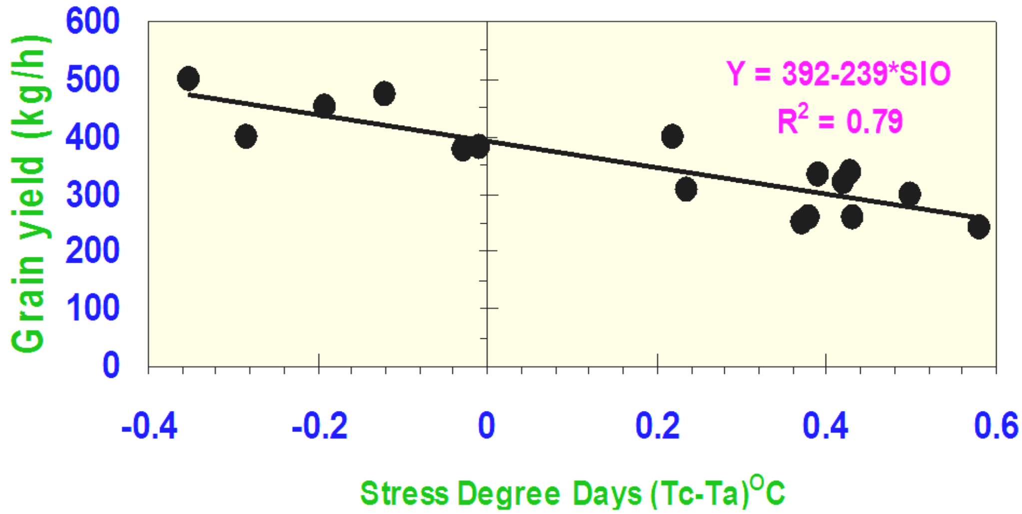


Fig 5. Relation between stress degree days and grain yield of pearlmillet at Solapur

Modeling the effect of cold and heat waves:

Modeling the effect heat and cold waves during critical stages of wheat were evaluated by relating yield with number of days with above and below normal temperature during the critical periods. The results showed that the cold wave conditions during jointing stage at Ludhiana(Fig 6) and hot wave conditions during flag leaf stage at Hisar (Fig 7) adversely affected the yield.

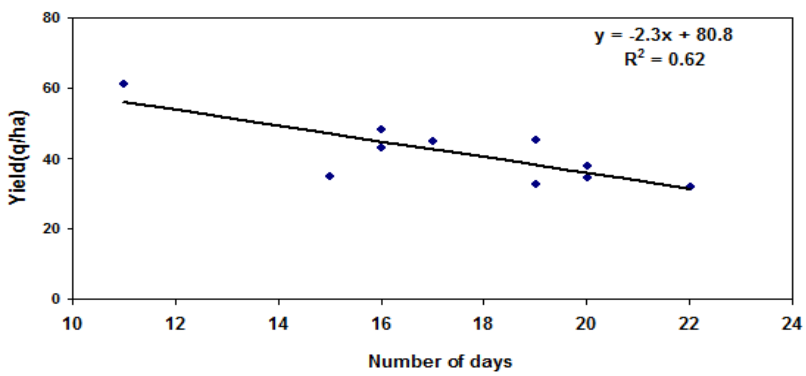


Fig 6. Relationship between wheat yield and number of days with less than base temperature during Jointing stage at Ludhiana

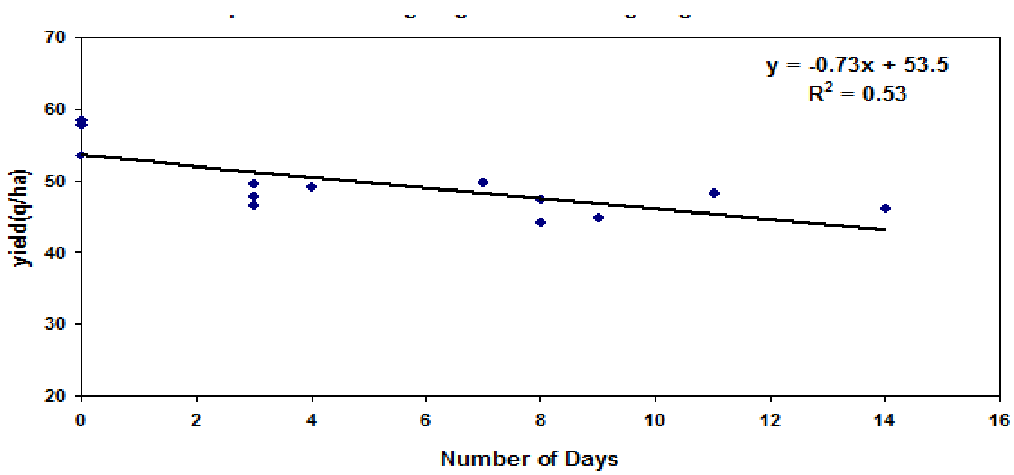


Fig 7. Relationship between wheat yield and number of days with hyper optimal temperature during flag leaf to milking stage at Ludhiana

Effect of de-trending the yield on predictability:

The grain yield of wheat showed significant positive relationship with diurnal temperature range(Fig 8). The coefficient of determination (R^2) of of this relationship improved very much after de-trending of yield, as revealed by the Figure 9.

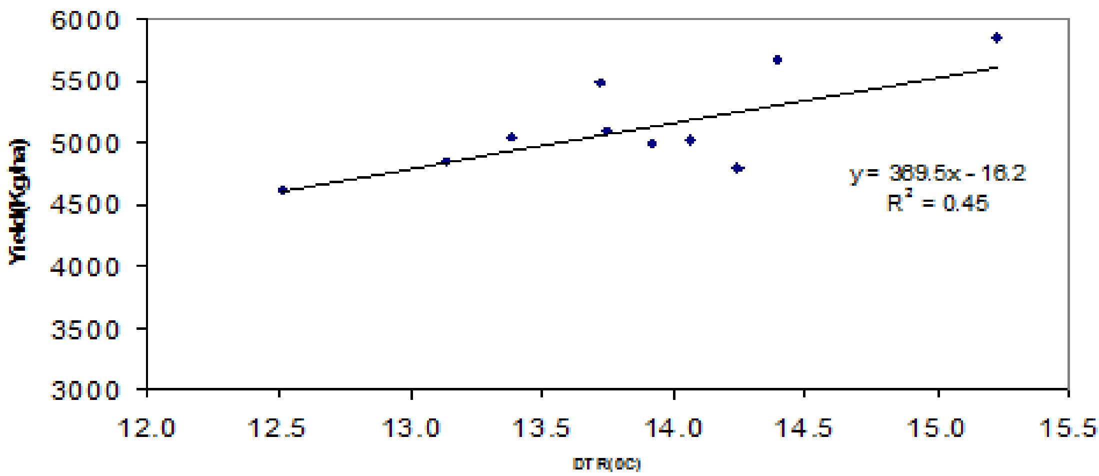


Figure 8 : Relation between yield and Diurnal Temperature Range (DTR)

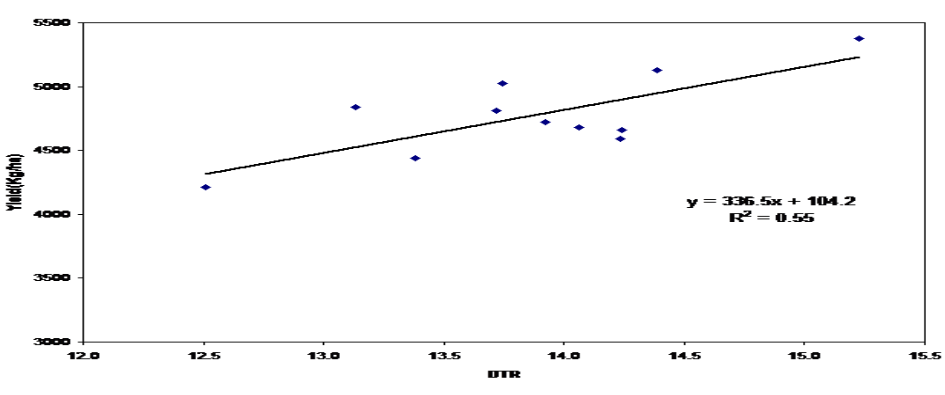


Figure 9: Relation between wheat yield (detrend) and Diurnal Temperature Range (DTR)

Conclusion

Weather is one of the important natural resources influencing crop growth and productivity across different agro-ecological regions of the country. Crop weather models help in assessing growth and yield of crops at different crop stages and also in quantifying the stress-yield relations in respect of moisture, thermal and radiation regimes. Though much work has been done in developing crop weather models and generating knowledge on the physical processes influencing plant growth and productivity, there is still a need to generate similar information in future for the upcoming promising genotypes and new crops that replace existing crops or cropping systems due to economical considerations and technological innovations.

References

Acock, B. and Acock, M.C.1993.Modelling approaches for predicting crop ecosystem responses to climate change, In: *International crop science*, vol.1. pp.299-306, Crop Science society of America, Madison,Wisconsin,USA.

Agarwal, R., Jain, R.C. and Jha, M.P. 1986. Models for studying rice crop-weather relationship. *Mausam 37*(1): 67-70.

Bhargava, P.N., Aneja, K.G. and Ghai, R.K. 1978. Influence of moist days on crop production. *Mausam*, **29**(2): 111-118.

de Wit, C.T. 1958. *Transpiration and crop yields*. Versl. Landbouwkd. Onderz, No. 64.6, Pudoc, Wageningen, The Netherlands, 88 p.

Doorenbos, J.and Kasam, A.H.1979.Yield response to water.*FAO Irrigation and Drainage Paper* no.33.Rome, Italy, FAO.

Fisher, R.A. 1924. The influence of rainfall on the yield of wheat at Rothamsted. *Roy. Soc. (London), Phil. Trans. Ser. B*., **213:** 89-142, Illus.

Frere, M. and Popov, G.F. 1979. Agrometeorological crop monitoring and forecasting. *FAO Plant Production and Protection Paper* **17**. Food and Agricultural Organization, Rome.

Hanks, R.J. 1974. Model for predicting plant growth as influenced by Evapotranspiration and soil water. *Agronomy Journal* **66:** 660-665.

Keating ,J.D.H.,Qi,A.,Wheeler,T.R.,Ellis,R.H.and Summerfield,R.J.1998.Effects of temperature and photoperiod on phenology as a guide to the selection of annual legume cover and green manure crops for hillside farming systems. *Field Crops Research* **57**(2):139-152.

Monteith, J.L. 1973.Principles of environmental physics.London, UK: Longman.

Penman, H.C. 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of Royal Society of London, Series A*. **193**: 120-145.

Rao, K.N. and Das, J.C. 1971. Weather and crop yields. Rice (Survey). *Pre Publication Science Report* **137**, Indian Meteorology Department.

Rao, D.G. and Rao, U.M.B. 1992. Simulation and regression models in dryland agricultural research. In: *Dryland Agriculture in India – State-of-art-of-research in India*, pp. 57-77. Somani, L.L., Vittal, K.P.R. and Venkateswarlu, B. (Eds), Scientific Publishers, Jodhpur.

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research* **8**: 1204-1213.

Rötter, R. and Van de Geijn, S.C. 1999.Climate change effects on plant growth, crop yield and livestock, *Climatic Change* **43**:651-681.

Sarkar, R.P. 1965. A curvilinear study of yield with reference to weather ï Sugarcane. *Indian Journal of Meteorology and Geophysics* **16**:103-110.

Thornthwaite, C.W. 1948. An approach towards a rational classification of climate. *Geographical Review* 38: 85-94

Venkataraman, S. 1972. Weather relations of crops. In: *Crops and Weather*, pp. 302-457.Venkataraman, S. and Krishnan, A. (eds.), Publication of Indian Council of Agricultural Research, New Delhi.

Virmani, S.M. 1994. Climatic resource characterization in stressed tropical environment: Constraints and opportunities for sustainable agriculture. In: *Stressed Ecosystems and Sustainable Agriculture*, pp. 149-160. Virmani, S.M., Katyal, J.C., Eswaran, H. and Abrol, I.P. (eds.), Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.

Water Balance by Thornthwaite & Mather

And FAO Methods

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Introduction

Estimations of water balance components, *viz*., actual evapotranspiration(AET), water surplus (WS)and water deficit(WD) over a region are extremely important in the field of Hydrology, Agriculture, Ecology, etc. in identifying the regions suitable for different crops. Water balance computation is one of the important tools in applied climatology that has innumerable applications, *viz*., climatic classification, agricultural crop planning, water harvesting potentials, and in climate change studies, Thornthwaite (1948) developed the procedure to compute the water balance by considering the monthly rainfall and potential evapotranspiration (PET) a new terminology introduce by him.

The procedure was slightly modified in 1955 by Thorthwaite and Mather by introducing the soil moisture retention tables for different types / depth of soils. Due to its wide applicability, the water balance computational procedures are in great demand. FAO (1979) also brought out a monograph to compute crop-specific water balance by considering the weekly rainfall and the corresponding crop water requirements instead of potential evapotranspiration. The required crop water requirements are computed by multiplying the PET with crop coefficient (Kc) values.

All water balance models attempt to determine what happens to water that is applied to or fall on a given area. The water balance of a system is the difference between the inputs to the system and the flow of water out of the system or storage of water within the system. The inputs are generally precipitation or in some cases, irrigation although, depending upon the boundaries of the system, it could also include water brought into the system through run off. An equation describing the water balance may be written as:

$$\mathbf{P + I = R + D + ET + \Delta SM}$$

Where,

P = Precipitation

I = Irrigation

R = Surface runoff

D = Deep drainage

ET = Evapotranspiration

æSM= Change in soil moisture storage

A. Calculation of Water Balance by FAO Method (1979)

In order to compute the weekly water balance according to FAO method, it is necessary to have the following information at a place.

- Weekly rainfall (mm)
- Weekly potential evapotranspiration (mm)
- Weekly crop coefficients
- Available water holding capacity of the soil (mm)

Procedure for calculating weekly water balance

The different steps involved in the computation of the cumulative weekly water balance for the specific crop are detailed below:

Step-1:

- Enter weekly rainfall (PPT)

Step-2:

- Enter weekly potential evapotranspiration in the same units as rainfall (PET)

Step-3:

- Enter crop coefficients (KCR)

Step-4:

- Compute water requirements of the crop (WR)
- Water requirements of the crops are worked out by multiplying the potential evapotranspiration of the week by the crop coefficient of that week and also calculate total water requirement of the crop for the season by adding the successive water requirements week by week.

Step-5:

- Compute (PPT-WR) for different weeks
- The difference between actual rainfall and water requirement expresses whether the rainfall is adequate to meet the demand of the crop, without, however, taking into account the water stored in the soil The negative value of the (PPT-WR) indicates, the water demand of the crop is not met by rainfall. In this case, the crop takes the water from the soil if water is available in the soil. The positive value of (PPT-WR) indicates,

the water supply is more than the water requirement of the crop. The excess water goes to recharge the soil upto its capacity.

Step-6:

- Surplus (SPL)
- Surplus refers to quantity of water whenever the soil moisture reserve exceeds water-holding capacity of the soil

  Surplus = (PPT-WR) + Previous weekõs soil moisture reserve ï Available water holding capacity

  Note: Whenever surplus occurs, the value of water holding capacity itself is the soil moisture reserve

Step-7:

- Deficit (DEF)
- When the difference between (PPT-WR) is negative, it indicates deficit. This refers to the short falls in the water requirement after taking soil moisture reserve into consideration.
- Deficit = (PPT-WR) (without sign) ï Previous weekõs soil moisture Reserve

Step-8:

- Water requirement satisfaction index (WRSI)
- It is assumed that sowing takes place when at least 75 mm of rainfall has been accumulated. So index is assumed to be 100 at the beginning of crop growing season. This index will remain at 100 for the successive weeks until either a surplus of more than 100 mm or a deficit occurs. If a surplus of more than 100 mm occurs during a week and the rainfall during the same week has fallen in less than 3 days, the index is reduced by 2.1 units during this week and remaining at the level until a further stress period occurs. If the deficit occurs, the index is calculated by subtracting the percentage reduction during the week from the preceding weekõs index. The percentage reduction during the week is calculated as the ratio of deficit during the same week and total water requirement of the crop expressed as percentage. The calculation is pursued to the end of the growing season taking into account the fact that the index starts in the first week at 100 and thereafter can only remain at 100 or goes down. The index at the end of the growing season will reflect the cumulative stress endured by the crop through excesses and deficits of water and will usually be closely linked with the final yield of the crop, unless some other harmful factors (eg. pests and diseases, strong winds etc.) have predominant affects.

B. Calculation of Weekly Water Balance by Thronthwaite and Mather's method (1955):

To compute the weekly water balance according to Thronthwaite and Matherês method (1955), following information at a place is required.

- Weekly rainfall in mm
- Weekly potential evapotranspiration in mm
- Available water holding capacity of the soil in mm

Procedure to calculate weekly water balance:

The different steps involved in the calculation of weekly water balance are given below:

Step-1: Enter weekly rainfall (P)

Step-2: Enter weekly potential evapotranspiration (PET)

Step-3: Enter available water holding capacity of the soil (AWC)

Step-4: Compute (P-PET) for different weeks

The difference between actual rainfall and potential evapotranspiration expresses whether the rainfall is adequate to meet the atmospheric demand, without, however, taking into account the soil moisture stored in the soil. The negative value indicates that the atmospheric demand is not met by the rainfall. In this case, soil moisture is taken from the soil, if it is available in the soil. The positive value indicates that the water supply (rainfall) is more than the atmospheric demand. The excess water goes to recharge the soil up to its capacity.

Step-5: Surplus (SPL)

Surplus refers to quantity of water wherever the soil moisture reserve exceeds water holding capacity of the soil

$SM_i = SM_{i-1} + (P_i - PET_i)$

If SM_i is greater than AWC, surplus occurs

$SPL_i = SM_i - AWC$

$SM_i = AWC$

$AET_i = PET_i$

Step-6: Deficit (D)

When the difference between (P-PET) is negative, it indicates deficit. This refers to short falls in the atmospheric demand.

Compute accumulated potential water loss (APWL)

$APWL_i = \sum (P_i - PET_i)$

$SM_i = AWC * \exp\left(\frac{-APWL}{AWC}\right)$

$AET_i = P_i + æSM_i$ $Di = PET_i - AET_i$

Where, æSM is change in the soil moisture storage

$æSM_i = SM_{i-1} - SM_i$

AET is actual evapotranspiration

SM is the soil moisture reserve

References

Frere, M., and Popov, G.F. 1979. Agrometeorological crop monitoring and forecasting, FAO Plant Production and Protection paper No. 17, Food and Agriculture Organization. Rome, Italy, 64 pages.

Thronthwaite, C.W. (1948). An approach toward a rational classification of climate, Georg. Rev., vol.38, No1, PP 55-94

Thronthwaite, C.W. and Mather, J.R. 1955. Water Balance: Publications in Climatology No. 8, Drexel Institute of Technology, Centerton, N.J. 104 pp.

Computation of water balance in crop growth models (DSSAT)

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The widely evaluated CROPGRO and CERES models use the one dimensional tipping bucket soil water balance of Ritchie (1985, 1998) and further modified by Porter et al. (2004). Soil water balance processes envisaged in these models include infiltration of rainfall and irrigation, runoff, soil evaporation, crop transpiration, distribution of root water uptake from soil layers, and drainage of water through the profile and below the root zone. The soil is divided into a number of computational layers, up to a maximum of 20. Water content in each layer varies between the lower limit of plant extractable soil water [LL(J)], the drained upper limit [DUL(J)], and the saturated soil water content [SAT(J)]. If water content of a given layer is above the DUL, then water is drained to the next layer with the ñtipping bucket approach, using a profile wide drain- age coefficient (SWCON). If available, saturated hydraulic conductivity (K_{sat}) for water flow of each specific soil layer can be entered to control vertical drainage from one layer to the next. This allows the soil to retain water above the DUL for layers that have sufficiently low K_{sat} for water flow, and in this case, soil layers may become saturated for sufficient time to cause root death, reduced root water uptake, Water between SAT and DUL is available for root uptake subject to the anoxia induced problem that is triggered when air filled pore space falls below 2% of total volumetric pore space. Infiltration and runoff of rainfall and applied irrigation water depends on the Soil Conservation Service runoff curve number.

Reference crop evapotranspiration

Three options are provided in these models for computing climatic potential evapotranspiration (PET, equivalent to ET_O): (i) Priestley Taylor method (Priestley and Taylor, 1972) also described by Ritchie (1985), (ii) FAO Penman 24 method described by Jensen et al. (1990), and (iii) the FAO 56 described by Allen et al. (1998). The default PET option is the Priestley Taylor option, primarily because it is the less demanding of weather data (it is the only one that does not require daily windspeed or dewpoint temperature as input). The other methods additionally require wind speed and humidity (actually dewpoint temperature).

Through the model has ETPHOT, which is a more mechanistic model, but this component was not discussed here.

Partitioning of PET into transpiration and Soil Evaporation

The DSSAT crop models partition the PET to potential plant transpiration (EP_O) and potential soil evaporation (ES_O), following the Ritchie (1972, 1985) approach, which considers the portion of net radiation that reaches the soil and that can be spent as latent energy to evaporate water from the soil surface if the soil is wet. The climatic EP_O is computed by multiplying the PET of Options 1, 2, or 3 by the exponential function of LAI shown in Eq. [1] using a KEP that is smaller than the extinction coefficient for photosynthetically active radiation. Energy not absorbed by the crop is transmitted to the soil surface (Eq. [2]) and is available to drive ES_O.

$$EP_O = PET \times [1.0 - \exp(-KEP \times LAI)] \quad [1]$$

$$ES_O = PET \times \exp(-0.40 \times LAI) \quad [2]$$

The actual soil evaporation (ES) and plant transpiration (EP) depend on the avail- ability of water to meet these potential rates. The current DSSAT models compute the ES following the two stage soil evaporation method of Ritchie (1985): (i) the energy limited stage (Stage 1); and (ii) the falling rate stage (Stage 2) that begins after the first stage loss has been met, after which ES declines as the square root of time. The Stage 1 soil water evaporation limit is a value defined for each soil pro- file; once this amount is achieved, the evaporation follows the falling rate stage. In addition, ES is allowed to have access only to the soil water in the top 5 cm of soil (for all soils) that limits the function. If the potential ES_O energy is not used for ES during Stage 2, it is presumed absorbed by the canopy as follows:

$$\text{IF } EP_O + ES < PET, \text{ THEN } EP_O = PET - ES \quad [3]$$

Root Water Uptake and Water Stress Factors

Root water uptake must be computed before the actual canopy transpiration (EP) is computed. Potential root water uptake per soil layer, RWU(L), is a function of root length density (RLD) and soil water content within each soil layer using a simplified computation of radial flow to roots (Ritchie, 1985) as shown in Eq. [4] where C_1, C_2, and C_3 are constants. The total potential root water uptake (TRWU) is integrated over RWU of root length in all soil layers, TRWU = × RWU(L), and is then compared with climatic EP_O. If EP_O is less than TRWU, then actual root water uptake is limited to EP_O (Eq. [5] and [6]). The TRWU is usually larger than EP_O, until the soil water reaches a given level of depletion.

$$RWU(L) = C_1 \times EXP[MIN(\{C_2(L) \times [SW(L) - LL(L)]\},40)] \{C_3 - ALOG[RLD(L)]\} \quad [4]$$

$$\text{IF } TRWU > EP_O, \text{ THEN } EP = EP_O \quad [5]$$

$$\text{IF } TRWU < EP_O, \text{ THEN } EP = TRWU \quad [6]$$

The ratio of TRWU to EPO is used to compute water deficit effects, via two different ratios (SWFAC and TURFAC) per Eq. [7] and Eq. [8]. These are signals that regulate crop processes. Figure 1 shows graphically the meaning of SWFAC and TURFAC. TURFAC and an ñearly signal are also computed from TRWU and EPO, but are scaled by 1.5 or Ki to act before photosynthesis is reduced. SWDF3 in Eq. [9] is a hypothetical ñearly signal with a Ki ranging from 2.5 to 5.0, and is designed to act sooner than TURFAC or SWFAC.

$SWFAC = TRWU\ EP_O$, limited to a maximum of **i**.0 [7]

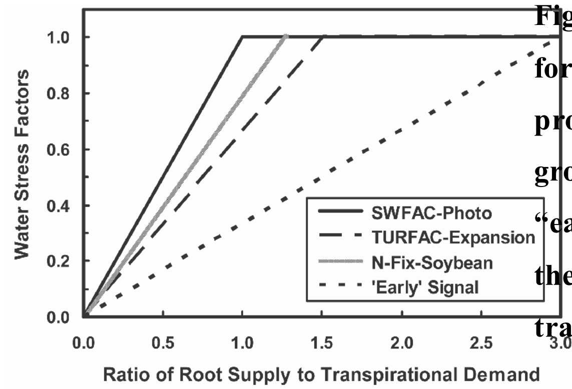

Fig. 1 Four water stress signals, SWFAC for photosynthesis, TURFAC for expansive processes, N–Fix–Soybean for nodule growth and nitrogenase activity, and an “early” signal, computed from the ratio of potential root water supply to transpirational demand for water

$TURFAC = TRWU\ (EP_O \ x\ 1.5)$, limited to a maximum of 1.0 [8]

$SWDF3 = TRWU\ (EP_O \ x\ K1)$, limited to a maximum of 1.0 [9]

When the SWFAC (Eq. [7]) is less than 1.0, then daily photosynthesis and transpiration are reduced in proportion to SWFAC. This is a mimic of stomatal action, allowing CO_2 to be fixed in proportion to the stomatal opening to allow for transpiration. CROPGRO has no vapor pressure deficit effect on photosynthesis or stomatal function. When SWFAC is less than 1.0, root depth progression is accelerated, leaf senescence is more rapid, crop phenology may be delayed or accelerated depending on the crop growth phase, and N is mobilized more rapidly during seed fill. When TURFAC (Eq. [8]) is less than 1.0, the expansion of new leaves and internode elongation (height and width increase) are reduced. A TURFAC less than 1.0 reduces rate of leaf appearance (V stage), specific leaf area of new leaves, the increase in height and width, N fixation, and it shifts allocation from leaf and stem toward root.

Root Growth function

Root mass and root length in each soil layer are computed on a daily step basis. New root length produced each day depends on daily assimilate allocated to roots and a constant length to weight parameter. Fraction partitioning of assimilate to root varies with crop growth stage and eventually becomes zero when reproductive growth uses all the daily assimilate. The distribution of the new RLD into respective layers depends on progress of downward root depth front, a soil rooting preference function (SRGF) describing the probability of roots growing in each soil layer, and the soil water content of each layer. The SRGF defines the hospitality of the soil (soil impedance, soil pH, soil nutrient effect, and organic matter effect) to root proliferation. Rate of root depth progression (RTPROG) in Eq. [10] is a function of thermal time accumulation (DTX), a species potential root depth progression rate in centimeters per thermal day (RFAC2), is accelerated as much as 15% by SWFAC, and is dependent on soil water status of the rooting front layer (reduced only when fraction available water is less than 0.25 or reduced if water content is very high, within 2% of saturation). The SWDF(L) in Eq. [10, 11, 12] is not fraction available water and is not SWFAC, rather SWDF(L) = {SW(L) · LL(L)] (0.25 x [DUL(L) · LL(L)]} and mimics increased soil impedance, occurring when available water in layer *L* is less than 25% of (DUL · LL). SWEXF(L) is anaerobic stress computed from fraction of pore space filled with water for the rooting front layer (*L*). While CROPGRO accelerates root depth with water stress, CERES Maize is different, and uses SWFAC as a third factor in the MIN part of the equation to limit root depth progression with plant water stress.

RTPROG = DTX x RFAC2 x MIN[SWDF(L), SWEXF(L)]

x {1.0 + 0.25 x [1.0 · MAX(SWFAC, 0.40)]} [10]

The fraction of new root length increase allocated to a given layer of soil, RLDF (L), is dependent on the Soil Root Growth preference Function [SRGF(L)], layer thickness [DLAYR(L)], the presence of the rooting front in that layer, and the soil water status of that layer [SWDF(L) and SWEXF(L)] defined the same as for root depth progression (Eq. [11]). It is assumed that roots will grow into a soil layer if its water content is above 25% of (DUL · LL).

RLDF(L) = SRGF(L) x DLAYR(L) x MIN[SWDF(L), SWEXF(L)] [11]

There is senescence of RLD in each layer as a function of thermal time, accelerated when available soil water content is below a critical fraction (0.25) or near saturation. Root senescence is influenced by soil water status and water excess of each soil layer. In Eq. [12], RTSURV is fraction root survival, RTSDF is fraction root death under zero water availability and RTEXF is fraction root death under fully saturated soil.

RTSURV(L) = MIN(1.0,{1.0 · RTSDF x [1.0 · SWDF(L)]},

{1.0 · RTEXF x [1.0 · SWEXF(L)]}) [12]

In addition, Eq. [13] provides a thermal time dependent rate of root length senescence in each layer, where RTSEN (0.02) is the fraction senesced per day if at optimum temperature:

RLSEN(L)=RLV(L) x RTSEN x DTX [13]

As a result of these equations, roots tend to grow and accumulate in moist soil layers and diminish in the saturated or drying soil layers (less than 25% available water). Typically, the simulated RLD of the top 5 cm layer is less than that in the 5 to 15 cm layer because of more frequent soil drying, despite both layers having the same soil hospitality factor.

Conclusions

Most widely used DSSAT models use the Ritchie tipping bucket soil water balance model that works satisfactorily, when the soil water holding traits (DUL, LL) are estimated properly for the soil in question and when root growth is adequately predicted. There are four PET options used with CROPGRO of which three (FAO 24, FAO 56, and a prototype hourly energy balance) require additional inputs of wind run and dew-point temperature.

References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrig. And Drainage Paper no. 56. FAO, Rome, Italy.

Jensen, M.E., R.D. Burmaan, and R.G. Allen (ed.) 1990. Evapotranspiration and irrigation water requirements: A manual. Am. Soc. Of Civil Engineers, New York.

Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat and evaporation using large scale parameters. Mon. Weather Rev. 100:81-92.

Porter, C.H., J.W. Jones, G. Hooogenboom, P.W. Wilkens, J.T. Ritchie, N.B. Pickering, K.J. Boote, and B. Baer. 2004. DSSAT v4 soil water balance module. P. 1-23. *In* J.W. Jones et al. (ed.) Decision support system for agrotechnology transfer Version 4.0, Vol. 4 DSSAT v4: Crop model documentation. Univ. of Hawali, Honolulu, HI.

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204 ï 1213.

Ritchie, J.T. 1985. A user-oriented model of the soil water balance in wheat. p. 293-305. *In* E. Fry and T.K. Atkin (ed.) Wheat growth and modeling. NATO-ASI Series, Plenum Press.

Ritchie, J.T. 1998. Soil water balance and plant water stress. p. 41-54. *In* G.Y. Tsuji et al. (ed.) Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, The Netherlands.

Minimum Dataset for simulation models

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Introduction

Crop growth simulation models are process oriented and intended to have wider applications, and work independent of location, season, crop cultivar, and management system. The models simulate the effects of weather, soil water, genotype, and soil water balance, and crop photosynthetic, nitrogene dynamics on crop growth and yield. In simple, these models / software integrate crop, weather, soil and management practices to simulate growth and development of various crops. For effective utilization of simulation models, good quality data are important and these models require exhaustive data on weather, soil, cultivar and management aspects. Practically, it is very difficult to have all required data for simulation. However, with the available data source it is possible to run the simulation models for various purposes. This is called as minimum dataset and it refers to a minimum set of data required to run the crop models and validate the outputs.

Types of data

Crop growth simulation models have Data Base Management System (DBMS) and are used to organize and store the Minimum Data Set (MDS). The minimum data required to run crop models are different for different crop growth models (INFOCROP, DSSAT, EPIC, APSIM etc.,). But, in general following datasets are required to run the crop models.

Weather Data This data base contains daily data of temperature (Maximum and minimum), sunshine hours / solar radiation, rainfall. In addition to this, data on wind speed, relative humidity, soil moisture at different depths if available, it is added advantage.

Soil Data

This data base is comprised principally soil physical, chemical and biological properties of the experimental site.

Crop management data

This data includes information on planting date, dates when initial soil conditions were measured before planting/sowing, plating density, row spacing, variety, irrigation and fertiliser practices.

Observed / measured crop data

This data comprises time series (phenology-wise or at preferred intervals) data on dry matter production, plant height, number of seeds/pods per plant, leaf area index, by product yield and grain yield etc., The minimum dataset required for running crop simulation for rice crop and soil profile data for DSSAT model are given in appendix 1 and 2.

Data requirements for agricultural crops are closely associated with the level of analysis (Nix, 1984; Bouman and Lansigan, 1994; Eswaran et al., 1996) and to the purpose, domain or level of analysis considered in the study. Each level of analysis of crop production has its own data requirements based on the details and the resolution required for the crop models. Alternatively, data requirements for crops may be specified based on the level of crop production (Lovenstein et al., 1993; Kropff et al., 1994) which considers the factors that define and/or limit crop growth and development.

Collaboration between organisations/research institutes needed

Efficient interchange of data among researchers, especially for use in simulation models and other decision support tools, requires use of a common terminology and approach for organizing data. The agricultural research community increasingly encounters research problems that require interdisciplinary collaboration. Agrometeorologists wish to study the impact of climate change of crop production/productivity. Physiologists and molecular biologists work together to develop a better understanding of the genetic control of productivity-related traits. Agronomists, soil scientists and irrigation specialists combine efforts in order to increase the efficiency of crop water use. In such collaborations, ready data interchange is possible. Genomic data are widely available through publicly accessible databases (Blanchard, 2004). Daily weather records and soil profile data are increasingly available through the Internet. The International Research Institute for Climate Prediction recently developed two daily weather data download options in ICASA format that can be accessed from the ICASA web site (www.icasa.net/weather_data). Efforts are also underway to make the ñWorld Inventory of Soil Emission Potentialsò (WISE) database developed by the International Soil Reference and

Information Centre in The Netherlands available for crop model applications. However getting field research data is very difficult through public databases. Although there have been various initiatives (Like INARIS) to develop systems for reporting and storing data from field research, to date, no system is available for perfect.

References

Nix, H.A., 1984. Minimum data sets for agrotechnology transfer. In: Proceedings of the International Symposium on Minimum Data Sets for Agrotechnology Transfer, March 21-26, 1983, ICRISAT, Patencheru, India, pp. 181-188.

Bouman,B.A.M. and F.P. Lansigan, 1994. Agroecological zonation and characterization. In: Bouman, B.A.M et al.(Eds.) Agroecological zonation, characterization and optimization of rice-based cropping systems. SARP Research Proceedings, Wageningen and Los Baños, pp.1-8.

Eswaran, H., F. Beinroth, and P. Reich, 1996. Biophysical consideration in developing resource management domains., Proceedings of the International Workshop on Resource Management Domains, Kuala Lumpur, Malaysia, August 26-29,1996.

Lovenstein, H., H.A. Lantinga, H. van Keulen, 1993. Principles of Production Ecology, Wageningen Agricultural University, Wageningen, The Netherlands.

Kropff, M.J., H.H. van Laar, and R.B. Matthews (Eds.), 1994. ORYZA1: An ecophysiological model for irrigated rice production, SARP Research Proceedings, AB-DLO/WAU and IRRI, Wageningen and Los Banos, 110 pp.

MINIMUM DATASET REQUIRED FOR CROP WEATHER RELATIONS AND CROP SIMULATION MODELS – RICE

I. Station details and weather data

Station details (Latitude, Longitude and Altitude) and daily weather data viz., Tmax & Tmin (°C), Rainfall (mm), sunshine hours (hrs), Solar radiation (MJ / m^2), Wind speed (km /hr), RH (% - I & II), Pan evaporation (mm) are needed throughout year.

II. Soil data

S. No	Parameters	Value / Text
1	Soil colour	
2	Soil texture	
3	Drainage (Very excessive / Excessive / Some what excessive / Well / Moderately well / Some what poorly / poorly / very poorly	
4	Soil series name	
5	Soil classification	
6	Slope (%)	
7	Electrical conductivity (dS / m)	
Layer wise / depth wise information (Minimum 3 layers)		
8	Clay (%)	
9	Silt (%)	
10	Sand (%)	
11	pH	
12	Cation exchange capacity (Cmol/kg)	
13	Total nitrogen (%)	
14	Field capacity (Volume basis)	
15	Wilting Point (Volume basis)	
16	Bulk density (Mg / m^3)	
17	Run off potential (Lowest / Moderately low / Moderately high/Highest)	
18	Organic carbon (%)	
19	Soil moisture at sowing (Volume basis)	
20	NO_3 content at sowing (Kg / ha)	
21	NH_4 content at sowing (Kg /ha)	

III. Experimental data

S. No	Parameters	Date / Value / Text
1	Variety name	
2	Type of variety (Short / medium / long duration)	
3	Duration of variety (in days)	
4	Previous season crop	
5	Experimental design	
6	Sowing method (Transplanted / direct seeded)	
7	Sowing depth (If, direct seeded)	
8	Puddling (Yes / No)	
9	Seed rate	
10	Row to row spacing	
11	Age of seedlings at transplanting day	
12	No of seedlings / hill	
13	Plant population (No of hill / m^2)	
12	Sowing date	
13	Transplanting date	
14	Panicle Initiation stage	
15	Heading stage	
16	50% flowering / Anthesis	
17	Beginning of grain filling	
18	End of grain filling	
19	Physiological maturity	
20	Harvesting	
21	*No of effective tillers / m^2	
22	*No of grains / ear	
23	*No of grains / m^2	
24	*Single grain weight (g)	
25	*Straw yield (Kg / ha)	
26	*Biomass yield (Kg/ha)	
27	*Grain yield (Kg / ha)	
28	Harvest index	
	Irrigation details	

29	Irrigation amount (mm)	
30	Date of irrigation (in DAT)	
31	Irrigation method	
	Fertiliser management	
32	Date of fertilizer (N, P and K) application (DAT)	
33	Amount of fertilizer (N, P and K) application	
34	Type of fertilizer (N, P and K)	
35	Depth of fertliser application	
36	Fertiliser application method	
	Farmyard manure / green manure applied, if any	
37	Name of green manure crop	
38	Application date	
39	Amount	

***Data needs replication-wise**

IV. Periodic measurements of crop growth parameters

Periodic measurements of **Leaf area index, Dry matter production** (leaf, stem, root, ear and total), **Plant height, Specific leaf area, Relative growth rate and PAR inside & outside canopy** are to be taken through out crop season. Measurements should be started at 30 DAS and continued at 15 days interval up to physiological maturity.

In addition to these observations, any biotic stress (Heavy weed infestation, insect and disease) and abiotic stress should be noted down during crop season.

Appendix-2: Inputs required for creating a new soil profile for DSSAT Crop Model

I. General Information

1. Country :	2. Site Name:
3. Latitude:	4. Longitude:
5. Soil Data source	6. Soil Series name
7. Soil Classification	

II. Surface Information

1. Colour (a) Brown (b) Red (c) Black (d) Gray (e) Yellow

2. Drainage (a) Very excessive (b) Excessive (c) Some what excessive
(d) Well (e) Moderate well
(f) Some what poorly (g) Poorly (h) Very poorly

3. % slope

4. Runoff potential (a) Lowest (b) Moderately low (c) Moderately high (d) Highest

5. Fertility factor (0 to 1)

6. Runoff Curve Number

7. Albedo

8. Drainage rate

III. Layer-wise soil information: No. of layers depends on the location. Here layers up to 120 cm depth are shown as a sample.

Depth (bottom) Cm	Master Horizon	Clay %	Silt %	Stones %	Organic Carbon %	pH in water	Cation Exchange Capacity C mol/kg	Total Nitrogen %
0-5								
5-15								
15-30								
30-45								
45-60								
60-90								
90-120								

Table continued….

Depth (bottom) Cm	Lower limit	Drainage Upper Limit	Saturation	Bulk Density g/cm3	Saturated Hydraulic Conductivity Cm/hr	Root growth Factor 0.0-1.0
0-5						
5-15						
15-30						
30-45						
45-60						
60-90						
90-120						

Agro-climatic analysis: Weathercock Software

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1. Introduction

Climate is the primary important factor for agricultural production. Concerning the potential effects of change in weather parameters on agriculture has motivated important change of research. The research on climate change concentrates on possible physical effects of climatic change on agriculture, such as changes in crop and livestock yields as well as the economic consequences of these potential yield changes. In order to achieve maximum and sustainable crop production from available farm resources, it is essential to have proper knowledge of the agro climatic resources of the location/region. Agroclimatological analysis is used to study about climatic characteristics and crop performance of a particular region and also to know the climatic variability/climate change and its impact on agriculture. Therefore, a thorough understanding of the climatic conditions would help in determining the suitable agricultural management practices for taking advantage of the favorable weather and avoiding or minimizing risks due to adverse weather conditions.

2. Purpose and scope

This hands-on-training on agroclimatic analysis will help to study location-specific and spatial based agroclimatic resource characterization especially for the Indian conditions. Agroclimatic information is necessary in enhancing crop productivity through better agricultural planning including land use planning, water resources availability, crop suitability, pests and disease management and also in weather based agro advisories. This particular hands-on-training is aimed to develop skills of technical persons/scientists towards agroclimatic analysis, which helps in efficient utilization of available resources, and also to develop the resources for sustainable agricultural growth. In this connection, agroclimatological analysis is helpful in understanding change and variability in climatic characteristics so as to get an idea on possible impacts on crop performance for a particular location / region. The reliance on the change / variability of climatic parameters at sub-district / block / mandal / tehsil level is increasing as there is paucity of reports and government agencies are in dire need. This compelled AICRPAM Unit of CRIDA, to develop a computer software program ñWEATHERCOCKò (Fig.1.) for agro-climatic analysis. Different agro-climatic analysis viz., converting daily weather data on to weekly, monthly, seasonal and annual data, rainy days analysis, meteorological and agricultural drought analysis, probability analysis, water balance, extreme event analysis for temperature and rainfall and to estimate length of growing season have been brought out in to one umbrella. This particular software is based on Visual Basic (VB) and easy to operate even by beginners. Doing agro-climatic analysis with MS ï EXCEL for individual stations is drudgery and may lead to wrong results. The weathercock software reduces this drudgery and eliminates any mistakes associated with MS-EXCEL. Moreover, ñbatch processingò a special provision was made in the weathercock to facilitate to run the analysis for hundreds of stations at a moment if input files are prepared in the said format as doing agro-climatic analysis at localized scale have hundreds / thousands of stations.

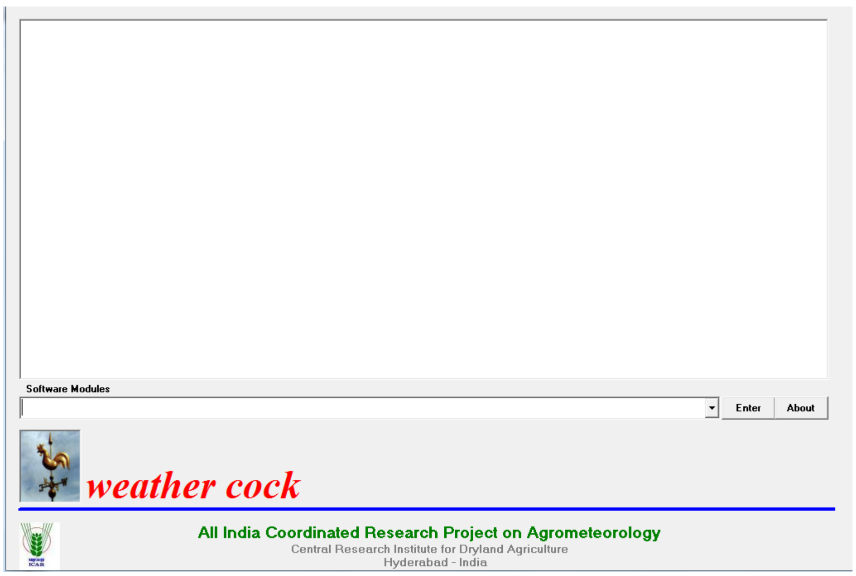

Fig.1. Main window of ñWEATHERCOCKò software program

3. Determining minimum weather data requirement

To characterize a place/region long-term weather data is basic requirement. Different type of analysis needs different weather elements either in single or in multiple. For example, rainfall analysis/drought analysis (meteorological & agricultural) and rainfall trend analysis require only rainfall data. In case of water balance analysis, seven weather parameters viz., temperature (maximum and minimum), relative humidity (morning and evening), wind speed, sunshine hours and evaporation are necessary to compute potential evapotarnspiration (PET). Thus, it is desirable to collect all weather parameters (minimum data set for agroclimatic analysis) at a time. The minimum data set for agroclimatic analysis includes (i) rainfall (ii) temperature (maximum and minimum) (iii) relative humidity (morning and evening) (iv) wind speed (v) sunshine hours and (vi) evaporation. In addition to these weather parameters, coordinates of place (Latitude, Longitude and Altitude), soil information like permanent wilting point and field capacity of the soil (maximum water holding capacity) are also needed for agro climatic analysis.

4. Description of programs

4.1. Converting daily weather data into weekly, monthly, seasonal and annual values along with CV and normals

Daily data of weather parameters is base for all agroclimatic analysis. Though it is base, it is necessary to convert these data in to weekly / monthly / seasonal / annual format in order to understand distribution of different weather parameters over different periods (weeks / months / season / annual). These tools (weeks / months / season / annual) are very useful to characterize the region in relation to weather.

4.1. Number of rainy days along with Coefficient of Variation

The number of rainy day analysis gives an idea on rainy days in a week / month / season / annual. Information of rainy days of a place over a period of time determine the need and design both for rainwater harvesting and structure to recharge groundwater aquifers. With the help of number of rainy days planners may plan cropping pattern/cropping systems.

Rainy day: A day with rainfall amount equal or more than 2.5 mm considered as a rainy day according to India Meteorological Department for Indian region.

4.2. Initial and conditional probabilities and probability for consecutive wet and dry weeks

Agricultural operations are determined by the certain amount of rainfall received in a period. There are specific amounts of rainfall required for the activities like land preparation, sowing and for various agricultural activities. Hence, estimation of probabilities with respect to a given amount of rainfall is useful for rainfed agricultural planning especially in semiarid region. Initial probability rainfall analysis will give percentage probability to get certain amount of rainfall in a given week. Probability of wet week is denoted as P(W) and dry week as P(D). Conditional probability rainfall analysis will give the percentage probability for wet week followed by wet week [P(W/W)], wet week followed by dry week [P(W/D)], dry week followed by dry week [P(D/D)] and dry week followed by wet week [P(D/W)]. Probability of wet and dry week program is used to find out percentage probability of consecutive wet weeks (2W, 3W, 4W) and consecutive dry weeks (2D, 3D, 4D). For efficient planning, research workers, farmers and planners stand to gain significantly by using quantified rainfall at different probability levels called assured rainfall. Incomplete gamma probability model is used for computing the assured rainfall amount at different probability levels.

Initial probability**:** It is the probability of receiving a certain amount of rainfall in a given week.

Conditional probability**:** It is the probability of getting a next week as a wet week, given the condition that the current week is also a wet week.

***Consecutive wet and dry weeks*:** It is the probability of getting two or three or four weeks as a wet week consecutively for a given amount of rainfall. The probability for getting consecutive dry weeks refers to probability for getting less than the given amount of rainfall consecutively for two/three/four weeks.

4.4. Drought analysis

4.4.1. Classification of droughts

Drought is a normal, recurrent climatic feature that occurs in virtually around the world causing huge loss for the farming community. Drought is universally acknowledged as a phenomenon associated with deficiency of rainfall. There is no single definition, which is acceptable universally. Droughts occur at random and there is no periodicity in its occurrence and cannot be predicted in advance. In semiarid stations, the occurrence of rainfall is seasonal and is known more for its variability with respect to space and time. Drought is characterized by moisture deficit resulting either from i) Below normal rainfall ii) erratic rainfall distribution iii) higher water need iv) a combination of all the three factors. Wilhite and Glantz (1985) analysed more than 150 such definitions of drought and thus broadly grouped these into four categories and explained below.

Meteorological drought: A period of prolonged dry weather condition due to below normal rainfall.

Agricultural drought: Agricultural impacts caused due to short-term precipitation shortages, temperature anomaly that causes increased evapotransipration and soil water deficits that could adversely affect crop production.

Hydrological drought: Effect of precipitation shortfall on surface or sub-surface water sources like rivers, reservoirs and groundwater.

Socio-economic drought: The socio-economic effect of meteorological, agricultural and hydrological drought in relation to supply and demand of the society.

4.4.2. Analysis of meteorological and agricultural drought

In agroclimatic analysis, meteorological and agricultural drought study is important. The frequencies of occurrence of different type of meteorological droughts (moderate and severe) over a period of year would give insight for vulnerability of a particular location/region to drought on annual basis. Agricultural drought analysis would give idea about susceptibility of a region to drought on seasonal basis, i.e., main crop growing season.

Meteorological Drought- According to India Meteorological Department

2 types: based on rainfall deficit from normal

- Moderate : 26-50%
- Severe : > 50%

Agricultural drought: According to National Commission on Agriculture, 1976, at least four consecutive weeks receiving less than half of the normal rainfall during *Kharif* season and six such consecutive weeks during *Rabi* season is considered as agricultural drought peiord.

Normal rainfall: Average rainfall for a location/region over a period of years (preferable 30 years).

4.5. Water balance analysis

a. Water balance analysis

Availability of water in right quantity and in the right time and its management with suitable agronomic practices are essential for good crop growth, development and yield. To assess water availability to crops, soil moisture is to be taken into account and the net water balance through soil moisture can be estimated using the water balance technique. The concepts of PET (Potential evapotransipiration) and water balance have been extensively applied to studies such as climatic classification, aridity, humidity and drought.

b. Computation of Potential Evapotranspiration (PET)

Information on PET for a location on a short timescale has great importance in agricultural water management. Many empirical methods are available viz., Thornthwaite (1948), Blaney and Criddle (1950), Hargreaves and Christiansen (1973) and others. Guidelines were developed and published in the FAO Irrigation and Drainage Paper No 24 ñCrop Water Requirementsò (Doorenbos and Pruitt 1977) to compute ETo using several methods. FAO Penman ï Monteith method is recommended as the sole standard method. FAO Penman-Monteith method is selected as the method by which the evepotranspiration of the reference surface (ETo) can be unambiguously determined, and this method provides consistent ETo values in all regions and climates.

c. Computation of indices like Aridity index (Ia), Humidity Index (Ih), Moisture Index (Im) and MAI

These indices are output of water balance analysis. The indices viz., Aridity index (Ia), Humidity Index (Ih), Moisture Index (Im) are useful in climatic classification and to find climatic type of a particular place. Moisture Adequacy Index (MAI) provides a good indication of the moisture status of the soil in relation to the water-need, high values of the index signifying good moisture availability and vice versa.

d. Components like water surplus, water deficit, Actual Evapotranspiration (AET)

Water surplus (WS) and water deficit (WD) occur in different seasons at most places and both are significant in water balance studies. The information about when the period of water surplus and deficit occurring in a season or year is helpful to find ideal period for starting of crop season and stages, which may fall in deficit period. It also helps in flood and drought analysis.

Potential evapotranspiration (PET): It is defined as the maximum quantity of water, which is transpired and evaporated by a uniform cover of short dense grass (Reference crop) when the water supply is not limited.

Reference crop: A hypothetical reference crop with an assumed crop height of 0.12m, a fixed surface resistance of 70s/m and an albedo of 0.23.

Water balance*:* It refers to the climatic balance obtained, by comparing the rainfall as income with evapotarnspiration as loss or expenditure, soil being a medium for storing water during periods of excess rainfall and utilizing or releasing moisture during periods of deficit precipitation.

Water surplus: It is the excess amount of water remaining after the evaporation needs of the soil have been met (i.e., when actual evapotranspiration equals potential evapotranspiration) and soil storage has been returned to the water holding capacity level.

Water deficit: It is the amount by which the available moisture fails to meet the demand for water and is computed by subtracting the potential evapotranspiration from the actual evapotranspiration for the period of interest.

Actual Evapotranspiration: It is the actual amount of water lost to the atmosphere by evaporation and transpiration under existing conditions of moisture availability.

Aridity Index Ia (%) = Water deficit / PET * 100

Humidity Index Ih (%) = Water surplus / PET * 100

Moisture Index Im (%) = Ih ï Ia

Moisture Adequacy Index MAI (%) = AET / PET *100

References

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. Geographic Review 38:55-94

Blaney, H.F. & Criddle, W.P. 1950 Determining water requirements in irrigated areas from climatological and irrigation data. U S Department of Agriculture, Soil Conservation Series (SCS) TP-96, 48

Doorenbos. J. And Pruitt, W.O. 1977. Crop water requirements, irrigation and Drainage Paper No. 24, (rev.) FAO, Rome,

Penman-Monteith method. 1977. Crop Evapotranspiration - Guidelines for computing crop water requirements, Paper No. 56, (http://www.fao.org/docrep/X0490E/X0490E00.htm)

Wilhite, D.A. and M.H. Glantz. 1985. Understanding the Drought Phenomenon: The Role of Definitions. Water International 10:111-120.

National Commission on Agriculture. 1976. Rainfall and Cropping Patterns; Vol. XIV, Government of India, Ministry of Agriculture, New Delhi.

The Fourth Assessment Report-AR4. 2007. IPCC - Intergovernmental Panel on Climate Change, Working Groups Report.(www.ipcc.ch/ -)

Modeling nitrogen dynamics in the soil-plant system

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Nitrogen modeling in CERES

The nitrogen dynamics routines of the CERES models were designed to simulate each of the major N loss processes and the contributions to the N balance made by mineralization. The routines also describe the uptake of N by the crop and the effects of N deficiency on crop growth processes. The transformations simulated are mineralization and/or immobilization, nitrification, denitrification, and urea hydrolysis. Nitrate movement associated with water movement in both an upward and downward direction is also simulated. Since the rates of transformation of nitrogen are very much influenced by soil water status, the simulation of nitrogen dynamics requires that water balance also be simulated. Soil temperature greatly influences many of the transformation rates. Therefore, a procedure to calculate soil temperature at various depths, based on the soil temperature is also invoked in the nitrogen component of the model.

The model does not simulate losses by ammonia volatilization or ammonium exchange equilibria and fixation. Under conditions of good fertilizer practice where fertilizer is either incorporated or placed beneath the soil surface, volatile ammonia losses should be small.

Initialization

Inputs describing the amount of organic matter and the amount of mineral nitrogen present in the soil are required to initialize the model. The model requires the organic carbon concentration in each layer (OC(L)) as an input and using an assumed soil C:N ratio of 10:1 calculates the amount of organic N associated with this organic matter (HUM(L)). These initializations are performed in subroutine SOILNI. To determine the contribution of recent crop residues to the supply of nitrogen in the soil, the model also requires an estimate of the amount of crop residue (STRAW) which is present. Based on this estimate and the depth of incorporation (SDEP) of the crop residue, the fresh organic matter content of each layer (FOM(L)) is estimated. An estimate of the amount of root residue remaining from the previous crop is also required for the calculation of FOM(L). Initial partitioning of the fresh organic matter into the component pools of carbohydrate (FPOOL(L,1)), cellulose (FPOOL(L,2)) and lignin (FPOOL(L,3)) is also performed in subroutine SOILNI.

NITRATE FLUX

Leaching of nitrates is probably the most common and best understood N loss process. Nitrates leaching from soil often become a source of contamination of groundwater and has recently generated interest in leaching from an environmental standpoint. There have been many approaches to modelling leaching based on numerical techniques which require solution in a manner inappropriate for use in a management level model such as CERES. In the CERES model, leaching is simulated using a simple approach based on the cascading system for drainage described in the previous chapter. Nitrate N may move between layers of the soil profile in the CERES models, but the movement of ammonium is not considered. Nitrate flux calculations are performed in subroutine NFLUX. Nitrate movement in the soil profile is highly dependent upon water movement. Therefore, the volume of water present in each layer (SW(L) * DLAYR(L)) and the water draining from each layer ((FLUX(L)) in the profile is used to calculate the nitrate lost from each layer (NOUT) as follows:

NOUT = SNO3(L) * FLUX(L)/(SW(L) * DLAYR(L) + FLUX(L))

A fraction of the mass of nitrate (SNO3(L)) present in each layer thus moves with each drainage event. A simple cascading approach is used where the nitrate lost from one layer is added to the layer below. When the concentration of nitrate in a layer falls below a critical level, no further leaching from that layer is deemed to occur. The method used may be termed a "reservoir mixing model", but water movement is controlled by the SWCON variable in the drainage routine. The implicit assumption is that all the nitrate present in a layer is uniformly and instantaneously in solution in all of the water in the layer. Thus no attempt is made to separate nitrate in solution between the retained water and the mobile water. Differences in the relative volumes of retained water and mobile water between clays and sands occur as a function of the relative magnitudes of LL(L), DUL(L), and SAT(L). The rate of nitrate flux is also sensitive to changes in SWCON since this variable determines the rate of drainage. Nitrate is more readily displaced from sands since the volume of water which can move ((SAT(L) - DUL(L)) * DLAYR(L)) is large in comparison to the retained water (DUL(L) * DLAYR(L)). Most of the difference in the simulated leaching rate between soils of different texture is explained by this difference in proportion of water which is mobile. Some difference is also attributable to the rate at which the soil profile can drain (SWCON). The upward flow of water in the top four soil layers will also cause some redistribution of nitrate. A second loop, commencing in the deepest layer of evaporative water loss (MU), is used to calculate this redistribution. Nitrate moving from a layer (NUP) is calculated as a function of upward movement (FLOW(L)) in a manner identical to leaching:

NUP = SNO3(L) * FLOW(L)/(SW(L) * DLAYR(L) + FLOW(L)) * 0.5

No upward loss from the top layer occurs by this process. Since there will occasionally be instances when this slowly moving water can move in a downward direction (negative values of FLOW(L)) a third loop is set up with calculations commencing in the top layer and running to lower layers. This is achieved by first reinitializing the array FLUX to 0 and reversing the sign (to make it positive) at the FLOW array and copying it to FLUX. When this has been done the normal leaching calculations used in the first loop can be used again. These instances would occur when a small rainfall wets the top layer of a very dry soil profile. There may have been insufficient water for drainage to occur but a moisture potential between the top layer and the second layer initiates this flow. The resultant movement of nitrate will be very small.

SOIL NITROGEN TRANSFORMATIONS

The CERES model simulates the decay of organic matter and the subsequent mineralization and/or immobilization of N, the nitrification of ammonium and denitrification in subroutine NTRANS. Fertilizer addition and transformations (assumed to be instantaneous) are also performed in this subroutine.

Fertilizer Additions

Fertilizer N is partitioned in the model between nitrate and ammonium pools according to the nature of the fertilizer used. Fertilizer products are specified by a numeric code IFTYPE. In addition to the numeric code for fertilizer type, inputs required to describe the fertilizer are: the date of application (FDAY), the amount of N applied (AFERT) and the depth of placement (DFERT). For any placement depth the assumption is made that the fertilizer is uniformly incorporated into the layer. Layer thicknesses are supplied as input and are usually based on natural horizonation in the profile. These must correspond with those used to describe the soil water inputs. Surface fertilizer applications are treated as being uniformly incorporated into the top layer. Up to 10 split applications can be accommodated by the model.

Mineralization and Immobilization

Mineralization refers to the net release of mineral nitrogen with the decay of organic matter and immobilization refers to the transformation of mineral nitrogen to the organic state. Both processes are microbial in origin. Immobilization occurs when soil microorganisms assimilate inorganic N compounds and utilize them in the synthesis of the organic constituents of their cells. A balance exists between the two processes. When crop residues with a high C:N ratio are added to soil, the balance can shift resulting in net immobilization for a period of time. After some of the soil carbon has been consumed by respiration, net mineralization may resume. N mineralized from the soil organic pool can often constitute a large part of the nitrogen available to the crop.

The perceived application for the CERES models in studies examining crop growth and fertilizer management requires that a mineralization model be simple, require few inputs, and work on a diversity of soils. Simulation studies examining the affects of crop residues also requires that the model be capable of simulating the fate of residues of different compositions. Other studies examining the potential role of nitrification inhibitors require a model wherein the processes of ammonification and nitrification are separated. The approach used in the CERES-WHEAT model is based on a modified version of the mineralization and immobilization component of the PAPRAN model (Seligman and van Keulen, 1981). This model is an attempt at maintaining some of the functionality of the microbiological level models but doing so at a very simplified level. The model's modifications have been to simulate nitrification separately and to partition the simulated fresh organic matter pools differently. Modifications were also made to temperature and water indices to fit the CERES water balance and soil temperature routines. Unless otherwise indicated, the coefficients used for the mineralization/immobilization functions described below were drawn from the PAPRAN model.

The mineralization and immobilization routine simulates the decay of two types of organic matter: Fresh organic matter (FOM) which comprises crop residues or green manure and a stable organic or humic pool (HUM). Three pools comprise the FOM pool in each layer (L), vis:

FPOOL(L,1) = carbohydrate

FPOOL(L,2) = cellulose

FPOOL(L,3) = lignin.

In PAPRAN, FOM is simulated as one pool and the decay rate constant is selected according to the proportion of the initial amount of FOM remaining. The CERES model separates FOM into three pools giving a better estimate of soluble carbon which is used in the denitrification routine. These three pools are initialized as a fraction of the FOM(L) pool in subroutine SOILNI.

Initially, the FOM(L) contains 20% carbohydrate, 70% cellulose and 10% lignin. The model requires as input data, the amount of straw added, its C:N ratio and its depth of incorporation (if any) and an estimate of the amount of root residue from the previous crop. Based upon these data, initial values of FOM and the N contained within it (FON) for each layer are calculated in subroutine SOILNI. The soil organic carbon in each layer (OC(L)) is also required by the mineralization routine. This is used to calculate HUM(L), and together with a simplifying assumption of a bulk soil C:N ratio of 10, is used to estimate the N associated with this fraction (NHUM(L)). Each of the three FOM pools (FPOOL (L,1 to 3)) has a different decay rate (RDECR

(1 to 3)). Under nonlimiting conditions the decay constants as reported by Seligman and van Keulen (1981) are 0.80, 0.05, and 0.0095 for carbohydrate, cellulose, and lignin, respectively. A decay constant at 0.20 for the carbohydrate fraction has since been found to be more appropriate. The decay constant for carbohydrate implies that under nonlimiting conditions 20% of the pool will decay in one day. Nonlimiting conditions very seldom occur in soils since one or all of soil temperature, soil moisture, or residue composition will limit the decay process. To quantify these limits three zero to unity dimensionless factors are calculated. A water factor (MF) is first determined from the volumetric soil water content (SW(L)) relative to the lower limit (LL), and drained upper limit (DUL). In accordance with the soil water balance model, provision is made for the water content of the uppermost layer to be lower than the lower limit. The variable SWEF determines the lowest possible value the uppermost soil layer water content have. When the soil is drier than DUL, MF is calculated as:

AD = LL(L)

IF (L.EQ.1) AD = LL(1) *SWEF

MF = (SW(L)-AD)/(DUL(L)-AD)

where:

AD = lowest moisture content for a layer (volume fraction)

When the soil is wetter than DUL, MF is calculated as:

MF = 1.0-(SW(L)-DUL(L))/(SAT(L)-DUL(L))*0.5

The functions follow the observations reported by Myers et al. (1982)

and Linn and Doran (1984) on moisture effects on ammonification. Under very wet conditions (100% of water filled porosity) ammonification proceeds at approximately half of the rate of ammonification at field capacity (Linn and Doran, 1984). The comparative effects of soil moisture on the simulated rates of ammonification, nitrification, and denitrification can be seen in Fig. 5.1. A temperature factor (TF) is calculated directly from soil temperature (ST(L)):

TF = (ST(L)-5.0)/30.0

This approximates the soil temperature effects on ammonification reported by others (Stanford et al., 1973; Myers, 1975). If the soil temperature (ST(L)) is less than 5^{o} C then TF is set to zero and no decay occurs. The C:N ratio (CNR) imposes the third limit on decay rate. In this case C:N ratio is calculated as the C contained in FOM divided by the N "available" for the decay process. This N available for decay is the sum of the N contained in the FOM, which is FON, and the extractable mineral N present in the layer (TOTN). Thus,

CNR = (0.4*FOM(l))/(FON(L)+TOTN)

From CNR an index (CNRF) is calculated which has a critical C:N ratio of 25.

CNRF = EXP(-0.693*(CNR-25)/25.0)

Thus, in low N containing residues (e.g., freshly incorporated wheat straw) with a high C:N ratio, the N available for the decay process will greatly limit the decay rate (Fig. 3.5). For each of the FOM pools a decay rate (GRCOM) appropriate for that pool (JP) can be calculated. G1 = TF*MF*CNRF*RDECR(JP)

GRCOM = G1*FPOOL1(L,JP)

The gross mineralization of N associated with this decay (GRNOM) is then calculated according to the proportion of the pool which is decaying.

GRNOM = G1 * FPOOL(L,JP)/FOM(L) * FON(L)

GRCOM and GRNOM are summed for each of three pools in each layer. The procedure used for calculating the N released from the humus (RHMIN) also utilizes TF and MF. In this case CNRF is not used and the potential decay rate constant (DMINR) is very small (8.3E-05). A further index (DMOD) was added to the RHMIN calculations to adjust the mineralization rate for certain atypical soils. On soils with chemically protected organic matter, a less than unity value of DMOD is required so that mineralization is not overestimated. On freshly cultivated virgin soils, a slightly greater than unity value has been found necessary to account for the sudden increase in mineralization activity. In all other circumstances a value of 1.0 is used for DMOD. Satisfactory alternatives for estimating DMOD are currently being sought. The procedure for calculating RHMIN, then is the product of the various indices and the N contained within the humus (NHUM(L)).

RHMIN=NHUM(L)*DMINR*TF*MF*DMOD

After calculating the gross mineralization rate, HUM(L) and NHUM(L) are updated.

HUM(L)=HUM(L)-RHMIN*10.0+0.2*GRNOM/0.04

NHUM(L)=NHUM(L)-RHMIN+0.2*GRNOM

These calculations also allow for the transfer of 20% of the gross amount of N released by mineralization of FON(L) (0.2*GRNOM) to be incorporated into NHUM(L). This accounts for N incorporated into microbial biomass and has a concentration of 4% (0.04) determined as 0.1 g N/g C (soil C:N ratio of 10) multiplied by 0.4 g C/g OM (40% of OM is C). As organic matter decomposes some N is required by the decay process and may be incorporated into microbial biomass. The N which is immobilized in this way (RNAC) is calculated as the minimum of the soil extractable mineral N (TOTN) and the demand for N by the decaying FOM(L).

RNAC=AMIN1(TOTN,GRCOM*(0.02-FON(L)/FOM(L))

where 0.02 is the N requirement for microbial decay of a unit of FOM(I). The value of 0.02 is the product of the fraction of C in the FOM(L) (40%), the biological efficiency of C turnover by the microbes (40%) and the N:C ratio of the microbes (0.125). FOM(L) and FON(L) are then updated.

FOM(L)=FOM(L)-GRCOM

FON(L)=FON(L)+RNAC-GRNOM

The balance between RNAC and GRNOM determines whether net mineralization or immobilization occurs. The net N released from all organic sources (NNOM) is:

NNOM=0.8*GRNOM+RHMIN-RNAC.

Note that only 80% of GRNOM enters this pool since the remaining 20% was incorporated into NHUM(L). NNOM can then be used to update the ammonium pool (SNH4(L)).

SNH4(L)=SNH4(L)+NNOM

If net immobilization occurs (NNOM negative) ammonium is first immobilized and if there is not a sufficient amount to retain this pool with a concentration of 0.5 ppm, withdrawals are made from the nitrate pool.

Nitrification

Nitrification refers to the process of oxidation of ammonium to nitrate. It is a biological process and occurs under aerobic conditions. The main factors which limit nitrification are: Substrate NH_4^+, oxygen, soil pH, and temperature. The approach used in the CERES models has been to calculate a potential nitrification rate and a series of zero to unity environmental indices to reduce this rate. This potential nitrification rate is a Michaelis-Menten kinetic function dependent only on ammonium concentration and is thus independent of soil type. A further index, termed a "nitrification capacity" index, is introduced which was designed to introduce a lag effect on nitrification if conditions in the immediate past (last 2 days) have been unfavorable for nitrification. Actual nitrification capacity is calculated by reducing the potential rate by the most limiting of the environmental indices and the capacity index. The capacity index is an arbitrary term introduced to accommodate an apparent lag in nitrification observed in some data sets. The functions reported below were found to be appropriate across the range of data sets tested. The nitrification routine in subroutine NTRANS calculates the nitrification of ammonium in each layer. First, an ammonium concentration factor (SANC) is calculated.

SANC=1.0-EXP(-0.01363*SNH4(L))

This is a zero to unity index which has approximately zero values when there is less than 1 ppm of ammonium present and has a value of 0.75 at 100 ppm. The temperature factor calculated above for mineralization (TF) and a soil water factor for nitrification (WFD) (Fig. 3.4) are used together with SANC to determine an environmental limit on nitrification capacity (ELNC).

ELNC=AMIN1(TF,WFD,SANC)

To accommodate lags which occur in nitrifier populations ELNC and the previous day's relative microbial nitrification potential in the layer (CNI(L)) are used to calculate the interim variable RP2 which represents the relative nitrification potential for the day.

RP2=CNI(L)*EXP(2.302*ELNC)

RP2 is constrained between 0.01 and 1.0. Today's value of the nitrification potential (CNI(L)) is then set equal to RP2. Since EXP(2.302*ELNC) varies from 1.0 to 10.0 when ELNC varies from 0.0 to 1.0, relative nitrification potential can increase rapidly, up to tenfold per day. An interim variable A is then determined from these indices and an index for pH effect on nitrification. This pH index is calculated in subroutine SOILNI and represents the conclusions drawn by Schmidt (1982) on the pH effect in nitrification.

A=AMIN1(RP2,WFD,TF,PHN(L))

This interim variable A is used together with the ammonium concentration (NH(L)) in a Michaelis-Menten function described by McLaren (1970) to estimate the rate of nitrification. The function has been modified to estimate the proportion of the pool of ammonium (SNH4(L)) which is nitrified on a day.

B=(A*40.0*NH4(L)/NH4(L)+90.0))*SNH4(L)

A maximum of 80% at the ammonium pool is allowed to nitrify in one day. A check is made to ensure some ammonium is retained in the layer and thus the daily rate of nitrification (RNTRF) is

RNTRF=AMIN1(B,SNH4(L))

Following this calculation, soil nitrate and ammonium pools can be updated.

SNH4(L)=SNH4(L)-RNTRF

SNO3(L)=SNO3(L)+RNTRF

Finally, the soil temperature, moisture and NH4 after nitrification are used to update (CNI(L)), which is used in the subsequent day's calculations.

SARNC=1.0-EXP(-0.1363*SNH4(L))

XW=AMAX1(WF,WFY(L))

XT=AMAX1(TF,TFY(L))

CNI(L)=CNI(L)*AMIN1(XW,XT,SARNC)

SARNC is a zero to unity factor for ammonium availability. WFD and WFY(L) are today's and yesterday's soil water factors, respectively, and TF and TFY(L) are today's and yesterday's soil temperature factors, respectively. The least limiting of the current day's and the previous day's water and temperature factors are used in the calculation of the new value of CNI(L). This prevents a single day of low soil temperature or water from severely reducing CNI(L). It is important to note that the relative nitrification potential CNI(L) is calculated twice each day. Since (EXP(2.302*ELNC)) varies from 1.0 to 10.0, CNI(L) increases prior to the calculation of the nitrification rate. After the nitrification calculations when the level of ammonium has declined, CNI(L) is reduced. The relative magnitudes of (EXP(2.302*ELNC) and AMIN1(XW,XT,SARNC)) determine whether relative nitrification potential increases or decreases over the short term.

Denitrification

Denitrification is the dissimilatory reduction of nitrate (or nitrite) to gaseous products including N0, N20, and N2 (Knowles, 1981).

Denitrification is a microbial process which occurs under anaerobic conditions and is influenced by organic carbon content, soil aeration, temperature and soil pH. The approach adopted in the CERES models has been to adapt the functions described by Rolston et al. (1980) to fit within the framework of the model and to match inputs derived from the water balance and mineralization components of CERES. The basic function used by these authors was also used by Davidson et al. (1978a) and was the subject of field testing under a variety of conditions in California. Predicted rates of denitrification compared favorably with direct measures of gaseous losses in the field experiments. Denitrification calculations are only performed when the soil water content (SW) exceeds the drained upper limit (DUL). A zero to unity index (FW) (see Fig. 5.1) for soil water in the range from DUL to saturation (SAT) is calculated.

FW = 1.0 - (SAT(L)-SW(L))/(SAT(L)-DUL(L))

Linn and Doran (1983) used percentage of water filled porosity as an index of soil water availability effects on soil N transformations. In their studies, denitrification commenced with a water-filled porosity of 60% and increased linearly up to 100% water filled porosity. This approximates the linear increase in FW as SW increases from DUL to SAT. A factor for soil temperature (FT) is also calculated.

FT=0.1*EXP(0.046*ST(L))

Rolston et al. (1980) using the data of Burford and Bremner (1976) and Reddy et al. (1971) to estimate the water-extractable C in soil organic matter (CW) as:

CW=24.5 + 0.0031*SOILC

In the CERES model, SOILC is calculated as 58% of the stable humic fraction. To this is added the carbon contained in the carbohydrate fraction organic matter pool (40% of FPOOL(L,1)). Appropriate unit conversions are made using FAC(L) and the total water extractable carbon (CW) estimated.

CW = FAC(L)*(SOILC*0.0031+0.4*FPOOL(L,1))+24.5

Denitrification rate (DNRATE) is then calculated from the nitrate concentration and converted to a kg N/ha basis for the mass balance calculations.

DNRATE = 6.0*1.0E-05*CW*NO3(L)*FW*FT*DLAYR(L)

Following the calculation of DNRATE the nitrate pool in the layer is updated with appropriate checks to ensure that a minimum concentration of nitrate is retained in the layer.

SNO3(L)=SNO3(L)-DNRATE

SOIL TEMPERATURE

The soil temperature in each layer is used in the functions describing most of the major soil N transformations. The soil temperature model used in CERES is based on that used in the EPIC model (Williams et

al., 1984). This method is based upon some simple empiricisms and requires only two additional inputs to those soil parameters required by the water balance and N transformation routines. These inputs are: TAV, the annual average ambient temperature and AMP the annual amplitude in mean monthly temperature. The method used to calculate the soil temperature at various depths in the profile requires the determination of a damping depth (the depth at which no diurnal variation in temperature is experienced). At depths more shallow than this, diurnal change in temperature occurs with the greatest fluctuation happening near the surface. The location of this damping depth (DD) is dependent upon parameters which influence the flux of heat in the soil, notably the bulk density and the moisture content. DD is updated daily to allow for changes in soil moisture content. Soil surface temperatures are modelled as a function of the ambient temperature, the solar radiation, and the albedo. The 5-day moving average surface temperature is used to compute the temperatures in each layer as follows:

TMA(1) = (1.0-ALBEDO) * (TEMPM + (TEMPMX - TEMPM) *

SQRT(SOLRAD * 0.03)) + ALBEDO * TMA(1)

where:

TMA(1) = Daily surface temperature

ALBEDO = The albedo of the soil surface and is an input variable for bare soils. As the crop canopy develops ALBEDO becomes a function of the leaf area. These calculations of albedo are performed in the water balance routine as they are a fundamental component of the evaporation model.

SOLRAD = Solar radiation in MJ/square metre.

TEMPMX,TEMPM = Daily maximum and mean temperature C, respectively.

The long-term average daily ambient temperature (TA) for the current day of the year can be estimated from TAV and AMP.

TA = TAV + AMP * COS(ALX)/2.0

ALX is a variable (in units of radians) to relate the current day of the year (XI) to the time of the hottest day of the year (HDAY). In the northern hemisphere this is assumed to be day 200 and in the southern hemisphere day 20.

ALX = (XI - HDAY) * 0.0174

The coefficient 0.0174 is 1/365 days multiplied by 2 radians. Deviations in the actual dates of the hottest day of the year in lower latitudes are of little importance since the volumes of AMP will be small and hence TA will approximate TAV. The departure (DT) of the moving average temperature from TA is used in the calculation of the soil temperature in each layer (ST(L)) as follows:

ST(L) = TAV + (AMP/2.0 * COS(ALX + ZD) + DT * EXP(ZD)

Where ZD = depth of layer L/current day's damping depth.

PLANT CRITICAL N CONCENTRATIONS AND N DEFICIT FACTORS

Plant growth is greatly affected by the supply of N. Typically the supply of N to plants at the beginning of the season is often relatively high and becomes lower as the plant reaches maturity. The concentration of N in plant tissues also changes as the plant ages. During early growth, N concentrations are usually high due to synthesis of large amounts of organic N compounds required by the biochemical processes constituting photosynthesis and growth. As the plant ages, less of this new material is required and export from old tissues to new tissues occurs lowering the whole plant N concentration. At any point in time there exists a critical N concentration in the plant tissue below which growth will be reduced. These concentrations are determined as a function of crop ontogenetic age and are used within the model as part of the procedure to simulate the effects of N deficiency. The model's critical concentration functions are based upon the often used Zadoks' growth scale (Zadoks et al. 1974). Zadoks' growth scale is a decimal index of crop development generalized for all cereals. The intervals between growth scale index values are based on crop morphological observations and are not related to a thermal time concept. To incorporate the Zadoks' scale, a scheme to provide a conversion between the integer growth stages recognized by the model (ISTAGE) and a functional form of the Zadoks' scale had to be devised. XSTAGE is a fractional growth stage which is used to determine an approximate value for the corresponding Zadoks' stage (ZSTAGE). The conversions were performed using several functions which are tabulated below (Table 1). The functions are located in subroutine NFACTO.

Table 1. Functions Used for Converting From Fractional Growth Stage (XSTAGE) to Zadoks'Growth Stage (ZSTAGE)

Morphological Stage XSTAGE Range Function

Emergence to terminal spikelet 0.0-2.0 ZSTAGE = XSTAGE

Terminal spikelet to booting 2.0-3.0 ZSTAGE = 2.0 + 2.0*(XSTAGE-2.0)

Booting to ear emergence 3.0-4.0 ZSTAGE = 4.0 + 1.7*(XSTAGE-3.0)

Ear emergence to anthesis 4.0-4.4 ZSTAGE = 5.7 + 0.8*(XSTAGE-4.0)

Anthesis to maturity 4.4-6.0 ZSTAGE = 6.02 + 1.86*(XSTAGE-4.4)

To develop appropriate relationships for critical N concentrations in wheat, published data from field experiments that met the following criteria were assembled:

1. Experiments had a series of N rates with sufficient range to define optimal or near-optimal growth patterns.

2. Experiments were considered to have been conducted under conditions where the potential effects of other interacting factors (e.g., heat stress, moisture stress, frost, supply of other nutrients, etc.) were minimized.

3. Plant tops N concentration was reported at several times during the growing season.

4. The growth stage or phenological age of the crop was reported for the times of plant sampling.

In some cases, critical concentrations were defined by the authors and where appropriate were adopted. In two studies only one N rate was used but was described as being an optimal rate by the authors. Data were drawn from the following sources (Table 2) representing a diversity of wheat genotypes and wheat-growing environments.

Table 2. Data Sources Used for Determination of Critical N Concentration Relationships

Author Spring or Winter Wheat Location

Engel and Zubriski (1982) Spring North Dakota

Campbell et al. (1977a) Spring Canada

Wagger et al. (1981) Winter Kansas

Leitch and Vaidanathan (1983) Winter U.K.

Wagger (1983) Winter Kansas

Waldren and Flowerday (1979) Winter Nebraska (?)

Page et al. (1977) Winter U.K.

Alessi et al. (1979) Spring North Dakota

Mugwira and Bishnoi (1980) Winter Alabama

Boatwright and Haas (1961) Spring North Dakota

Gasser and Thorburn (1972) Spring U.K.

Bhargava and Motiramani (1967) Spring Australia

Walia et al. (1980) Spring India

McNeal et al. (1968) Spring Montana

Spratt and Gasser (1970) Spring U.K.

From these data, relationships defining critical N concentration as a function of Zadoks' growth stage were determined. The critical N concentration was defined as the N concentration in the plant tissues at optimal or near optimal growth (as defined by biomass, yield or leaf area from the response data). The relationship thus determined is defined as the concentration above which no further increases in crop growth occur and below which some effect on a growth process will occur. Winter wheats and spring wheats were found to have different relationships (Fig. 3.7). The differences between winter and sprin wheats may be an artifact created by the different growing conditions of the experiments cited above. It has been difficult to characterize critical concentrations particularly for the period of rapid growth in the spring when phenological age, N uptake and biomass are all increasing rapidly. These relationships for the tops critical N percentage TCNP) appear in subroutine NFACTO as a function of Zadoks' growth stage (ZSTAGE).

For winter wheats:

TCNP = -5.0112 - 6.3507 * ZSTAGE + 14.9578 * SQRT(ZSTAGE) +

0.2238 * (ZSTAGE * ZSTAGE)

For spring wheats:

TCNP = 7.4532 - 1.7908 * ZSTAGE + 0.6093 * SQRT(ZSTAGE) +

0.0934 * ZSTAGE * ZSTAGE

Root critical N concentration (RCNP) relationships were derived from the greenhouse data of Peterson et al. (1983) and Day et al. (1985).

$$RCNP = 2.10 - 0.14 * SQRT(ZSTAGE)$$

The minimum concentration of N in plant tissues as a function of plant age is seldom reported. To formulate an appropriate relationship for use in the model, some of the minimum concentrations reported in the above studies were used as well as those reported from an extensive survey of N concentration in wheat crops spanning several years and locations in South Australia by Schultz and French (1976). In the model the tops minimum concentration (TMNC) is calculated as a function of model growth stage (XSTAGE):

$$TMNC = 2.97 - 0.455 * XSTAGE$$

Root critical minimum N concentration (RMNC) is used during the grain filling calculations (in subroutine GROSUB) and is assumed to be a constant 75% of the critical concentration.

$$RMNC = 0.75 * RCNP$$

The coupling of these functions to the phenology routines thus enables critical concentrations to be determined for any variety growing in any environment. The critical and minimum concentrations are used to define a nitrogen factor (NFAC) which ranges from zero to slightly above unity. NFAC is the primary mechanism used within the model to determine the effect of N on plant growth. It is an index of deficiency relating the actual concentration (TANC) to these critical concentrations. NFAC has a value of zero when TANC is at its minimum value of TMNC and increases to 1.0 as concentration increases toward the critical concentration. NFAC is calculated as:

$$NFAC = 1.0 - (TCNP - TANC)/(TCNP - TMNC)$$

Since all plant growth processes are not equally affected by N stress, a series of indices based on NFAC are used. For photosynthetic rate (NDEF1) the index is calculated as:

$$NDEF1 = 0.10 + 2.0 * NFAC \quad (NDEF < 1.0)$$

For leaf expansion growth (NDEF2) a more sensitive factor is used:

$$NDEF2 = NFAC$$

For tillering (NDEF3) the index is calculated as:

$$NDEF3 = NFAC * NFAC$$

For the calculation of these indices NFAC has a maximum value of 1.0. This implies that when TANC exceeds TCNP no extra growth occurs. A fourth factor used to modify the rate of grain N accumulation (NDEF4) is also calculated from NFAC, and can range from 0.0 to 1.5.

NDEF4 = NFAC * NFAC

These relations are depicted in Fig. 3.8. In the growth subroutine, GROSUB, the law of the minimum is used extensively to modify rates of plant growth. For each of the major functions (e.g., photosynthetic rate, leaf expansion rate, tiller number determination) the minimum of several zero to unit stress indices is used to modify a potential rate for the process.

N UPTAKE

The approach used in the CERES models has been to separately calculate the components of demand and supply and then use the lesser of these two to determine the actual rate of uptake. Demand can be considered as having two components. First there is a "deficiency demand." This is the amount of N required to restore the actual N concentration in the plant (TANC for tops) to the critical concentration (TCNP for tops). Critical concentrations for shoots and roots are defined in section 3.7. This deficiency demand can be quantified as the product of the existing biomass and the concentration difference as below:

TNDEM = TOPWT * (TCNP - TANC)

Similarly for roots the discrepancy in concentration (difference between RCNP and RANC) is multiplied by the root biomass (RTWT) to calculate the root N demand.

RNDEM = RTWT * (RCNP-RANC)

If luxury consumption of N has occurred such that TANC is greater than TCNP then these demand components have negative values. If total N demand is negative then no uptake is performed on that day. The second component of N demand is the demand for N by the new growth. Here the assumption is made that the plant would attempt to maintain a critical N concentration in the newly formed tissues. To calculate the new growth demand, a potential amount of new growth is first estimated in the GROSUB subroutine. New growth is estimated from potential photosynthesis (PCARB) and is partitioned into a potential root growth (PGRORT) and a potential tops growth (PDWI). Partitioning between potential shoot and root growth occurs as a function of phenological age:

PGRORT = PCARB * (60 - XSTAGE * 8)/100

PDWI = PCARB - PGRORT

These potential growth increments provide a mechanism for the tops actual N concentration (TANC) to exceed TCNP. This occurs when some stress prevails and the actual growth increment is less than the potential. New growth demand for tops (DNG) is calculated as

DNG = PDWI * TCNP

and the new growth demand for roots is calculated as

PGRORT * RCNP.

During the early stages of plant growth the new growth component of N

demand will be a large proportion of the total demand. As the crop biomass increases the deficiency demand becomes the larger component. During grain filling, the N required by the grain is removed from the vegetative and root pools to form a grain N pool. The resultant lowering of concentration in these pools may lead to increased demand. The total plant N demand (NDEM) is the sum of all of these demand components. Calculations of soil supply of N are on a per hectare basis which necessitates recalculation of the per plant demand into a per hectare demand (ANDEM).

ANDEM = NDEM * PLANTS * 10.0

To calculate the potential supply of N to the crop, zero to unity availability factors for each of nitrate (FNO3) and ammonium (FNH4) are calculated from the soil concentrations of the respective ions:

FNO3 = 1.0 - EXP(-0.0275 * NO3(L))

FNH4 = 1.0 - EXP(-0.025 * NH4(L))

The coefficients used in these two functions, obtained by trial and error, were found to be appropriate over a range of data sets. The greater mobility of nitrate ions in soil is reflected by the larger coefficient (0.0275) in these equations. A zero to unity soil water factor (SMDFR) which reduces potential uptake is calculated as a function of the relative availability of soil water:

SMDFR = (SW(L) - LL(L)/ESW(L)

To account for increased anaerobiosis and declining root function at moisture contents above the drained upper limit, SMDFR is reduced as

saturation is approached.

IF(SW(L) . GT . DUL(L))SMDFR = 1.0 - (SW(L) - DUL(L))/(SAT(L) - DUL(L))

The maximum potential N uptake from a layer may be calculated as a function of the maximum uptake per unit length of root and the total amount of root present in the layer. The first of these is a temporary variable (RFAC) which integrates the effects of root length density (RLV(L)), the soil water factor described above, and the depth of the layer:

RFAC = RLV(L) * SMDFR * SMDRF * DLAYR(L) * 100.0

The second of these equations incorporates the ion concentration effect (FNO3) and the maximum uptake per unit length of root (0.009 kg N/ha cm root) to yield a potential uptake of nitrate from the layer (RNO3U(L)).

RNO3U(L) = RFAC * FNO3 * 0.009

(RNO3U(L)) is thus the potential uptake of nitrate from layer L in kg N/ha constrained by the availability of water, the root length density and the concentration of nitrate. Initial estimates for the maximum uptake per unit length of root coefficient were obtained from the maize root data of Warncke and Barber (1974). This estimate was the subject of continuing modification during early model development. The value reported here appears to be appropriate across a broad range of data sets. The effect of each of these parameters on determining potential uptake can be seen in Fig. 3.9. A similar function is employed to calculate the potential uptake of ammonium (RNH4U(L)).

RNH4U(L) = RFAC * FNH4 * 0.009

Potential N uptake from the whole profile (TRNU) is the sum of RNO3U(L) and RNH4U(L) from all soil layers where roots occur. Thus TRNU represents an integrated value which is sensitive to (a) rooting density, (b) the concentration of the two ionic species, and (c) their ease of extraction as a function of the soil water status of the different layers. This method of determining potential uptake enables the common condition, where N is concentrated in the upper layers of the profile, where most of the roots are present and where a nutritional drought due to shortage of water in these upper layers may occur, to be simulated. This can occur when the crops demand for water is satisfied from soil water located deeper in the profile but where there may be little N present. If the potential N supply from the whole profile (TRNU) is greater than the crop N demand (ANDEM) an N uptake factor (NUF) is calculated and used to reduce the N uptake from each layer to the level of demand.

NUF = ANDEM/TRNU

This could occur when plants are young and have a high N supply. If the demand is greater than the supply then NUF has a value of 1.0. When NUF is less than 1.0, uptake from each layer is reduced as follows:

UNO3 = RNO3U(L) * NUF

UNH4 = RNH4U(L) * NUF

Following these calculations the soil mineral N pools can be updated for the actual uptake which has occurred.

SNO3(L) = SNO3(L) - UNO3

SNH4(L) = SNH4(L) - UNH4

Under conditions of luxury N uptake (TANC > TCNP) exudation of organic N compounds can occur. Rovira (1969) found changes in the shoot environment which cause more rapid growth can increase exudation. Bowen (1969) reported that N deficiency can cause exudation to decrease. In the CERES-N model this exuded N is added to the fresh organic N pool (FON(L)) and can be mineralized and subsequently made available to the plant again. The amount of N which can be lost from the plant in this manner is calculated as 5% of the N contained in the roots/day. These losses are distributed to the FON(L)) pool according to the differing root length densities present in each layer as a proportion of the total root length.

IF(TANC . GT . TCNP)RNLOSS = RANC * RTWT * 0.05 * PLANTS * RLV(L)/TRLV

Following uptake, concentrations of N in each of the shoots and roots are updated. To do this TRNU is converted from kg N/ha to a g N/plant basis.

TRNU = TRNU/(PLANTS * 10.0)

The proportion of the total plant demand (NDEM) arising from shoots (TNDEM) and roots (RNDEM) and the total root N loss (TRNLOS) are used to calculate the changes in N content of the shoots (DTOPSN) and roots (DROOTN).

DTOPSN = TNDEM/NDEM * TRNU - PTF * TRNLOS/(PLANTS * 10.0)

DROOTN = RNDEM/NDEM * TRNU - (1.0 - PTF) * TRNLOS/(PLANTS * 10.0)

TRNLOS is distributed over shoots and roots according to the plant top fraction (PTF) and must also be converted from a unit area basis to a per plant basis. Shoot and root N pools (TOPSN and ROOTN, respectively) can then be updated and new concentrations calculated:

TOPSN = TOPSN + DTOPSN

ROOTN = ROOTN + DROOTN

TANC = TOPSN/TOPWT

RANC = ROOTN/(RTWT - 0.01 * RTWT)

When updating the root concentration allowance is made for the losses in root biomass occurring due to root exudation.

N REDISTRIBUTION DURING GRAIN GROWTH AND GRAIN N DETERMINATION

In many wheat-growing areas when the crop reaches the grain-filling stage soil supplies of N are very low. In these cases the nitrogen requirement of the developing grains is largely satisfied by remobilization of protein from vegetative organs. When nitrogen supply is increased, the proportion of grain N arising from remobilization declines, and the proportion from uptake increases (Vos 1981). Many studies (e.g., Benzian et al., 1983, Terman et al., 1969) have found negative correlations between grain yield and grain protein concentration. Temperature and soil moisture also affect the grain nitrogen content. When constructing the N grain-filling routines, procedures were adopted to closely mimick those predicting grain mass (or carbon) accumulation. In this procedure the rate of grain filling (RGFILL) (mg/day) is determined by temperature and thermal time (DTT).

To define similar functions for the rate of grain N accumulation (RGNFIL) (in micrograms per kernel per degree C day), the controlled environment studies of Sofield et al. (1977), Vos (1981) and Bhullar and Jenner (1985) were used. These studies examined various cultivars over a range of temperature conditions and other treatments. The relationship which best described these studies and mimicked the grain mass accumulation functions was:

RGNFIL = 4.8297 - 3.2488 * DTT + 0.2503 *(TEMPMX - TEMPMN) +

4.3067 * TEMPM

and when the mean temperature is less than 10

RGNFIL = 0.483 * TEMPM

Where TEMPMX, TEMPMN, TEMPM are the maximum, minimum, and mean temperatures (C), respectively. A whole plant grain N sink (NSINK) can then be determined in similar manner to GROGRN.

NSINK = RGNFIL * GPP * 1.E-6 (g N/plant)

Since N stress will affect the rate at which plant tissues can mobilize N and supply it to the grain, an N stress factor NDEF4 from subroutine NFACTO is also introduced.

NSINK = NSINK * NDEF4

If N is present in the plant vegetative tissues (TANC greater than TCNP) the size of the sink is increased. If there is no grain N demand (NSINK = 0) on a day then no grain N accumulation occurs. Two pools of N within the plant are available for translocation, a shoot pool (NPOOL1) and a root pool (NPOOL2). These pools are determined from the N concentration (VANC or RANC) relative to the critical concentration (VMNC or RMNC) and the biomass of the pool (RTWT or TOPWT).

NPOOL1 = TOPWT * (VANC-VMNC)

and

NPOOL2 = RTWT * (RANC-RMNC)

Not all of the N contained within these pools can be immediately mobilized. The fraction of these pools which is labile will depend on the N status of the plant. this fraction (XNF) is calculated by considering the N stress index NDEF2 used for vegetative growth and senescence.

XNF = 0.15 + 0.2 * NDEF2

The labile fraction will range between 15% and 35% of each of the pools depending on the plant N status. The labile poos can be calculated as:

For tops:

TNLAB = XNF * NPOOL1

and roots:

RNLAB = XNF * NPOOL2

The total N available for translocation (NPOOL) is the sum of these two labile pools. When NPOOL is not sufficient to supply the grain N demand (NSINK), NSINK is reduced to NPOOL. If NSINK is greater than that which can be supplied by the tops (TNLAB), then TNLAB is removed from TOPSN and the remaining NSINK which must come from the root pool (RNOUT) is calculated. If (NSINK.GT.TNLAB) Then

TOPSN = TOPSN - TNLAB

RNOUT = NSINK - TNALB

TNLAB = 0

ROOTN = ROOTN - RNOUT

When NSINK is less than TNLAB it can be totally satisfied from the shoot pool and the root pool need not be modified.

TOPSN = TOPSN ï NSINK

Following the removal of N from shoot and root pools the simulated tissue concentrations (VANC and RANC) are updated. The total amount of N contained in the grain can then be accumulated.

GRAINN = GRAINN + NSINK

The grain nitrogen concentration will vary daily but is only calculated at the end of the simulatin run (in subroutine PHENOL) as:

GNP = GRAINN/GRNWT

These procedures together with the remainder of the growth routine and the N deficiency indices can provide several pathways by which N stress during grain filling can affect grain yield and grain protein content. First, as N is removed from the vegetative tissues NFAC will become lower. This will in turn lower NDEF4 and lower the sink size for N thus providing for the capability of reduced grain N concentration. Lowering NFAC will also lower NDEF1 which will cause the rate of crop photosynthesis to fall thus lowering the assimilate available for grain filling. A declining NFAC will also speed the rate of senescence which will reduce the leaf area available for photosynthesis. Different temperature regimes during grain filling will also affect the final grain N concentration since the function for RGNFIL is more sensitive to temperature than RGFILL. Soil water stress during grain filling can also increase the grain N concentration since SWDF1 will reduce photosynthesis, lowering assimilate availability and thus not diluting grain N as much as would occur in an unstressed crop.

Agro-Hydrological Modelling

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Introduction

Dryland agriculture still remains the backbone of Indian agliculture, as large areas of cultivated land are rainfed, which contribute about 42 per cent to country's food basket. Characterization and understanding of the environment is imperative to dryland agricultural research. To formulate judicious soil and crop management practices for varied dryland conditions, the crop growth processes under stress conditions are to be properly understood. The information on moisture and nutrient uptake pattern under moisture stress condition is presently incomplete. The studies on these lines will unravel many of the unanswered questions that would lead to a better understanding of nutrient and moisture interactions. Moreover, information on moisture deficits in different periods is very helpful in crop planning. The efforts are on for some years to develop models that would predict the crop water use pattern. An attempt is made here to present a comprehensive review of the currently available agro-hydrological models and to illustrate the basics behind the development of such models.

Some of the currently available agrohydrological/soil water balance models are listed in Table 1. They differ in complexity, operation and purpose. The models also differ in the use of theoretical or empirical descriptions of the process in the model. These can be broadly classified as:

(a) Agroclimatic models - These are usually single layer models used for regional characterization of environments for water availability.

(b) Management models - In these models the soil profile is divided into two or three layers. Information generated on soil moisture availability is used for soil and crop management.

(c) Physical process models - The soil profile is divided into many layers for studying the flow processes more precisely.

Table 1. List of some agro-hydrological models

Name of the model	Reference
Versatile Soil Moisture Budget (VSMB)	Baler *et al.* (1979)
WATER	Burt *et al.* (1980)
Unnamed	Belmans *et al*.(1983)
Unnamed	Brisson *et al.(*1992*)*
Unnamed	Cordery and Graham *et al*.(1989)
SMEP	Edey (1980)
Unnamed	Greacem and Hignett.(1984)
SWATRE	Feddes *et al*(1976)
Unnamed	Jagtap and Jones (1989)
SWACRO	Feddes *et al(*1984*)*
Unnamed	Hansen (1975)
Unnamed	Holst and Madsen (1984)
Unnamed	Jones and Smajstrla (1980)
Unnamed	Lascano and van Bavel (1986)
Unnamed	Norman and Campbell (1983)
Unnamed	Place and Brown (1987)
Unnamed	Rama Prasad (1984)
PLANTGRO	Retta and Hanks (1980)
Unnamed	Robinson and Hubbard (1990)
SPAW	Saxton *et al(*1974*)*
Unnamed	Seliorio and Brown (1979)
Unnamed	Stockle and Campbell (1985)
SIMBAL	Stuff *et al(*1975*)*
EMWATBAL	Van Bavel and Lascano (1987)
Unnamed	Victor *et al(*1988*)*
Unnamed	Visser (1974)
Unnamed	Vossen (1990)
Unnamed	Wright *et al(*1994*)*

1.1 Model components

The basic components of all the soil water balance models are presented in Fig. 1. The components are not independent but they are interrelated. For instance, amount of runoff depends partially on the rainfall intensity, hydraulic properties of the soil, and surface water content.

Precipitation or irrigation is usually measured and the other components of water balance are estimated, in the same units.

1.2 Surface runoff and infiltration

Whenever rainfall occurs, some amount of water often runs off and becomes unavailable to the crop. Therefore, to estimate the recharge of soil profile it is important to estimate the amount of runoff that occurs with each rainstorm. Various approaches have been made to estimate this component in water balance models. Some models do not consider runoff and deep drainage separately. Any amount of water input into the soil after the soil profile is full to its maximum storage capacity (field capacity) is considered as water loss (runoff + deep drainage). However, in some models the runoff or infiltration is estimated to calculate profile recharge. Kanemasu *et al*. (1978) calculated effective precipitation (Pe) and runoff as follows:

$Pe = R^{0.75}$ when R> 25.4 mm;

Pe = R when RÒ25.4 mm

Therefore, runoff = R-Pe (1.1)

Baier *et al.* (1978) used a simplified relationship between moisture content in the topsoil zone and daily total precipitation to estimate infiltration into the soil. On days with rainfall 25.4 mm, the total amount of rainfall is considered to infiltrate into the soil. On days with rainfall 25.4 mm. the amount of infiltration (Infl) into the soil is less than the daily rainfall, because it is limited by run- off as a function of rainfall and the moisture already in the top zone of soil, and is computed as

Infl = 0.9177 + 1.811 log RR_i ï 0.97

[$S_{j(i-1)}C_j$] log RR_I (1.2)

where,

RR_i = rainfall on day i

$S_{j(i-1)}$ = soil moisture in the j^{th} zone on day i-1

C_j = available water capacity of the j^{th} zone

j = 1

The remainder of the daily rainfall is assumed to be lost as runoff. Dale et *al.* (1982) employed the same relation in their SIMBAL model for cropland drainage effects on soil moisture and evapotranspiration.

1.3 Soil water recharge and drainage

The soil profile in the water balance models is either considered as a single layer or divided into discrete layers of either uniform or variable thickness. Infiltration and redistribution of water throughout the layered soil profile is often treated in two rather in different procedures. In simple models, the infiltrated water is freely transmitted to lower layers by gravity or out of the profile if it was the lower most layer. The upper limit of water for each layer is set at field capacity. When the antecedent water content plus inflow of water exceeds field capacity of that layer then the excess water is allocated to next lower layer. This process is repeated for all layers and excess water from the lowest layer is considered as deep drainage. In this method upward movement or redistribution of water is not allowed unless it is an added feature.

In the Versatile Soil Moisture Budget (VSMB) of Baier *et al* (1979), the partitioning of infiltrated water to each zone is simulated by the following function.

$Infl_{ij} = \{ 1- [S_{j(i-j)} / C_j) b\} \{Infl_i - Infl_{in}\}$ (1.3) where, $Infl_{ij}$ = new infiltration into each zone of soil $S_{j\{i-1)}$ = soil moisture in the j^{th} zone on day i-1 C_j = available water capacity of the j^{th} zone b = percolation coefficient ranging from 0 to 1.

This equation is applied only when the ratio of soil moisture to capacity in any zone is less than 0.9. The amount of water that can infiltrate into and remain in each zone can not exceed the deficit (DEF) for that zone (j) and day(i). The DEF is given by

$DEF_{ji} = C_j$ ï $S_{j(i-l)} + AE_{ji}$ (1.4)

In addition, the VSMB assumes that the amount of water that can be budgeted to the j^{th} zone can never exceed what remains from the total water infiltrated after water has been budgeted to zones 1 to j-l. If, after all zones have been recharged, there is still infiltration water remaining, then this water is allocated to subsurface drainage. This means that the infiltration is distributed over the zones as a function of the amount of infiltration, the relative moisture content in each zone, and the percolation coefficient (b). The percolation coefficient is the fraction of water infiltrating to the next zone. For b=O, the water content of each zone must reach field capacity before the remaining water infiltrates into the next zone. For b= 1, a fraction of the infiltration water percolate to the next zone before field capacity is reached, depending on the moisture content in the upper zone. This feature of the infiltration equation was found to be useful in heavy textured soils.

In WTGROWS - a wheat growth model of Aggarwal *et* al. (1994), the amount of water available either by rainfall or irrigation after deducting runoff is allocated to various soil layers starting from the surface layer. In this model, inter layer fluxes of water are considered only at the time of rainfall or irrigation and at all other times the fluxes are considered negligible. Depending upon the amount of water available, the layers are charged to field capacity. Water in excess of field capacity of a layer, if available, is immediate drained to the next layer. The amount water above field capacity of the bottom layer is drained out of the profile and is not available for crop use. Similar procedure was adopted for profile recharge COTTAM model of Jackson *et al. (1990).*

In tlie other method of profile recharge, it is customary to use Darcy's unsaturated flow equation, in which each layer assumed to be uniform in moisture content, capillary pressure, and unsaturated conductivity. Mathematical solutions vary from the simple finite difference with large time steps to finite element with near analytical results. There are several models considering soil water movement in response to pressure-head gradients in accordance to the Darcy and continuity equations, for example, SWACROP of feddes *et al* (1978), SPAW of Saxton *et* al. (1974) and Rama Prasad (1984). This treatment of water flow can be used to represent nearly all situations including upward or downward flow between layers, widely varying characteristics within the profile, time distribution of infiltration and redistribution among layers, water tables and plant water withdrawal. But this approach requires specifications of the soil water retention and hydraulic-conductivity curves, upper boundary conditions of precipitation and potential evapotranspiration and a lower boundary condition appropriate for the site under consideration. The choice of which soil water movement calculation to employ depends upon the accuracy required. For readily drained soils where withdrawal of water by the profile development and casual accuracy is required, the free flow procedure would suffice.

Potential evapotranspiration

The estimation of potential evapotranspiration (PET) is essential to know the evaporating power of the environment so crop evapotranspiration (ET) could be estimated. Soil moisture models use different methods for estimating PET. In IBSNAT crop models, PET is calculated using an equilibrium evaporation concept developed from the Priestley and Taylor (1972) model. The equation calculates the approximate daytime net radiation and equilibrium evaporation, assuming that stomata are closed at night and no ET occurs then. Equilibrium evaporation, E_{eq}, is computed in CERES - Maize model of Johnôs *et al.* (1986) as

$E_{eq} = R_s(4.88* 10^{-3}$ ï $4.37 * 10 -^{3*}$ Ŭ) (T+29) (1.5) where,

R_s = solar radiation, MJ m^{-2} day^{-1}

Ŭ = albedo of crop soil surface

T = average daily temperature (°C), estimated as

$T = 0.6 * T_{max} + 0.4 * T_{min}$ (1.6)

T_{max} = daily maximum temperature (°C)

T_{min} = daily minimum temperature (°C)

The PET is then computed by

$PET = 1.1 * E_{eq}$ if $5< T_{max}$ Ò35°C (1.7)

$PET = E_{eq} [1.1 + 0.05 (T_{max} -35\}$ if $T_{max}> 35$°C (1.8)

$PET = E_{eq} *0.01\ e^{[0.18\ (Tmax+20)]}$

If $T_{max} >5°$ (1.9)

The PET is calculated as the equilibrium evaporation times 1.1 to account for the effects of unsaturated air. The multiplier is increased above 1.1 to allow for advection effect when the maximum temperature is greater than 35°C, and reduced for temperatures below 0°C to account for the influence of cold temperatures on stomatal closure.

The versatile soil moisture budget (VSMB) of Baier *et* al. (1979) uses regression formulae for estimating PET from various combinations of available meteorological data. This is because cf the development of these relations, for most of the Canadian sites where the VSMB was tested, from the historical weather data. For the sites where these regression equations are not available, the VSMB calculates PET from the daily maximum (T_{max}) and minimum (T_{min}) temperatures and radiation at the top of the atmosphere (Q_a) as

$PET = 0.0034 [T_{max}*0.928] + 0.933 (T_{max}$ ï $T_{min}) + 0.0486\ Q_a$ ï 87.03] (1.10)

The Penman's formula has been used to compute PET in several models like WTGROWS of Aggarwal *et al.* (1994) and WATER of Burt *et al.* (1980). In determining the PET, primarily the choice of method should be based on the type of meteorological data available.

1.5 Actual evapotranspiration

The actual evapotranspiration (AET) is generally estimated by two approaches in water balance models as

(a) using crop coefficients and soil dryness curves

(b) separating: evapotranspiration into evaporation and transpiration.

1.5.1 Crop coeffICients

Crop coefficients are generally empirical ratios of crop ET (ET_c) to some reference ET (PET) that have been derived from experimental data according to the relationship

$K_c = ET_c/PET$ (1.11)

where,

K_c = crop ceofficient for a particular crop for a given growth phase and soil moisture condition ï dimensionless

ET_c = daily crop ET (mm)

PET = daily reference ET (mm)

The reference ET characterizes the evaporative demand determined by meteorological conditions and a standard crop surface and K_c indicates the relative ability of a specific crop - soil surface to meet that demand. Since PET is affected by many variables, it can not be simplified for all climate and crop situations. This is because of the effects of relative leaf area and the morphological and physiological characteristics of the reference crop canopy on the energy exchange and aerodynamic diffusion processes within the atmosphere over a field. Different methods have been proposed for estimating PET for either grass or alfalfa with corresponding crop coefficients (Doorenbos and Pruitt, 1979: Wright, 1981).

Normally, the crop coefficient includes the effects of evaporation from both plant and soil surfaces and is dependent upon available soil water within the root zone and the wetness of the exposed soil surface. Soil water depletion data obtained by gravimetric or neutron probe methods and lysimetric data can be used to obtain K_c values.

Table 2. Crop coefficients (Kc) values for different crops and weather conditions (after Doorenbos and Pruitt, 1979)

Crop	Crop stage	Humidity windspeed (m/sec)	>70 %		<20%	
			0-5	5-8	0-5	5.8
Wheat	3		1.05	1.10	1.15	1.20
	4		0.25	0.25	0.20	0.20
Maize	3		1.05	1.10	1.15	1.20
	4		0.55	0.55	0.60	0.60
Cotton	3		1.05	1.15	1.20	1.25
	4		0.65	0.65	0.65	0.70
Millet	3		1.00	1.05	1.10	1.15
	4		0.30	0.30	0.25	0.25
Groundnut	3		0.95	1.00	1.05	1.10
	4		0.55	0.55	0.60	0.60
Sorghum	3		1.00	1.05	1.10	1.15
	4		0.50	0.50	0.55	0.55
Soybean	3		1.00	1.05	1.10	1.15
	4		0.45	0.45	0.45	0.45
Sunflower	3		1.05	1.10	1.15	1.20
	4		0.40	0.40	0.35	0.35
Potato	3		1.05	1.10	1.15	1.20
	4		0.70	0.70	0.75	0.75
Onion (dry)	3		0.95	0.95	1.05	1.10
	4		0.75	0.75	0.80	0.85
Cabbage & Cauliflower	3		0.95	1.00	1.05	1.10
	4		0.80	0.85	0.90	0.95
Carrot	3		1.00	1.05	1.10	1.15
	4		0.70	0.75	0.80	0.85
Sugarbeet	3		1.05	1.10	1.15	1.20
	4		0.90	0.95	1.00	1.00
Radish	3		0.80	0.80	0.85	0.90
	4		0.75	0.75	0.80	0.85

The crop coefficient values for different crops are presented in Table 2. A generalized crop coefficient curve proposed by Doorenbos and Pruitt (1979) is presented as Fig 2. The Kc values for growth stages 1 and 2 for the crops in Table 2 can be obtained by interpolation from Fig 2. A crop coefficient curve represents the seasonal variation of the empirically derived K_c values. Once this curve has been developed for a given location, daily crop ET can be estimated using Eq. 1. 11. The variation in time of season of the crop coefficient in Eq. (1.11) has not proven to be generalizable because it is often management, site and weather specific as evident from the values furnished in Table 2. Values of K_c may be management specific as a result of planting date, plant population and row spacing. The value may be site specific because of large-scale soil spatial variability and may not be reproducible from one year to the next for a given location because weather sequence are usually not reproducible from year to year. Crop coefficients are dependent on weather because air temperature, radiation and frequency of rainfall effect E_s and E_p directly and temperatures influence the rate of crop development. Hanks (1985) compared crop coefficients measured at Logan and Davis for the same crop. The crop coefficient curve differed markedly for the two locations, especially early in the conditions where the soil surface is dry. He attributed this site specificity to the dependence of Es on the rainfall frequency and amount or irrigation regime when plant cover is low and suggested that the crop coefficient vary from year to year for the same reason. Wright and Jensen (1978) recognized this limitation of the crop coefficient procedure and developed a crop coefficient curve that was based only on conditions where the soil surface is dry. Their model accounts for increased evaporation when the soil surface is wet and efficiently reduced the estimation of ET of snap bean during the leaf area development. Wright (1982) defined these modified crop coefficients, designed to represent conditions where the soil surface is dry but water is readily available, as ñbasal ET crop coefficients (K_{cb})". Estimates of an adjusted crop coefficient in terms of K_{cb} were accomplished through use of the following equation : .

$$K_a = K_{cb} + (1-K_{cb}) [1-(t/td)^{0.5}] f(w) \qquad (1.12)$$

where,

K_a = adjusted crop coefficient

t = number of days after major rain or irrigation

t_d = usual number of days for the soil surface to dry

f(w) = relative proporation of the soil surface originally wetted

Most of the adjustment takes place in the first few days after wetting the soil. The usefulness of this adjustment procedure may be extended mainly to arid regions where evaporative conditions are relatively uniform during the season and t_d may indeed be constant for a given soil. In humid regions, it may be necessary to accommodate the unpredictable temperature and radiation conditions by considering the constant rate stage of soil evaporation and its upper limit (Ritchie and Johnson, 1990). However, Eq. 1.12 helps to diminish the year-to-year variation of the crop coefficients caused by varying frequency of rainfall and irrigation. Ritchie and Johnson (1990) proposed the following relationship which incorporates the effects of temperature and leaf appearance and expansion for the influence of varying plant population on ET as :

$K_s +_p = (E_s + Ep)/PET$ (1.13)

where,

Ks+p = a daily crop coefficient based on separate calculation of E_s and E_p.

The calculations of E_s and E_p require prediction of daily values of LAl and a temperature-based relation for leaf area development can accomplish this. Several authors have developed relations to evolve Kc values as a function of thermal time or days after emergence. Sammis *et al.* (1986) applied the following polynomial for estimating K_c values of winter wheat and spring barley as

$K_c = B_o + B_1$ɆG $+ B_2$ɆG$^2 + B_3$ɆG^3 (1.14)

where,

ɆG = accumulated growing degree days starting planting

B_1 = regression coefficients.

The CALEX/COTTON irrigation module program has been evaluated by Plant *et al.* (1992) with the following relation for K_c as

$K_c = 0.038 + 21.158\ x$ ï $56.579\ x^2 - 263.86\ x^3$ (1.15)

where,

$x = DD / 10000$

DD = total elapsed growing degree days 15°C

The K_c values for spanish peanuts were determined from the third-order polynomial (Elliott *et al.*. 1988) as a function of the fraction of the peanut growing season as

$K_c = -1.644 + 12.05\ F$ ï $17.155\ F^2 + 7.499\ F^3$ (1.16)

where,

F = fraction of the growing season (ratio of days since planting to days between planting and harvesting)

In this case, a growing season length of 140 days was assumed when calculations of F were made. Since this polynomial relationship gives a negative result for mall values of F, a minimum value of 0.4 for K_c is suggested.

A second order polynomial equation has been employed by Idike *et al.* (1982) for estimating K_c of corn as function of days after emergence as

$$K_c = 0.152 + 0.0164\,D - 0.00012D^2 \qquad (1.17)$$

where,

D = days after emergence of the crop

A third degree polynomial has been fitted for spring wheat, barley, canola. sugarbeet and potatoes by Foroud *et* al. (1992) with a lower and upper limit of 0.1 and 1.2 for K_c respectively.

1.5.2 Soil dryness curves

Depending on the energy available in the atmosphere, the soil is able to provide all or part of the water requirement of the plant for transpiration. This depends on soil characteristics, crop type, crop stage and the magnitude of PET itself. As the soil dries, its hydraulic conductivity decreases, and water moves more slowly towards the roots. Only in certain circumstances AET becomes equal to the PET, and normally the former is a fraction of the later. When the moisture tension becomes too high, AET becomes less than PET. This break - off tension is higher for lower values of PET and vice - versa. It is high for some crops like horsegram (drought - resistant) and low for sugarcane. For a given crop it is higher during the initial and late stages than during mid-season stage (Rama Prasad, 1984). In the range of plant available water i.e., amount of water from field capacity (FC) to permanent wilting point (PWP), the amount of available soil water gradually decreases to become zero when PWP is reached. Contradictory view points exist on the availability of soil moisture and the versatile soil moisture budget of Baier *et al.* (1979) who have used 8 types of relationships between the available water for plants and the ratio AET /PET. From these, an adjustment factor 'z' was proposed for different types of soil dryness curves as :

$$Z = [AET / PET] / [AW / AWC] \qquad (1.18)$$

where,

AW = available water in the zone concerned on a given day

AWC = available water capacity of that zone

The AET on a given day can thus be computed as

$$AET = [AW/AWC] * Z * K_c * PET \quad (1.19)$$

1.5.3 Separating PET into evaporation and transpiration

Several types of models are available for calculating E_s and $E_{p.}$ Because of their differences in their purposes and organization, they can be broadly categorized according to Addiscott and Wagenet (1985) into (a) deterministic or stochastic (b) mechanistic or functional and (c) rate or capacity types.

The deterministic models produce a unique outcome for a given set of events. However, due to the spatial variability of the mediating processes there will be a certain degree of uncertainty associated with the results. Stochastic models have been developed to accommodate this spatial variability and to quantify the degree of uncertainty. Stochastic models produce an uncertain outcome because they include one or more parameters that are random variables with an associated probability distribution. But stochastic models have been applied little in modelling ET (Ritchie and Johnson, 1990).

Most models used for estimating E_s and E_p are deterministic and can be further categorized as mechanistic or functional. The mechanistic models are based on dynamic rate concepts and incorporate basic mechanisms of processes such as Darcyǿs law or Fourierǿs law and the appropriate continuity equations for water and heat fluxes respectively. Functional models are usually based on capacity factors and treat processes in a more simplified manner, reducing the amount of input required. Mechanistic models are useful primarily as research tools for better understanding of an integrated system, and are usually not used by non-authors due to their complexity. On the other hand, the functional models have modest input requirements making them useful for management purposes. Because of their simplicity, functional models are more widely used and independently validated than mechanistic models.

The most important causes ofunproductive loss of water is direct evaporation from the soil surface and especially so under arid and semi-arid conditions where deep drainage can generally be ignored. Thus, the ratio of soil evaporation to transpiration is of decisive importance for overall water use efficiency. Evapotranspiration can be divided into two parts as follows

(a) firstly, under fallow conditions evaporation proceeds at rate depending upon soil type, frequency of wetting and evaporative demand; and

(b) secondly, under a cropped situation evaporation and transpiration proceed and in turn depend on the soil type, evaporative demand, available water in the root zone and the type of crop cover at different stages of crop gtowth.

1.5.2. 1 Soil evaporation (E_s)

There are several mechanistic models available on E_s in which general equation of water flow is used. Some of these models predict evaporative losses of water from a bare soil (Gardner and Gardner, 1969: van Bavel and Hillel. 1976; Hillel and Talpaz, 1977; Lascano and van Bavel, 1986). Some models facilitate the separate calculation of E_s and E_p in the presence of a crop (Feddes *et aI.,* 1976; Norman and Campbell, 1983; Huck and Hillel, 1983; Lascano *et al.,* 1987). Functional models are less evident in the literature and some models that have been used to calculate E_s and E_p separately are the models of Ritchie (1972), Hanks (1974), Kanemasu *et al.* (1976) and Tanner and Jury (1976). Because of the complexity in applying mechanistic models, as explained in section 1.5.2, the review presented here mostly deals with functional models.

The rate of evaporation from the soil can be grouped into several stages. During the first stage, which may be lost for only one to three days in mid-summer, the rate of evaporation is controlled by heat energy input and is about 90 percent of PET (Jensen *et aI.,* 1990). The duration of first stage is influenced by the rate of evaporation, soil depth and hydraulic properties of the soil (Gardner and Hillel, 1962). By noting the changes in albedo, the transition from first to second stage of drying can be identified (Jackson *et al.,* 1976). Immediately after wetting, the evaporation from a wet bare soil is approximately same as that from a free water surface, the duration of which is again dependent on soil type and evaporative demand of the atmosphere. The period is shortened under coarse textured soils. This relates to the amount of water retained in the top 10 cm of soil layer (Reddy, 1993).

During the second or falling stage, the surface has begun to dry and evaporation is occurring below the soil surface. Water vapor reaches the surface by molecular diffusion and mass flow caused due to the fluctuations in soil air pressure. The dry surface soil greatly influences the effective internal resistance. After the mulch has been formed then the rate of evaporation is less than PET and the rate is controlled by soil characteristics like hydraulic conductivity but not by the meteorological conditions. During the second stage the cumulative evaporation tends to increase with the square root of time for a given soil and evaporation potential as

$$Es\ dt = K\ (t-t_1)^{0.5} \text{ if } t > t_1$$

where,

K = empirical constant for a given soil that depends on the soil characteristics and water content (Black et al. 1969)

t_1 = time at which the falling stage begins.

The value of K can be determined experimentally from cumulative evaporation data for a single drying cycle of a given soil. Several direct measurements of the coefficient K in a diversity of soils have consistently resulted in values of about 3.5

mm $day^{-0.5}$. Mason and Smith (1981) used a value of 5 in their model. Thus, the cumulative loss of water after an irrigation or rain can be approximated by

E_c = 0.9 PET dt for t t_1 and E_c = 0.9 PET dt + K $(t-t_1)^{0.5}$ for t t_1

where,

Ec = cumulative evaporation

t_1 = time since evaporation began

Ritchie (1972) summarized Ec at tl and K value for several soils and the values are reproduced in Table 3.

Table 3 . Typical coefficients for second stage evporation

Soil	Ec (mm)	K (mm $day^{-0.5}$)
Adelanto clay loam	12	5.08
Yolo loam	9	4.04
Houston black clay	6	3.50
Plain field sand	6	3.34

PLANTGRO model of .Retta and Hanks (1977) computes E_s on the assumption that E_s occurs only from the top layer, usually of 20 to 30 em in thickness, as

$E = PET\ t^{-0.5}$ (1.23)

where,

t = time in days since last irrigation or rain.

It also allows the top layer to loose moisture below wilting point to the airdrying moisture content. The amount of water that may be lost by evaporation after the soil has reached its permanent wilting water content is taken as equal to the amount of water lost when the first 10 cm of the top layer is dried to air-drying. Thus during the constant rate stage, the evaporation occurs at the potential rate until the upper limit of stage 1 evaporation (U) is reached (Ritchie and Johnson, 1990). This U is reached more rapidly under condition of high PET than under low PET. Ritchie and Johnson (1990) reported value of U to be about 5 mm in sands and heavy shrinking clays to about 14 mm in clay loams. Mason and Smith (1981) assumed a value of 7 mm.

However, contradictory view point exists on the second-stage evaporation rates. Arora *et* al. (1987) used the following empirical relation for sandy loam soils

$E = PET\ t^{-0.30}$ (1.24)

It was also assumed that the top 30 cm soil layer contributed towards soil evaporation. Hill *et a1*. (1979) used the following relation to estimate E_s as

$E_s = E_p / 2 (2^{t-1})$ (1.25) and $E_p = K_s * PET$ (1.26)

where,

E_p = potential soil evaporation

K_s = soil evaporation factor which depends on the value of Kc.

t = time in days since the last soil surface wetting.

It is subject to the constraint that the surface soil can not be drier than air-dry. The top 10 cm soil is assumed to be dried by evaporation and transpiration to the wilting point and then by evaporation only to air dry.

However, Ritchie's (1972) model is the most frequently used model for E_s. This has been used by Cull *et* al (1981), Mason and Smith (1981), Sharpley arid Williams (1990) and Jain and Murthy (1985).

The calculation of E_s in the Ritchie's (1972) model requires prediction of the net radiation through the canopy to the soil surface. Ritchie and Burnett (1971) quantified the influence of partial cover on ET and found that LAI of sorghum and cotton were more generally related to plant evaporation (ET) as fractions of PET than ground cover or plant dry weight. The empiricism used to estimate ET from crops with an adequate supply of water in the root zone usually make ET a function of PET. LAI or plant cover.

In the presence of canopy, the fraction of energy (Rso) supplied to the soil surface depends on crop cover or leaf area index (LAI) and is given by

$R_{so} = R_{ns} / R_n = \exp(-0.4 \text{ LAI})$ for LAI <2.7 (1.27)

where,

R_{ns} & R_n = 24 hour net radiation at soil surface and above the crop canopy, respectively.

Thus, the soil evaporation during the constant rate stage (stage 1) is calculated using a Priestley - Taylor type equation (Ritchie, 1974);

$$E_{sp} = \frac{\Delta}{\Delta+\gamma} \theta_n R_{so} \quad (1.28)$$

where,

$\theta_n = 0.92 + 0.4 [R_{ns} / R_n]$ for LAI < 2.7 (1.29)

$\theta_n = 1$ for LAI >2.7 (1.30)

Some of the functional relations reported in the literature are presented here. CERES-Maize model of Jones et al. (1986) computes potential soil evaporation as

Esp = PET [1.0 -.0.43 (LAI)] for

LAI <1 (1.31)

and Esp = (PET /1.1) $e^{-0.4 (LAI)}$ for

LAI <1 (1.32)

In this case, a modified Preistley-Taylor equation is used to calculate daily values of PET although other equations could be used. The potential rates for PET and Esp are equivalent in this example when applied to bare soil conditions (i.e.: LAI = 0).

For wheat crop of North-Western part of India, Jain and Murthy (1985) computed Esp as '

$$E_{sp} = 0.1 \frac{\Delta}{\Delta + \gamma} R_n \exp(-0.428\ LAI)$$

Sammis *et* al.(1986) used the following relation for winter wheat and spring barley to compute daily soil evaporation as

$$Es = PET * e^{-0.623\ LAI}$$

In a water balance model that was used to calculate dry matter yield of wheat, Hanks and Puckridge (1980) computed potential soil evaporation as a function of LAI and dry matter production (DM) in g m^{-2} as

E_{sp} = [PET - T_p] [1 ï DM/2000] (1.35)

where,

T_p = 0.9 PET if LAI>3 (1.36)

and T_p = 0.9 PET (LAI/3) if LAI <3 (1.37)

In the Soil Water Leaf. Extension of Winter Wheat and Wheat Growth [SWLEWW-WTGRO) model of Farshi *et al.* (1987) for the values of ground cover (Gc) smaller than 0.45, it was assumed that PET f winter wheat was equal to ET_o, the PET of a full grown grass cover. The PET was separated into potential transpiration and evaporation on the basis of predicted values of leaf area index as

Gc = 1 - exp (-0.6 LAl) (1.38)

E_p = PET if Gc = 0 (1.39)

E_p = 0.9 (1 - Gc) PET if Gc > 0 (l.40)

The equation (1.32) was used for LAI up to 3.5. For LAI >3.5, it was assumed that the crop covers the ground surface completely, consequently Gc was put equal to 1.

In an attempt to simulate water content under barley using simple empirical approach, AI Khafaf *et* al. (1989) estimated bare soil evaporation using the expression

$E_s = a\ (t)^b - a\ (t\text{-}l)^b$ (1.41) where,

a,b = empirical coefficients depending on soil type

t = time after irrigation [days).

The potential soil evaporation was calculated as

Esp = PET if Fs < 0.08 (1.42)

that is, if PET is not higher than the value of 'a' in Eq.(1.41), otherwise E_{sp} = 7.24 mm day$^{-1.}$ Further, they used

E_{sp} = (1.21 - 2.343 Fs) PET

if 0.08 < Fs < 0.48 [1.43)

,E_{sp} = 0.08 PET if 0.48 < Fs (1.44)

where, Fs is fraction of degree of shading which is the ratio of LAl at any given time to the maximum value of LAl during the season under non-limiting water conditions.

1.5.2.2 Plant transpiration (E_t)

As the case with modeling $E_{s,}$ there are also mechanistic and functional models for estimating plant transpiration. Two classical examples of mechanistic models are Penman-Monteith model (Monteith, 1973) and the EMWATBAL model (Lascano *et al,* 1987). Though they differ in their, input requirement and detail but were stated to have good theoretical bases, the former being simpler than the later and intended to calculate E_t or AET. Both these models operate on 1-hour time step and Penman-Monteith has been used extensively to estimate AET in recent years. This equation requires hourly input or estimates from empirical functions for humidity, temperature, net radiation, soil heat flux, heat storage rate in the canopy air column, transport resistance from the leaf surface to instrument height (r_a), and the resistance of the crop (r_c). However, use of this relation to predict AET in applications such as irrigation scheduling is a problem because the required meteorological inputs are difficult to obtain. The value of the surface resistance is a complex function of many climatological and biological factors (Monteith, 1985). All the meteorological variables that must be known are dependent to some extent on the properties of the vegetation. Thus, they must be estimated on the basis of previous experience or calculated from models of the exchange processes (McNaughton and Jarvis, 1984).

The other mechanistic model, EMWATBAL calculates the water and energy balance for both the soil surface and crop canopy. This model calculates water evaporation and transpiration fluxes. At each time step, the model calculates and updates values of water content and temperature for each soil layer. From these values the inter-layer fluxes of water and heat below the soil surface are calculated. At the soil surface the net radiation, latent, sensible, and soil heat fluxes are calculated from an energy balance equation. Instead of assuming that evaporation at the soil surface at the equilibrium rate corresponding to the net radiation flux above that surface (Ritchie, 1972), the EMWATBAL calculates evaporation at the soil surface by finding the surface temperature that satisfies the energy and water balance at the soil surface by the method of van Bave1 and Hillel (1976). The model requires information on soil water retention curve and the unsaturated hydraulic conductivity for each soil horizon, and the number and thickness of the soil layers that determine the geometry of the soil system. Plant inputs are the relation between leaf conductance and leaf water potential, the root distribution as a function of soil depth and time, and the LAI as a function of time. Weather inputs are daily total solar radiation, daily maximum and minimum air and dew point temperatures, daily wind speed, and the quantity of rain or irrigation as a function of time of day. In addition, initial values of the water and temperature profiles must be specified at the start of the simulation period. The daily weather data will be disaggregated into hourly values using empirical relations to produce 24 estimated values from one or two measured values.

Though EMWATBAL is a mechanistic model, it uses empirical relations also. For example, several polynomials were used to compute short wave absorptance of the crop (ABSC) , of the soil (ABSS) , and the view factor from soil to sky (FTSR), all as a function of LAI, as

$$ABSC == 0.5809\ LAI - 0.2231\ LAI^2 + 0.04640\ LAI^3 - 0.004759\ LAI^4 + 0.0001875\ LAI^5 \quad (1.45)$$

$$ABSS= 0.825-0.6447LAI +0.2646LAI^2 - 0.05695\ LAI^3 + 0.005937\ LAI^4 - 0.0002355\ LAI^5 \quad (I.46)$$

$$FTSR == 1.0 - 0.6780\ LAI + 0.2052\ LAI^2 - 0.02799\ LAI^3 + 0.001383\ LAI^4 \quad (1.47)$$

Further, the LAI is estimated with third-order polynomials as a function of calendar day number (CD). For the irrigated cotton crop, this relationship was given as

$$LAI = 105.6713 - 1.61088\ CD + 0.008035084\ CD^2 - 0.0000130257\ CD^3 \quad (1.48)$$

and for the dryland cotton crop, the relation was given as

$$LAI=70.93205-1.13014CD+0.005848976CD^2-0.0000097607CD^3 \quad (1.49)$$

Ritchie and Johnson (1990) have identified several problems that may reclude the use of a mechanistic model for rediction purposes and for supporting farm decisions such as irrigation scheduling. Mechanistic models may provide the information needed to derive some of the empiricism upon which functional models are based.

The second type of models for estimating E_t are functional models. These are quite widely used in many crop growth models because they require few inputs, most of which are readily obtainable.

In an earlier attempt to estimate the evaporation rates from developing cotton and grain sorghum canopies under water non-limiting conditions, Ritchie and Burnett (1971) estimated the potential transpiration (T_p) as

$$T_p = PET\ (- 0.21 + 0.70\ LAI^{0.5}),$$
$$0.1 \grave{O} LAI \grave{O} 2.7 \quad (1.50)$$

The non-linearity of the relation between T_p and LAl is stated to be the result of two interacting factors

(a) less competition for radiation per unit of leaf area during initial stages of plant growth and

(b) the partitioning of a large fraction of net radiation at the dry soil surface between plant rows to sensible heat flux causing increased canopy temperature and consequently increased T_p (Ritchie and Burnett, 1971).

Upper limit of 2.7 of LAl represents minimum requirement of LAI necessary for full cover of canopy. For crop canopies with LAl> 2.7, T_p = PET. When LAl < 0.1, T_p is considered negligible.

The T_p is computed from actual (Ea) and potential soil evaporation (Esp) and PET by Brisson *et al.* (1992)using the following relation

T_p = (PET - E_p) [ϐ + (1 - ϐ) Es/Espl (1.51) where, the value of ϐ was 1.1, which simulates a 10% increase in Tp/PET between wet soil conditions (Es=E_p) and dry soil conditions (Es=O).

The potential transpiration for a wheat crop was estimated by Hanks and Puckridge (1980) using the relations already explained in section 1.5.2.1 as Eq.

i (1.53) to (1.54), which are reproduced here, as T_p = 0.9 PET if LAI is 3

T_p = 0.9 PET (LAl/3) if LAI is 3.

Assuming that T_p is largely controlled by evaporative demand and degree of shading under non-limiting water conditions, Al-Khafaf *et al.* *(1989)* estimated T_p using the following functional relations

$T_p = 0$ ifFs< 0.08 (1.52)

T_p= [l - (1.21 - 2.343 Fs)J PET if 0.08 <Fs<0.48 (1.53)

T_p= 0.92 PET if 0.48 < Fs (1.54)

where,

Fs = fraction of degree of shading .

In most of the soil water balance models like that of Farshi *et al.* (1987), Murthy *et. al* (1992) and Sammis *et al.* (1986), the T_p is calculated as

T_p = PET - E_s (1.55)

where E_s is calculated by one or the other method discussed in section 1.5.2.1

In CERES-Maize,the calculation of E_t is through a functional model on the lines of Ritchie (1972). The functional model for estimation of E_s has been described earlier in section 1.5.2.1. Where the soil water is non-limiting the functional model calculates E_t using the relationships

E_t = PET (1.0 ï e $^{-LAI}$) if LAI Ò3 (1.56)

E_t = PET if LAI > 3

and if $E_s + E_t$ > PET, then

E_t = PET - E_s (1.58)

The conditional Eq (1.58) was felt necessary because values for E_s and E_t are calculated independentIy and their sum can exceed the potential rate on a given day because Eq (1.56) and (1.57) are for estimating E_t when the soil surface is dry.

Once the potential transpiration (Tp) is computed, most of the models estimate actual transpiration (E_t) on the basis of soil water availability. As the soil dries, the conductivity of soil to water flow decreases, thereby decreasing the uptake of water by the root system. Actual transpiration (E_t) by the crop falls below the potential transpiration demand (T_p). There are essentially two approaches to estimate E_t. In the first approach T_p is decreased in proportion to the water deficit in the rooting zone. The transpiration from sorghum or corn as observed by Ritchie (1973) is not affected by soil water deficit until the available water ($ɗ_A$) in the root zone is less than 0.3 of the maximum available moisture content ($ɗ_{max}$). Thus, when the available water content in the root zone is in between 1 and 0.3 of the maximum, E_t is considered equal to T_p. When available water content is less than 0.3 of the maximum then

$E_t = T_p\, ɗ_A/0.3\, ɗ_{max}$ (1.59)

The concept was used by Cull. et *al.* (1981) for cotton crop. However, Hanks (1974), Sammis et *al.* (1986) and Abdul Jabbar et *al.* (1983) assumed a value of 0.5 of $d_{max.}$ Singh and Wolkewitz (1988) adopted the critical value of 0.65 to 0.84 for different growth stages of wheat. In the second approach, potential water supply (Pw) by the root system is considered in relation to the potential demand by the crop (T_p). If water supply is greater than demand, then demand is the actual transpiration. If water supply falls below the demand due to water deficits in the soil, then supply is the actual transpiration.

Overview of crop-weather models with emphasis on empirical crop-weather relationships

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Crop-weather models integrate the crop development growth and production as a function of weather and has many uses in agriculture. They serve as tools in land use planning, crop adaptation, crop monitoring and forecasting, crop management, pest and disease control and finally in prioritizing the research needs.

The main purpose of developing the crop-weather models are:

1. To understand crop weather interactions, processes involved and their limitations.
2. To assess the affect of environment, crop genotype and management of input resources on crop yields, and to quantify the yield gaps with existing knowledge.
3. To undertake strategic and policy decisions to increase the productivity of resource based efficient cropping systems.

During the last four decades, crop weather models have been used to solve practical problems such as

1. Yield assessment of cereals, pulses an oilseed crops based on varying crop management decisions during the growing season as well as over different rainfall years for risk analysis using CERES models for cereal, pulses and oilseed crops (Boote *et al.,* 1998).
2. Potential productivity of crops for regional agricultural planning. Yield gaps and decision support systems (Naab *et al.,* 2004).
3. Genetic improvement of cereals, pulses and oilseeds for yield, pest resistance food value and input requirements (CERES models, IBSNAT programme, 1988).
4. Quantifications of impact of global climate change on agricultural productivity (Pickering *et al*., 1995).
5. Management decisions on evaluating sowing date, row spacing, plant populations, scheduling irrigation, evaluation of yield variations in different rainfall years, impact of moisture and temperature stresses on yield.
6. To simulate growth, development and yield levels.
7. To define optimum management strategies regarding drainage, irrigation, soil, water, weather, fertilizer, pest control, planting dates, tillage, crop residue management (For example EPIC Model-Sharpley and William, 1990).
8. Evaluation of new crops for introducing at al location (Jones, 1990).

The models can be broadly categorized into Empirical statistical models, crop weather analysis models and crop growth simulation models.

Empirical-statistical models

In this type of models, one or more variables representing weather/climate, soil water availably, cropĝs biological character etc., are related to crop responses such as dry matter yield or seed yields. The independent variables are climatic or derived agrometeorological variables such as moisture adequacy index (MAI) or soil water availability parameter or crop biological characters such as LAI or GDD or plant characters. After removing the technological trend, the significant agrometeorological variables are related to crop yield through standard statistical procedures such as multivariable regression analysis. The weighing coefficients of these expressions are obtained. Variance analysis, regression analysis, correlation and multivariable regression analysis are some other common procedures. Ulanova (1975) forecasted winter wheat using agrometeorological variables such as soil moisture reserves in growing season, average number of head per m^2, average height of plant, average number of kernels per head at heading stage explaining 86 per cent of variability of wheat crop yields expressed as

$Y = -19.92 + 0.29 X_1 - 0.0013 X_1^2 + 0.045 X_2 - 3 \times 10^{-5} X_2^2 + 0.23 X_3 - 14 \times 10^{-5} X_3^2 - 0.805 X_4 + 0.057 X_4^2$ ...(Eq. 1)

where, Y is winter wheat yield in q/ha, X_1 is soil moisture reserve in mm at heading stage in 100 cm of soil depth, X_2 is average number of heads per m^2, X_3 is average plant height in cm, X_4 is average number of kernels per head at heading stage.

Crop yields need predicted on operational mode utilizing agrometeorological parameter/variables like rainfall, reference croo evapotranspiration temperature, soil moisture, leaf area index etc. Empirical statistical relationships thus developed helps in

1. Assessing regional crop yields at regional level,
2. Evaluating impact of technology on crop yield production,
3. Assessing suitability of area for growing crops and yield potential and zoning of crop productivity,
4. Assessing impact of climatic variability on agricultural production.

(A) Crop weather analysis models

These models are based on the product of two or more factors each representing the functional relationship between a particular plant response i.e., crop yield and the variations in selected weather variables at different crop development stages.

Input requirement of the models are only two to three effective weather variables influencing crop growth and development at different phenophases, but the output is dependent on the interactions of input factors with grain yield at different phenophases. However conventional statistical procedures are used to determine the coefficients relating to crop responses to agrometeorological data. There are two important examples in this category (i) Baierôs crop weather analysis model (1973), and (ii) Robertsonôs factorial yield weather model (1974).

(i) Baier's crop weather analysis model:

Baier (1973) studied the responses of daily contributions of upto three selected agrometeorological variables at different phenophases in wheat. Fig. 1 illustrates the crop response to each of the three input variables is either linear or quadratic, and this response gradually changed during the crop life cycle as a function of biometeorological time (Robertson, 1968). A fourth power polynomial, with biometeorological time as independent term, was adequate for fitting daily weighing factors associated with the daily contribution of each variable to the final yield. Baier (1973) selected solar energy, temperature and soil moisture-the three variables for predicting Canadian wheat yields. These three variables modify each other on any particular day during the life cycle of a crop and produce a positive or negative effect on the final yield expressed as

$$Y = \sum_{t=1}^{m} V_1 \cdot V_2 \cdot V_3, \qquad \text{...(Eq. 2)}$$

Where, Y is depen $\sum_{t=1}^{m}$ variable grain yield, is the summation of daily V values from

biometeorological time t = 0 (sowing) to m (physiological maturity) with intermediate values expressed in decimals of the time units.

On the above relation (Eq. 2), V_1, V_2 and V_3 are functions of the selected independent agrometeorological variable. Each V function is of the form as

$V_j = (u_1t + u_2t^2 + u_3t^3 + u_4t^4) + (u_5\, t + u_6t^2 + u_7t^3 + u_8t^4)\, X_j + (u_9t + u_{10}t^2 + u_{11}t^3 + u_{12}t^4)\, X_j^2$ ...(Eq. 3)

Where, u_1, u_2, é u_{12} are coefficients which are evaluated for each V_j in an iterative regression analysis in which the intercept has been suppressed and X_j in V_j represents a specific selected variable for the analysis. Computer analysis is done to evaluate and testing of 12 coefficients in each of V_1, V_2 and V_3 after every iteration. Model output provides the daily contribution to the final yield in response to the variations in each of the input variables. The critical threshold values for each of three variables are also provided as shown in figure 1 with dashed lines of lower and upper thresholds. Baier used daily minimum temperature in °C(V_1), daily maximum temperature in °C(V_2), and daily soil moisture parameter as the ratio of estimated soil moisture (AET) to maximum available soil moisture (PET) within the crop rooting zone varying between 0 to 1. The combination of minimum temperature, maximum temperature and AET/PET ratio was found to give the closest estimate with CD value of 0.77 for wheat yield.

(ii) Robertson's factorial yield weather model (FYWM)

Robertson (1974) proposed a factorial yield weather model, which involved the summation of the products of several quadratic functions for different weather variables. The weather variables adopted are precipitation, maximum and minimum temperatures, global radiation and pan evaporation. Time was used as an indicator of advancing technology and one function was involved for the antecedent crop condition.

The model is of form readily adaptable for assessing, at anytime during crop development period, the influence of past and current weather on future expected yield as

$\ddot{r}_t = V_1(\hat{R}_{t-1}, P_t)\ V_2(T_1)_t \ X\ V_3(T_2)_t \ X\ V_4(Q)_t$ ...(Eq. 4)

Where, $\ddot{r}_t$ is the expected estimated yield at anytime t at a given crop stage, $\hat{R}_{t-1}$ is the estimated yield at the end of the previous stage, P_t is the rainfall between stages, T_1 is average daily maximum temperature during the period between stages, T_2 is average minimum temperature between stages, Q is average daily solar radiation during the period between stages.

V_1, v_2, V_3 and V_4 functions are of the form.

$V_1(\hat{R}_{t-1}, P_t) = a_0 + a_1 \hat{R}_{t-1} + a_2 P_t$ ...(Eq. 5)

$V_2(T_1)_t = b_0 + b_1 T_1 + b_2 T_1^2$ ...(Eq. 6)

$V_3(Y_2)_t = c_0 + c_1 T_1 + c_3 T_2^2$ ...(Eq. 7)

$V_4(Q)_t = d_0 + d_1 Q + b_2 Q^2$ ...(Eq. 8)

Where, a, b, c and d with subscripts 0, 1 and 2 are regression coefficients for each crop period evaluated through statistical procedures.

The crop weather analysis models can also be used to study

1. The impact of climatic variability on crop yield in order to study the sensitivity analysis and relative importance of various input weather elements in crop yield,
2. The analysis of crop weather data to illustrate their relative contributions to crop yields as a function of biometeorological time, and
3. Evaluation of crop responses to weather elements at different critical phenophases in crops life cycle.

(B) Crop growth simulation models

Crop growth simulation models are dynamic in nature considering physical, biological and chemical processes in the system. They are intended to mimic the crop growth and several models of varying degree of accuracy are available (Table 1). The processes considered in these models are as follows:

1. PAR interception and biomass growth.
2. Carbon dioxide fixation.
3. Dry matter accumulation and its partitioning.
4. Tissue expansion and leaf area development.
5. Morphological development.
6. Phenological development
7. Soil water balance and soil water movement.
8. Grain yield prediction relations.
9. Soil environmental and crop management stresses.
10. Model testing, validation and sensitivity analysis.
11. Crop monitoring, yield forecasting and potential productivity of ecosystem.
12. Crop breeding.
13. Physiological insight into the crop and cropping systems.
14. Insect and disease management and linkage with pest and disease models.
15. Expert system for crop risk insurance management.
16. Soil erosion and long term soil productivity, soil conservation relations with time.
17. Crop adaptation and introduction of new crops.
18. Agro-ecological characterization and crop zonations.
19. Feasibility of inter-cropping, crop rotations and multiple cropping.
20. Operational programmes for agroadvisory services for assessing crop conditions with prevailing weather conditions.
21. Operational on farm crop management decisions for crop production for determining appropriate sowing dates, row spacing, plant population, fertilizer requirement, irrigation scheduling, cultural operations, monitoring of soil and water resources.
22. Future trends in use of models for identifying research gaps and priorities, matching technology with resources, yield forecasting and global food management, tactical and strategic decisions (Bishnol, 2007).

The principles underlying in some of the processes considered in majority of crop growth models are presented here under.

(A) Light interception and dry matter production:

The amount of biomass w(gm^{-2}) accumulated by a vegetative crop stand can be expressed as (Monteith, 1977).

$w = \int R_s \, . \, e . f \, dt$ ...(Eq. 9)

where, R_s is the incident solar radiation (MJ d^{-1}), t is time in days, *e* is coefficient or constant for conversion of radiant energy into biomass dry matter (g MJ^{-1}), *f* is the fraction of incident radiation intercepted by the foliage ($1-R_g/R_s$) and R_g is transmitted radiation at ground surface after passing through the foliage. The radiation/light use efficiency varies directly with crop attenuation coefficient, crop genotypes, sowing date, plant population and environmental variables particularly temperature and vapour pressure deficit (Rosenthal and Gerik, 1991b).

These models of biomass growth depend on leaf area index to accurately determine PAR interception or absorption. LAI needs to be accurately depicted with the advancement of thermal time. Several crop models use empirically derived relationship describing the leaf area as a function of thermal time (EPIC, COTTAM, AUSCANE) in the form as (Sharpley and Williams, 1990)

$LAI_i = LAI_{i-1} + \Delta LAI$ ...(Eq. 10)

$\Delta LAI = \Delta TT \, . \, LAI_{Max} \, [1 - \exp\{5(LAI_{i-1}$ ï $LAI_{Max})\}]$ X ãREG_i ...(Eq. 11)

$$LAI_i = LAI_d \left(\frac{1 - TTI_i}{1 - TTI_d} \right)^a \text{, and} \quad ...(Eq. 12)$$

$$TTI_i = \frac{\sum_{k=1}^{i} TT_k}{PTT} \quad ...(Eq. 13)$$

Where, TTI_i is thermal time index for day *i* and PTT is the potential thermal time required for maturity of crop, a is a parameter that regulates LAI decline rate of the crop and TTI_d is the value of thermal time index factor when LAI starts declining attaining LAI_d value.

Monteith (1977) approach for assimilate production rate during vegetative cycle of crop also works well for potential increase in daily biomass (EPIC, RESCAP models) as

$\Delta DM = LUE \times PAR_i \times (1 + \Delta DL)$ ...(Eq. 14)

Where, ΔDL is the change in day length in hours per day. PAR_i is daily intercepted or absorbed PAR, ΔDM is daily increase in biomass productivity.

In carbon driven models leaf area growth depends on the assimilate supply and leaf specific weight. In RESCAP model, daily increase in leaf area was augmented as product of increase in dry weight with leaf area ratio (LAR) (Monteith *et al.*, 1989) expressed as

$\Delta LAI = \Delta DM \times LAR$

Where, LAR is leaf area ratio expressed as the ratio of leaf area to dry weight of the plant leaves.

$$LAR = \frac{LAI_t - LAT_{t-1}}{LnLAI_t - LnLAT_{t-1}} \times \frac{LnW_t - LnW_{t-1}}{W_t - W_{t-1}}, \quad \text{...(Eq. 15)}$$

Where, LAI_t and LAI_{t-1} are leaf area at time *t* and *t-1*, and W_t and W_{t-1} are dry weight during the same period, respectively.

(B) Partitioning of assimilates

Partitioning of dry matter or carbon to various plant organs in the plant is facilitated with the use of appropriate partitioning factors varying with plant development in the growing season (Wilkerson *et al.*, 1981; Van Heemest, 1986).

(C) Water use

Monteith *et al.*, (1989) assumed that the amount of dry matter produced per unit of water transpired (q) is inversely proportional to mean saturation deficit (SD) expressed as

q. SD = Constant

The quantity (q) is conservative for most of crops and will have a value around 9 gm kg^{-1} KPa (Monteith, 1989).

$$\text{Therefore } q = \frac{9 \times 10^{-3}}{\overline{SD}} \text{ kg kg}^{-1} \text{ KPa}$$

The demand for water to transpire (T_p) in producing daily dry matter φDM is

$$T_p = \Delta DM.\frac{\overline{SD}}{9 \times 10^{-3}} \quad \text{...(Eq. 16)}$$

It T_p is less than the amount of water which the roots can supply then growth is assumed to be light limited and dry matter or biomass accumulation is computed as

$$\text{If } T_p < \Delta DM.\frac{\overline{SD}}{9 \times 10^{-3}} \quad \text{...(Eq. 17)}$$

$$\Delta DM \geq Tp.\frac{9 \times 10^{-3}}{\overline{SD}} \quad \text{...(Eq. 18)}$$

EPIC model uses Ritchie (1972) model for potential water use (PET) as a fraction of potential evaporation (PE_0) by using leaf area index (LAI) relationship on any *i*th day and expressed as

$$PET = PE_0 \frac{LAI}{3} \quad \text{for } PET \le PE$$
$$0 \le LAI \le 3.0 \qquad \text{...(Eq. 19)}$$
$$= PE_0 \quad \text{for } LAI > 3.0$$

Where PET is predicted plant water evaporation rate (mm/day). Potential soil water evaporation is simulated by considering soil cover according to

$PE_s = \min[PE_0$ ï PET]

Actual soil water evaporation rate is estimated on the basis of root depth as

$$ET = \frac{PET}{1-\exp(-\lambda)}\left\{1-\exp\left\{-\lambda\left(\frac{z}{R_z}\right)\right\}\right\}, \qquad \text{...(Eq. 20)}$$

Where ET is total water used (mm) to depth z(m) on any day, R_z is the root zone depth in m which is simulated as a function of thermal time and potential root zone depth (RDMX) expressed as

$$R_z = 2.5 \frac{RDMX}{TTI} \qquad \text{...(Eq. 21)}$$

The constant 2.5 allows root depth to reach its maximum when TTI reaches 0.4. The parameter λ is a water use distribution parameter.

(D) Yield estimations

In EPIC model harvest index increased non-linearly from zero at planting to maximum value in the form of an expression as (William *et al*., 1989)

$$HI_i = HI_c \left(\sum_{k=1}^{i} TTFH_k\right), \qquad \text{...(Eq. 22)}$$

Where, HI_i is harvest index on day *i* and HI_c is harvest index of crop and TTFH is thermal time factor that affects harvest index.

The influence of stress parameters on harvest index is reflected though growth constraints. Crop yields are reduced through reduction in harvest index caused by water, nutrient and crop management stresses. Most grain crops are very sensitive to water stress at flowering and anthesis when major yield components are determined. Optimum conditions for growth may reduce harvest index slightly where economic yield is limited by sink size. Harvest index is affected by water stress expressed (William *et al.,* 1989) as

$$AHI_i = HI_{i-1} - HI_c \left\{1 - \frac{1}{1+(WSYF_c)(CGS_i)(0.9 - SMS_i)}\right\}$$ ...(Eq. 23)

Where AHI is adjusted harvest index, $WSYF_c$ is a crop parameter representing the sensitivity of harvest index to soil moisture stress for the crop, CGS is a function of crop growth stage and SMS is soil moisture stress factor for day *i*.

Therefore soil water stress influence harvest index between 0.3 to 0.9 of maturity with maximum effect at 0.6. The water stress factor limiting biomass production is in proportion to transpiration reduction. (Hanks, 1983).

Fischer model (1979) determines kernel number as the final outcome of vegetative matter in pre anthesis period. A critical period of 25 days before anthesis and anthesis duration during which the radiation and temperature values influence the kernel number in wheat. Accumulated dry matter at anthesis (DMa) is strongly related to kernel number (KNO) in wheat (Fischer and Kohn, 1966) expressed as

KNO(Cv. Yecora 70) = 4000 + 13 DM_a $R^2 = 0.35$ ...(Eq. 24)

KNO (Heron) = 2360 + DM_a $R^2 = 0.83$ ...(Eq. 25)

(E) Influence of stress factors on yield

(i) Water stress factor: It is ratio of actual daily water used by the crop to the potential water use on the same day. Hanks (1983) proposed moisture stress limits in biomass production in proportion to transpiration reduction are useful and can be linked with the crop model-water use functions.

(ii)Temperature stress: William et al., (1984) proposed plant temperature stress factor (TSF) expressed as

$$TSF = \mathrm{Sin}\left\{\frac{\pi}{2}\left(\frac{T_s - T_b}{T_0 - T_b}\right)\right\} \text{ for } 0 \le TS \le 1$$ ...(Eq. 26)

(iiI) Nutrient stress factor: The N and P stress factors arebased on the ratio of simulated plant N and P contents to the optimal values. Jones (1983) expressed nutrient stress factors as a non-linear term varying from 1.0 at optimal N and P to zero when N or P is half the optimum level. The scaling factor expression (SF) for N stress was expressed as

$$SF = 2\left\{\frac{\sum_{k=1} UN_k}{(ON)(B)}\right\}$$ ...(Eq. 27)

(iv) Aeration stress factor: When soil water content approaches saturation, plants may suffer from aeration stress. Water contents in top 100 cm soil depth is considered for assessing degree of aeration stress expressed as (William et al., 1984)

$$STF = \frac{SWI}{POI} - CAF, \text{ and} \qquad ...(Eq. 28)$$

$$ASF = \frac{STF}{STF + \exp(-1.291 - 56.1\ SAT)} \qquad ...(Eq. 29)$$

Conclusion:

A variety of crop-weather models are developed varying from simple empirical to complex process oriented models. The accuracy with which they can mimic he crop growth depends largely on the input data requirement and spatial attributes. A good data base essential for the development of models that can simulate the system more accurately.

References

Angus, J.F. and Zandstra, H.G. 1980. Climatic factors and the modeling of rice growth and yield. In: Proceedings of Syms on Agrometeorology of Rice Crop. IRRI, Los Banos, p. 189-99.

Baker, D.M., Lambert, J.R. and McKinion, J.M. 1983. GOSSYM: A simulation of cotton crop growth and yield. South Carolina Agril. Expt. Station, Tech. Bull. 1089, Clemson.

Boote, K.J., Jones, J.W., G. Hoogenboom, G.G. Wilkerson, and S.S. Jagtap 1989. PNUTGRO. Peanut crop growth simulation model. Userȏs guide departments of agronomy and agricultural engineering. Univ. of Florida, Gainesville, Florida, p. 1-76.

Curry, R.B., Baker, C.H. and Streeter, J.G. 1975. SOYMODI: A dynamic simulation of soybean growth and development. TSAE ï 18, p. 963-68.

de Wit, C.T. 1982. Simulation of living systems. In: F.W.T. Penning de Vries and H.H. Van Laar (Eds.). Simulation of plant growth and crop production. Simulation monograph series. PUDOC, Wageningen, p. 3-8.

Duncan, W.G. 1975. SIMAIZ: A model simulation growth and yield in corn. In: D.N. Baker, P.G. Creech and F.G. Maxwell (Eds.). An application of system methods to crop production. Miss. Agric. and for. Expt. Stn., Miss. State Univ., Miss., p. 32-48

Hodges, T., Johnson, B.S. and Manrique, L.A. 1989. SUBSTOR. A model of potato growth and development. In: Agronomy abstracts. Amer. Soc. Of Agron., Madison, p.16.

Hoogenboom, G., J.W. White, J.W. Jones and K.J. Boote, 1990. Dry bean crop growth simulation model. Florida Expt. Station., Jour. No. N ï 00379 Univ. of Florida, Gainesville, Florida, p. 1-120.

Jackson, B.S., G.F., Arkin and A.B. Hearn, 1988. The cotton simulation model COTTAM: Fruiting model calibration and testing. Trans. ASAE, 31, p. 846-54.

Jones, C.A., Wegener, M.K., Russell, J.S., McLeod, I.M., and Williams J.R. 1989a AUSCANE. Simulation of Australian sugarcane with EPIC. CSIRO, Division of Tropical crops and pastures, Tech. Paper no. 29.

Kiniry, J.R., J.R. Williams, P.W. Gassman, and P. Debaeke 1992. A General process oriented model for two completing plant species. ALMNC 2. Texas A & M ï BRC Report, p. 1-34.

Monteith, J.L., A.K.S. Huda and D. Midya 1989. Modelling sorghum and pearl millet. ICRISAT, Bulletin no. 12, p. 30-39

Ng, E. and Loomis, R.S. 1984. Simulation of growth and yield of potato crop. Simulation monograph series. PUDOC, wageningen.

Retta, A. and Hanks, R.J. 1980. Manual for using PLANTGRO. Utah Agr. Exp. Stn., Res. Rep. No. 46, Logan, Utah, USA, p. 1-14.

Ritchie, J.T. and G. Algaswamy 1989. Physiology of sorghum and pearl millet. In: Modelling of the growth and development of sorghum and pearl millet. Res. Bull. No. 12, ICRISAT, India, P. 24-29.

Ritchie, J.T., Alocilja, E.C., Singh, U., and Uchara, G. 1986. CERES ï Rice Model. In: Proc.in workshop on Impact of Weather Parameters on Growth and Yield of Rice IRRI, Los Banos.

Ritchie, J.T., Godwin, D.C., and Otter ï Nacke, S. 1985. CERES ï Wheat. A simulation model of wheat growth and development. Texas A & M Univ. Press College Station.

Shawcroft, R.W., Lemon, E.R., Allen, L.H. Stewart, D.W., and S.E. Jensen 1974. The soil-plant atmosphere model and some of its predictions. Agril. Meteorology, 14(1/2), p. 287-307.

Stapper, M. 1984. SIMTAG. A simulation model of wheat genotypes. Univ. of New England, Dept. of Agron & Soil Science, Armidale.

Stapper, M. and G.F. Arkin 1980. CORNF: A dynamic growth and development model for maize (Zea mays L.) Texas A & M, BRC, documentation no. 80-82, p. 1-83

Van Keulen and Seligman, N.G. 1987. Simulation of water use, nitrogen nutritio, and growth of a spring wheat crop. PUDOC. Wageningen.

Wilkerson, G.G., Jones, J.w., Boote, K.J., and Mishoe, J.W. 1985. SOYGRO. Soybean crop growth and yield model. Tech. Documentation, Univ. of Florida, Gainesville, p. 1-253.

Williams, J.R., C.A. Jones and P.T. Dyke 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE. 27(1), p. 129-144.

Table 1: Crop growth simulation models for different crop/processes

Model Name	Crop	Processes involved	Reference
CERES-Sorghum	Sorghum	Growth and development, grain yield	Ritchie and Alagarswamy (1988)
RESCAP	Sorghum	Dry matter, water use, grain yield, radiation interception	Monteith *et al.,* (1989)
RESCAP	Pearl Millet	Dry matter accumulation, water use, grain yield	Monteith *et al.,* (1989)
SIMAIZ	Maize	Growth, grain yield	Duncan (1975)
CERES-Maize	Maize	Growth and development, grain yield	Stapper and Arkin (1980)
COTTAM	Cotton	Growth, development, soil water budget, morphology	Jackson *et al.* (1988)
GOSSYM	Cotton	Growth, yield	Baker *et al.* (1983)
SUBSTOR	Potato	Growth, development, yield	Hodges *et al.* (1989)
IRRIMOD	Rice	Growth, development, yield	Angus and Zandstra (1980)
CERES-Rice	Rice	Growth, yield, phenology	Ritchie *et al.* (1986)
AUSCANE	Sugarcane	Growth, development, cane yield	Jones *et al.* (1989)
SOYGRO	Soybean	Vegetative, reproductive, grain yield, phenology	Wilkerson *et al.* (1985)
SOYMOD	Soybean	Growth, development, yield	Curry *et al*. (1975)
BEANGRO	Dry bean	Growth, development, phenology, grain yield	Hoogenboom *et al.* (1990)
PNUTGRO	Peanut	Growth, development, phenology, yield	Boote *et al.* (1989)
POTATO	Potato	Growth, yield	Loomis (1984)
SIMTAG	Wheat	Genotypes growth and development, grain yield	Stapper (1984)

CERES-Wheat	Wheat	Growth, development, grain yield	Ritchie *et al.* (1985)
	Wheat	Water use, nitrogen nutrition, growth, grain yield	Van Keulen and Seligman, (1987)
	Any living systems	Plant growth and crop production	de Wit (1982)
EPIC	Any crop and cropping	Soil productivity, erosion, plant growth processes, yield	William *et al.* (1984)
SPAW	Any crop	Plant environment interaction, microclimate, dry matter, grain	Shawcroft *et al.* (1974)
ALMANAC	Crop-weed competitions	Crop-weed competition	Kiniry *et al.* (1992)
PLANTGRO	Any crop	Evapotranspiration and grain yield	Retta and Hanks (1980)

Climate Change Research in India : Past, Present and Future

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Introduction

Climate change impacts on agriculture are being witnessed all over the world, but countries like India are more vulnerable in view of the high population depending on agriculture and excessive pressure on natural resources. The warming trend in India over the past 100 years (1901 to 2007) was observed to be 0.51^0 C with accelerated warming of 0.21^oC per every10 years since 1970 (Krishna Kumar 2009). The projected impacts are likely to further aggravate yield fluctuations of many crops with impact on food security and prices. Climate change impacts are likely to vary in different parts of the country. Parts of western Rajasthan, Southern Gujarat, Madhya Pradesh, Maharashtra, Northern Karnataka, Northern Andhra Pradesh, and Southern Bihar are likely to be more vulnerable in terms of extreme events (Mall *et al.* 2006).

Rainfall and Temperature Trends

Rainfall is the key variable influencing crop productivity in rainfed farming. Intermittent and prolonged droughts are a major cause of yield reduction in most crops. Long term data for India indicates that rainfed areas witness 3-4 drought years in every 10-year period. However, no definite trend is seen on the frequency of droughts as a result of climate change so far. For any R&D and policy initiatives, it is important to know the spatial distribution of drought events in the country. A long term analysis of rainfall trends in India (1901 to 2004) using Mann Kendall test of significance by CRIDA indicate significant increase in rainfall trends in West Bengal, Central India, coastal regions, south western Andhra Pradesh and central Tamil Nadu. Significant decreasing trend was observed in central part of Jammu Kashmir, Northern MP, Central and western part of UP, northern and central part of Chattisgarh. Analysis of number of rainy days based on the IMD grid data from 1957 to 2007 showed declining trends in Chattisgarh, Madhya Pradesh, and Jammu Kashmir. In Chattisgarh and eastern Madhya Pradesh, both rainfall and number of rainy days are declining which is a cause of concern as this is a rainfed rice production system supporting large tribal population who have poor coping capabilities.

Due to increase in CO_2 levels the earth is warming up. In the last 15-20 years, there has been a sharp rise in the global temperature. While there are varying projections of temporal variations in temperature, there is a near unanimity in its direction and trend (Figure 1). In India too, the overall mean temperature is showing an increasing trend in most parts of the country. The central and western parts showed decreasing trend in maximum temperature while increasing trend of minimum temperature was observed in east, north & southern parts. Until last year, 2009 was the warmest year on record since 1901 (+0.913o C above the normal of 24.64oC) and now 2010 has surpassed it (+0.93oC). The other warmer years on record in order are 2002(0.708), 2006(0.6), 2003(0.560), 2007(0.553), 2004(0.515), 1998(0.514), 1941(0.448), 1999 (0.445), 1958(0.435), 2001(0.429), 1987(0.413) and 2005(0.410).

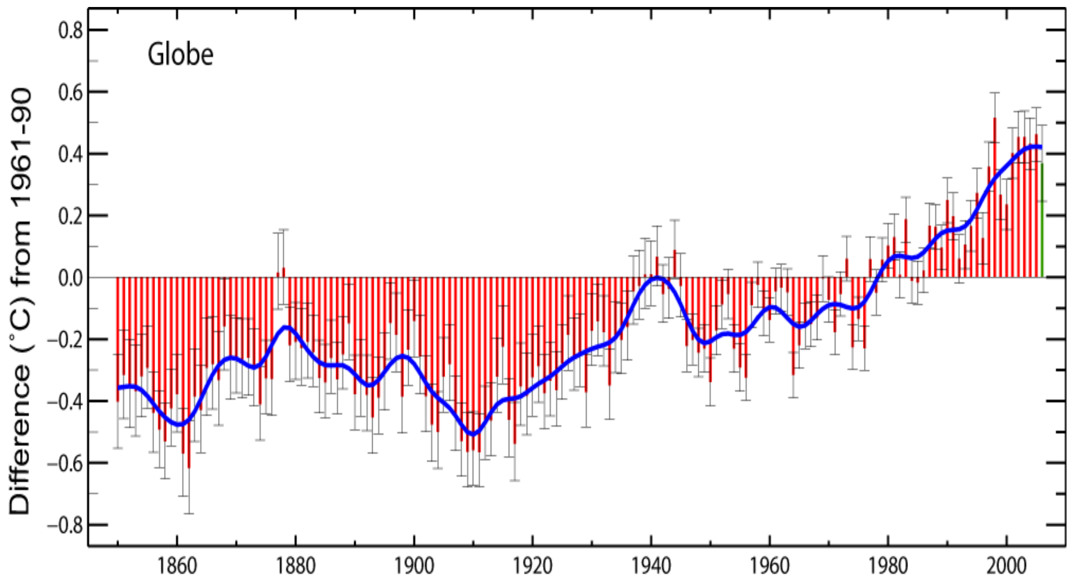

Fig.1 Changes in global temperature trends over the last century

As far as Indian agriculture is concerned, temperature rise during rabi is of more significance. For minimum temperatures, most of the locations in India are showing an increasing trend. This is a cause of concern for agriculture as increased night temperatures accelerate respiration, hasten crop maturity and reduce yields. The increasing trend is more evident in central and eastern zones where rainfall is also showing a declining trend which makes this area more vulnerable and requiring high attention for adaptation research.

Impact on agriculture, livestock and fisheries

The impact of climate change on agriculture may accentuate at regional level creating more vulnerability in food security rather than global level as a whole. The potential impact will be shifts in sowing time and length of growing seasons, which may necessitate adjustment in sowing and harvesting dates, change in genetic traits of cultivars and sometimes total adjustment of cropping system itself. With warmer environment associated with erratic rainfall distribution the rate of evapotranspiration will increase and quick depletion of soil nutrient reservoir would call for much greater efficiency in use of water and nutrients to sustain crop productivity. Apart from these, tackling with frequent and more intense extreme events like heat and cold waves, droughts and floods may become norm of the day for common farming community (IPCC, 2001). Such phenomena will impact agriculture considerably through their direct and indirect effects on crops, livestock, and incidences of pest-disease-weeds, increasing deterioration of soil health in totality and thereby threatening the food security like never before.

Crop production

The Indian Council of Agricultural Research (ICAR) initiated an all India Network project in 2004 to study the possible impacts of climate change on major crops, livestock, fisheries, soils and other biotic factors as well as to understand natural adaptation capabilities of both flora and fauna. The possible interventions to increase the adaptability of crop-livestock systems and mitigation measures to minimize the adverse impacts were studied across different agro-ecosystems of India. The output of the studies (Aggarwal, 2009) so far indicated that a marginal 1 ^{0}C increase in atmospheric temperature along with increase in CO_2 concentration would cause very minimal reduction in wheat production in India if simple adaptation strategies like adjustment of planting date and varieties are adopted uniformly. But in absence of any adaptive mechanism, the yield loss in wheat may go up to 6 million tones. A further rise by 5 ^{0}C may cause loss of wheat production up to 27.5 million tones. Similarly, rice yields may decline by 6% for every one degree increase in temperature (Saseendran *et al.* 2000). In addition to direct effects on crops, climate change is likely to impact natural resources like soil and water. Increased rainfall intensity in some regions would cause more soil erosion leading to land degradation. The study on wheat and rice suggested that high temperature around flowering reduced fertility of pollen grains as well as pollen germination on stigma. These effects are more pronounced in *Basmati* rice as well as *Durum* wheat cultivars. A positive finding of the study was that the *Aestivum* wheat cultivars are more or less tolerant to such adverse affects. But differential impact of increasing temperature is observed with respect to grain quality of wheat where it is found that *Aestivum* wheat cultivars are more prone to reduced grain quality due to increasing temperature during the fruit setting stage than *Durum* cultivars.

Field experiments using advanced óTemperature gradient tunnelsô with different dates of sowing to study impact of rising temperature on growth and development of different crops revealed that an increase of temperature from 1 to 4 ^{0}C reduced the grain yield of rice (0-49%), potato (5-40%), green gram (13-30%) and soybean (11-36%). However, one of the important pulse, chickpea, registered 7-25% increase in grain yield by an increase in temperature up to 3 ^{0}C, but was reduced by 13% with further 1 ^{0}C rise in temperature.

Horticulture

A significant decrease in average productivity of apples in Kullu and Simla districts of Himachal Pradesh have been reported which is attributed mainly to inadequate chilling required for fruit setting and development. Reduction in cumulative chill units of coldest months might have caused shift of apple belt to higher elevations of Lahaul-Spitti and upper reaches of Kinnaur districts of Himachal Pradesh. However results from simulation models suggest that climate change could benefit coconut crop. Coconut yields are likely to increase by 4, 10, and 20% by 2020, 2050 and 2080, respectively, in the western coastal areas of Kerala, Maharastra, Tamil Nadu and Karnataka. But the impact may be negative in east coast areas as they are already facing a much warmer atmospheric thermal regime than western coast.

Insect and pest dynamics

The impact of rising temperature and CO_2 are also likely to change insect pest dynamics. Dilution of critical nutrients in crop foliage may result in increased herbivory of insects. For example, Tobacco caterpillar (*Spodoptera litura*) consumed 39% more castor foliage under elevated CO_2 conditions than controlled treatments (Srinivasa Rao *et al*. 2009). The advancement of breeding season of major Indian carps as early as March has been reported from West Bengal which is extended from 110 to 120 days due to increase in environmental temperature, which stimulates the endocrine glands of fish and helps in the maturation of the gonads. This brings about a possibility to breed these fishes twice a year at an interval of 30 to 60 days. Increased heat stress associated with rising temperature may, however, cause distress to dairy animals and possibly impact milk production. A rise of 2 to 6 ^{0}C in temperature due to climate change is expected to negatively impact growth, puberty and maturation of crossbred cattle and buffaloes. As of now, India losses 1.8 million tones of milk production annually due to climatic stresses in different parts of the country. The low producing indigenous cattle are found to have high level of tolerance to these adverse impacts than high yielding crossbred cattle.

Soil and water resources

Besides, the nutrient loss from soil through high rate of mineralization and CO_2 emissions from soil could be accelerated as a result of increase in temperature. Low carbon soils of mainly dryland areas of India are likely to emit more CO_2 compared to high or medium carbon temperate region soils. Simulation of water balance using Global and Regional Climate Models revealed likely increase in annual as well as seasonal stream-flows of many Indian river basins pointing to the need for adoption of more effective runoff and soil loss control measures to sustain crop production across the country. At the farm level increased temperatures will also increase crop water requirement. A study carried out by CRIDA (unpublished) on the major crop growing districts in the country for four crops, viz., groundnut, mustard, wheat and maize indicated a 3% increase in crop water requirement by 2020 and 7% by 2050 across all the crops/locations. The increase in water requirement for major crops like maize, cotton and groundnut in different agroclimatological zones of AP by 2020 is given Table 1. The crop duration is also likely to be reduced by 1-2 weeks.

Table 1. Crop water requirements to rise: crop duration to decrease (eg. AP in India)

Station	Crop	Increase in water requirement in mm (2020-2025)	Reduction in crop duration (weeks)
Anankapalli	Maize Groundnut	51.7 61.3	1 1
Anantapur	Groundnut Redgram	70.1 174.3	1 1
Jagityal	Cotton Maize	60.5 49.0	2 1
Rajendranagar	Red gram Groundnut	114.5 73.0	2 1
Tirupathi	Groundnut	73.0	1

(Source : NPCC, CRIDA, 2007)

Managing Weather Risks in Agriculture

A comprehensive strategy of utilization of existing knowledge, strengthening R&D in key areas and evolving a policy frame work that builds on risk management and providing incentives to sustainable use of natural resources will be required for successful adaptation by farm sector to climate. The goal of this strategy is to minimize as risks associated with farming and enable farms to cope with these risks (Singh *et al.*, 2009).

Technology options

Small changes in climatic parameters can often be managed reasonably well, by altering dates of planting, spacing, input management, new cultivars adapted to drier conditions, salt water resistant varieties of crops in the areas where drainage is poor development of irrigated agriculture and farming systems like mixed cropping, crop-livestock and that are more adapted to changed environment can further ease the pressure. In addition to these, improving technology to increase production in climate favourable sites in order to offset uncertain production in marginal areas, better adaptation of agricultural calendar, crop diversification to spread risks and setting up processing and storage facilities.

World over, crop diversification is regarded as the most common and effective risk management strategy that is employed by farm households. Multiple cropping system is another strategy that even if a particular crop does not do well, the loss will be compensated by gains in another crop. Optimum use of fertilizers and ecologically clean agro technologies would be another risk management strategy. There are some limitations of this strategies however. First, diversification is clearly a feasible strategy to the extent that crop risks are independent, however, if returns are strongly correlated across crops, the risks facing farmers are similar to systemic risks and crop diversification will not be effective in reducing producer risk. Second, crop diversification calls for spreading resources across crops even when a particular crop offers higher average net returns than other crops. Therefore, the price of diversification is the income foregone, on average, by not growing the remunerative crop. Third, if there are fixed costs in the cultivation of a particular crop, then there is a minimum efficient scale and that may conflict with the requirements of crop diversification. Farmers with smallholdings are likely to run into this constraint. The major impact of climate change in arid and semi-arid regions is likely to be an acute shortage of water resources associated with significant increases in surface air temperature. Some of the management strategies in semi-arid and arid region are as follows:

Semi-arid regions:

1. Shift to drought tolerant cultivars
2. Enhancement and maintenance of soil fertility and protection of soils from degradation
3. Development of complementary irrigation
4. Development of early warning system on drought and other climate induced natural disasters
5. Implementing crop livestock integration
6. Implementing agroforestry systems

Arid regions:

1. Shifting from agriculture to other less climate sensitive activities (Livestock, Agroforestry)
2. Use of short duration varieties
3. Optimize planting dates

Policy Options

Apart from the use of technological advances to combat climate change, there has to be sound and supportive policy framework. The frame work should address the issues of redesigning social sector with focus on vulnerable areas/ populations, introduction of new credit instruments with deferred repayment liabilities during extreme weather events, weather insurance as a major vehicle to risk transfer. Governmental initiatives should be undertaken to identify and prioritize adaptation options in key sectors (storm warning systems, water storage and diversion, health planning and infrastructure needs). Focus on integrating national development policies into a sustainable development framework that complements adaptation should accompany technological adaptation methods.

In addition, the role of local institutions in strengthening capacities e.g., SHGs, banks and agricultural credit societies should be promoted. Role of community institutions and private sector in relation to agriculture should be a matter of policy concern. There should be political will to implement economic diversification in terms of risk spreading, diverse livelihood strategies, migrations and financial mechanisms. Policy initiatives in relation to access to banking, micro-credit/insurance services before, during and after a disaster event, access to communication and information services is imperative in the envisaged climate change scenario. Some of the key policy initiatives that are to be considered are: Mainstreaming adaptations by considering impacts in all major development initiatives Facilitate greater adoption of scientific and economic pricing policies, especially for water, land, energy and other natural resources. Consider financial incentives and package for improved land management and explore CDM benefits for mitigation strategies. Establish a ñGreen Research Fundò for strengthening research on adaption, mitigation and impact assessment. (Venkateswarlu and Shanker 2009).

Globally, weather insurance plays an important role in mitigating climatic risks. In several developed countries this strategy has worked successfully as these countries have excellent long term weather data, farmers have large holding and have a business approach for farming. In India, the small holders are generally more prone to risks but they are averse to buy insurance policies. The crop insurance scheme has made some progress but it is a long way to go. Considering the climate trends being witnessed in recent years all over the country, weather based insurance appears to be a better alternative for mitigating risks in agriculture for Indian farmers. The research institutes and insurance companies jointly should develop crop wise data on the weather sensitivity so that appropriate policies can be designed which are friendly to farmers, at the same time keep the insurance companies viable. The Government also should share the premium burden. Instead of spending huge amounts of money on rehabilitation after the disaster, it is prudent to spend on premium subsidy.

Finally, there is a need to make climate change adaptation and mitigation measures as an integral part of overall planning and development strategy of the country on long term. (Venkateswarlu and Shanker, 2009).

References

Agarwal, P.K. 2009. Global Climate change and Indian agriculture; Case studies from ICAR network project. Indian Council of Agricultural Research. 148p.

IPCC. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group ï I to the Third Assessment Report of the IPCC. [Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (Eds)]. Cambridge University Press, United Kingdom and New York, USA, 94p.

Krishna Kumar. 2009. Impact of climate change on Indiaøs monsoon climate and development of high resolution climate change scenarios for India. Presented at MoEF, New Delhi on October 14, 2009 (http: moef.nic.in)

Mall, R. K., Gupta, A., Singh, R., Singh, R.S. and Rathore, L. S. 2006a. Water resources and climate change: An Indian perspective. *Current Science*. 90 (12): 1610-1626.

NPCC, 2007. Consolidated Annuall Report 2004-2007. Network Project on Climate Change, Central Research Institute for Dryland Agriculture, Hyderabad, 317p.

Saseendran, A.S.K., Singh, K.K., Rathore, L.S., Singh, S.V. and Sinha, S.K. 2000. Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climate Change*. 44: 495-514

Singh, A. K., Aggarwal, P. K., Gogoi, A. K., Rao, G. G. S. N. and Ramakrishna, Y. S. (2009). Global Climate Change and Indian Agriculture: Future priorities. *In*: Global Climate Change and Indian Agriculture: Case studies from the ICAR Network Project (Ed. Aggarwal, P. K.), ICAR, New Delhi. 146-148

Srinivasa Rao, Ch., Ravindra Chary, G., Venkateswarlu, B., Vittal, K.P.R., Prasad, J.V.N.S., Sumanta Kundu, Singh, S.R., Gajanan, G.N., Sharma, R.A., Deshpande, A.N., Patel, J.J. and Venkateswarlu, B. and Arun K. Shanker. 2009. Climate change and agriculture: Adaptation andmitigation strategies. *Indian Journal of Agronomy*. 54(2): 226-230

World Bank. 2008. Climate change impacts in drought and flood affected areas: Case studies in India. *Report No.43946-IN*, South East Asia Regional Office, New Delhi.

Agrometeorological instruments and data collection

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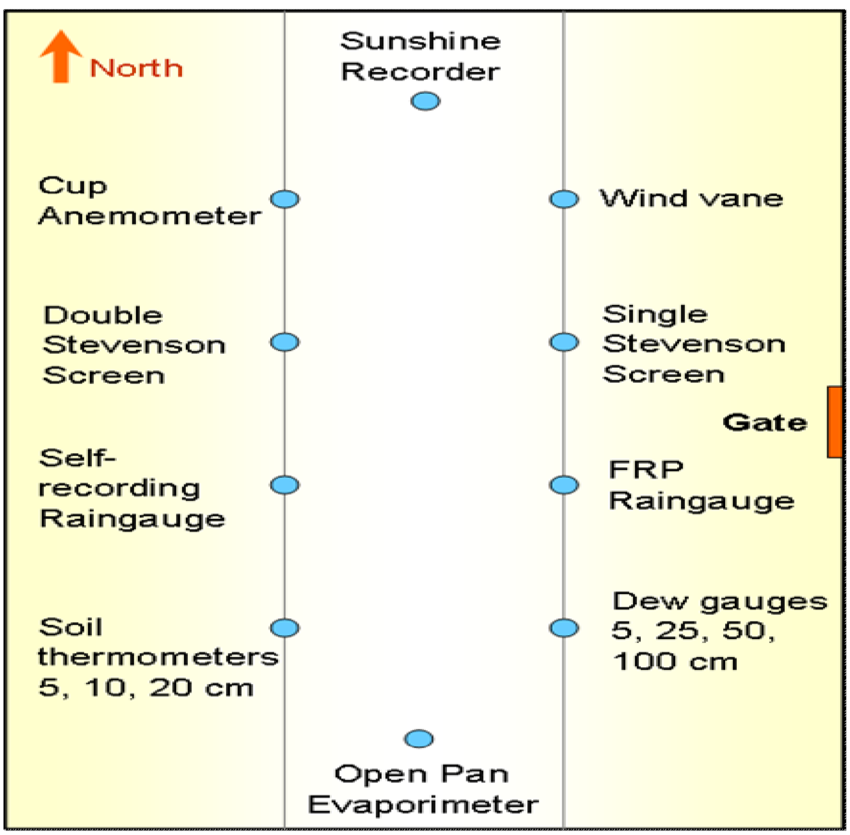
Introduction

Agroclimatic analysis and characterization of watersheds is carried out based on the long-period weather data. To assess the impacts of interventions made during the development phase, weather needs to be monitored by establishing a manual agromet station or by installing an automatic weather station (AWS). Manual agromet station is to be established by following the standard procedures prescribed by the India Meteorological Department (IMD) and the observer or the volunteer has to be properly trained in recording the data and maintaining the instruments.

Layout of agrometeorological observatory



The site for the agromet observatory at the watershed is to be selected is such a way that it represents the general climatic conditions of the area. The site should not be on the top of a hill or at the bottom of a valley. No tall tress or buildings should be near the observatory which will affect the wind flow and exposure to sunshine. As per the IMD, a site with dimensions of 55 m in the N-S direction and 36 m in the E-W is required for a class-A type observatory. A site having 25 x 15 m area is sufficient for a class-B observatory. Class-A observatory will have all the manual / eye-reading and automatic instruments, while class-B will have only manual reading instruments.

The IMD has prescribed the specifications for all the agrometeorological instruments and these can be procured from various supplying firms in the country. Once procured, these instruments are to be installed as per the standard lay-out. The observatory should be protected with a barbed wire fence and suitable gate with locking arrangements is to be provided.

Basic weather parameters useful for agricultural research purpose are maximum temperature, minimum temperature, soil temperatures at different depths, relative humidity (morning), relative humidity (afternoon), wind speed, wind direction, rainfall, soil moisture at different depths, evaporation, sunshine and dew at different heights. Air temperatures are measured by four thermometers installed in a single Stevenson screen. These are dry bulb, wet bulb, maximum and minimum thermometers. Relative humidity is computed from the dry bulb and wet bulb temperatures using hygrometric tables. Soil temperatures are generally measured at soil depths 5, 10 and 20 cm. Rainfall is manually measured from an ordinary raingauge (also called FRP raingauge). Wind speed is measured by a cup anemometer and wind direction by wind vane. Evaporation is measured by an open pan evaporimeter and hours of bright sunshine by a sunshine recorder. Duvdevani dew gauges are used to measure dew at different heights. Soil moisture is measured using gravimetric method, neutron-probe equipment, tensiometers or time domain reflectometers.

Times of observation

Air temperature, soil temperature, relative humidity, wind speed and wind direction are recorded everyday at 07:00 h and 14:00 h Local Mean Time (LMT). These are the normal times of minimum and maximum temperature conditions. Rainfall and evaporation are observed at 08:30 h Indian Standard Time (IST) and 14:00 h LMT. Depending on the longitude of the watershed location the time in IST corresponding to the time in the LMT can be computed. Soil moisture is observed at specific intervals based on experimental requirement. Dew is recorded just before sunrise and sunshine card is changed for exposure everyday morning before sunrise or after sunset for estimating bright sunshine hours in a day.

Proper protection against theft and damage is to be ensured for the instruments. Weather data monitored at the watersheds need to be quality checked and datasets developed.

Quality checking and database development

Quality of agromet data is essential for proper understanding the weather of the watershed and for later computing the derived parameters for interpretation. Instruments in the observatory are to be inspected by authorized personnel once in every year by comparing with standard equipment and identifying the calibration errors and calibration drifts if any. Meteorological observer needs to be trained in following the times of observations, maintaining of instruments, recording the measurements with sincerity and keeping the data forms and books. Agromet data once collected needs to be entered in to a computer in the form of an MS-Excel file or a MS-Word file. Agromet Databases can be developed using the data of one watershed or multiple watersheds using software like MS-Access with the help of professional software developers. While developing databases, crop and soil data may also be considered for inclusion. Suitable data retrieval programmes and software for computing derived weather parameters like reference crop evapotranspiration, water surplus, water deficit and various agroclimatic indices are to be developed along with the databases.

Automatic Weather Station

Automatic Weather Station (AWS) is a system to record the changes in the weather continuously without any human intervention. The AWS consists of a datalogger, set of sensors, power supply, solar panel, mounting stand and other accessories. The AWS should be located in such a place that it represents the general agroclimatic conditions of the watershed area. Datalogger program should be optimized for power and memory usage and checked thoroughly for any programming bugs. Depending on the manufacturer and model, the cost of the AWS can vary between 1.0-4.5 lakh Rupees. While choosing the model of the AWS, budget will obviously be one important factor, but there are other key considerations like sensor quality, communication and data transfer facility, data storage capacity and battery back-up time. A balance between cost and these is required. Proper protection against theft and damage is to be ensured.

Benefits of AWS:

- AW Stations can run for weeks and months without attention. Weather can be easily read direct from the console display or monitored from faraway places using wired or wireless modem, mobile phone or satellite communication.
- AW Stations automatically record maximum and minimum values for all weather elements through each day and also keep track of total daily, monthly and yearly rainfall. Routine daily maintenance like setting of maximum and minimum thermometers, emptying the raingauge, change of sunshine card etc., are not required.
- Much greater within-the-day details are available, like complete pattern of wind speed & direction.

- Derived parameters like degree days, reference crop evapotranspiration can be automatically computed using specific software.

Agromet Database Management

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Reliable and long-term agroclimatic data are needed for undertaking climatic analyses, particularly those aiming to assess climate variability and change and their impact on agricultural production. Data on crops, varieties, and production at district-level for several years is needed to understand the variations in agricultural productivity and changes in the cropping patterns at the region. Data on crop morphology, phenology and yield characters obtained from the various field experiments conducted by the State Agricultural Universities and ICAR Institutes in the country, when made available at one location and provided easy access, will be of great use to quantify crop -weather relationships and validating the crop-growth simulation models. Use of meteorological instruments and dedicated meteorological observers and organizations in country have paved the way for the availability of a very long-period weather data in India. With the availability of electronic computer systems, database management has become a reality.

"Database is a collection of non-redundant data, sharable between different application programs"

Conventional method:

The conventional method of handling data is to store it in a *file.* User requires application programs to manipulate the data stored in files.

> **Example:** Agromet Department in a State Agricultural University contains data on different weather parameters as recorded at the various research stations under the SAU.

Database management following conventional method requires application programs or software to:

- Add new stations and related data
- Calculate means, sums etc. on weekly and monthly basis
- Compute derived parameters and indices
- Generate various reports

These application programs are developed according to the needs of the user. New programs are to be added to the system as need arises. New files with different record format may have to be added after some time. New programs have to be developed or existing programs updated to manipulate the data in the new files. Thus, as the time goes by, more files and more application programs are created. In file management system, data declarations and executable statements are all part of the application program, while the actual data is in a file. If any changes are made in data file structure, all the application programs that use this particular data file need modifications. Any program that does not reflect this change will suffer ñ**Data Inconsistency**ò.

Some other disadvantages of this scheme are:

- Files may have more redundant data
- Data stored in such files may not be secure

Therefore, we can conclude that this method of handling data is not suitable and we need a system specifically for managing a database i.e., Database Management System.

Data Base Management System

A database management system (DBMS) is a set of application programs that acts as a layer between the physical database and its users. All the requests from users for access to the database are handled by the DBMS. One general function provided by the DBMS is shielding database design details to users.

Features of DBMS:

1. Data Independence:

A database management system with its catalog facility helps to achieve application programs ñData Independenceò. It also provides for a centralized management and control of data avoiding the ñData Inconsistencyò that is faced in conventional file system. This also allows sharing of data, thus avoiding data redundancy.

2. Data Integrity:

DBMS overcomes the problem of data inconsistency by providing integrity constraints with data definition.

3. Data Representation:

DBMS provides conceptual representation of data, which frees users from the details of how data is stored.

4. Data Security:

DBMS ensures security of data by providing different security and access levels to different types of users. Therefore rights of users on database can be controlled effectively.

5. Data Concurrency:

DBMS takes care of multi-user issues by providing powerful locking mechanisms. It places automatic locks on database and records when any operation that affects the data takes place. These prevent updating of record or field by more than one user at a time in a multi-user environment.

6. Data Sub language:

DBMS provides DDL (Data Definition Language), DCL (Data Control Language) and DML (Data Manipulation Language), which allow defining data structure, data control and easy retrieval / updating of data.

Data Models Supported by DBMS

Three most popular data models are:

- Hierarchical Model
- Network Model
- Relational Model

Hierarchical Model:

IBM has developed the Hierarchical Model database management system in 1968, also known as Information Management System (IMS). A Hierarchical Model is a simple parent-child structure or tree structure; each child can have only one parent. The data is represented as a collection of trees. Data items are grouped into logical records.

Network Model:

The Network Model was designed as an improvement over hierarchical model. Here multiple parent-child relationships are allowed. This reduces data redundancy and provides easy access to information. It consists of a database of records where each record has a pointer to the record preceding or following record.

Relational Model:

The Relational Model eliminates explicit parent-child relationships. There are no pointers maintained and records are logically connected by key values. Hierarchical and network models deal with one record at a time while relational model reads and writes data in units of a set of records. In this model, data is organized in the form of tables comprising rows and columns. Any row is identified by a column or set of columns that form a primary key. Dr. E.F. Codd of IBM has proposed the relational model in 1985. He presented 12 rules that a database must obey if it is to be considered as truly relational.

Codd's Twelve Rules:

1. Information Representation at the logical level.
2. Guaranteed Access
3. Systematic treatment of Null values
4. Dynamic catalog based on relational model
5. Comprehensive data sub-language
6. View updating
7. High-level update, insert, delete
8. Physical Data Independence
9. Logical Data Independence
10. Integrity Independence
11. Distribution Independence
12. Non-Subversion Rule

No currently available relational DBMS fully satisfies all twelve of Coddôs rules. But it has become a common practice to compile óscore-cardô for commercial relational DBMS products to show how well they satisfy each of the rules.

Concepts of Relational Model:

The relational DBMS takes its concepts from Relational Algebra.

In a relational literature, tables are considered as relations, rows are termed as tuples and columns as attributes. The equivalent terms used by different people are

Relational Model	**Programmer**	**User**
Relation	File	Table
Tuple	Record	Row
Attribute	Field	Column

A domain is a pool of values from which the actual values appearing in given column are drawn. The relational model provides a relational language, called SQL (Structured Query Language).

To summarize, Agromet database management system includes:

- Data acquisition, entry, storage and archiving
- Data quality control

- Designing an appropriate Agroclimate database management system with a scope for scalability
- Computer hardware and software
- Data access and application software development
- Data administration and monitoring
- Policy on data sharing

Applications of the Agromet database management include:

- Climate change assessment and impact studies
- Crop weather modelling
- Developing strategies for sustainable agricultural production
- Urban and tourism development
- Coastal zone management
- Resource characterization and research prioritization

General guidelines regarding agrometeorological observations:

Observations should be taken in as little time as possible (to avoid vitiation due to presence of the observer). Punctuality is a matter of prime importance in recording the observations. Faithful recording is important and every observation should be recorded as faithfully as read. Each observation must be written down in the meteorological register immediately after it is taken. Each observation must be checked after it is noted down in the meteorological register to make sure that no mistake has been made. The observatory surroundings need to be maintained in such a way that there are no tall buildings or trees nearby which may affect the weather measurements. The positions of the instruments must never be changed.

Important agromet data entry forms of the IMD are:

1. CWS 1 MET-1 (AGRI)-1 - Agromet observations
2. CWS 2 MET-1 (AGRI)-2 - Micrometeorological observations
3. MET-T-149 - Hours of bright sunshine observations
4. MET-1 (AGRI)-56 - Pocket Register for agromet observations
5. MET-1 (AGRI)-65, CWS-27 (a) - Dew observations
6. MET-1 (AGRI)-66, CWS-27 (b) - Dew observations

Benefits of automated measurements are:

- AW Stations can run for weeks and months without attention. Weather can be monitored from indoors; data can also be easily read direct from the console display. Detailed weather conditions may be viewed at any distance from the station itself, for example over the Internet.

- Routine daily maintenance like setting of maximum and minimum thermometers, emptying the raingauge, change of sunshine card etc., are not required.

- AW Stations automatically record maximum and minimum values for all weather elements through each day and keep track of total daily, monthly and yearly rainfall.

- Much greater within-the-day details are available, like complete pattern of wind speed & direction.

- Derived parameters like degree days, reference crop evapotranspiration can be computed using specific software

Choosing and setting up of AWS

While choosing, budget will obviously be one important factor, but there are other key considerations like:

- Which sensors? Recording of the basic meteorological parameters is the minimum requirement. However, very often, value of the meteorological observations is increasingly appreciated after the station is installed. More and more parameters are required to be monitored and hence, planning initially (by choosing a suitable datalogger) for having the option of adding more sensors later will help. Measurement of UV intensity, leaf wetness and soil moisture may become very relevant in the near future.

- Sensor sensitivity is an important factor, however a balance between accuracy, cost and data application is required.

- Communication and data transfer mechanisms, special data handling requirements like a live weather reporting website on Internet.

- Memory requirements of the datalogger in case of long-period unattended operation to be worked out. Other important factors are the availability of matching software for data download, export to various other software applications like spreadsheets or databases, automated graphical display of parameters, computation of derived parameters like PET and indices for pest and disease forecasting.

- The AWS should be located in such a place that it represents the general agroclimatic conditions of the area. Height of the sensors and other exposure criteria are similar to that of a manual observatory, such that the data generated from the AWS is comparable and reliable to that generated from a manual observatory. The AWS is to be installed initially near a manual observatory and the data compared for a few days and then only is shifted to the proposed location.

- Datalogger program should be optimised for power and memory usage and checked thoroughly for any bugs.

- Proper protection against theft and damage is to be ensured.

Crop simulation models in agricultural research and management: steps

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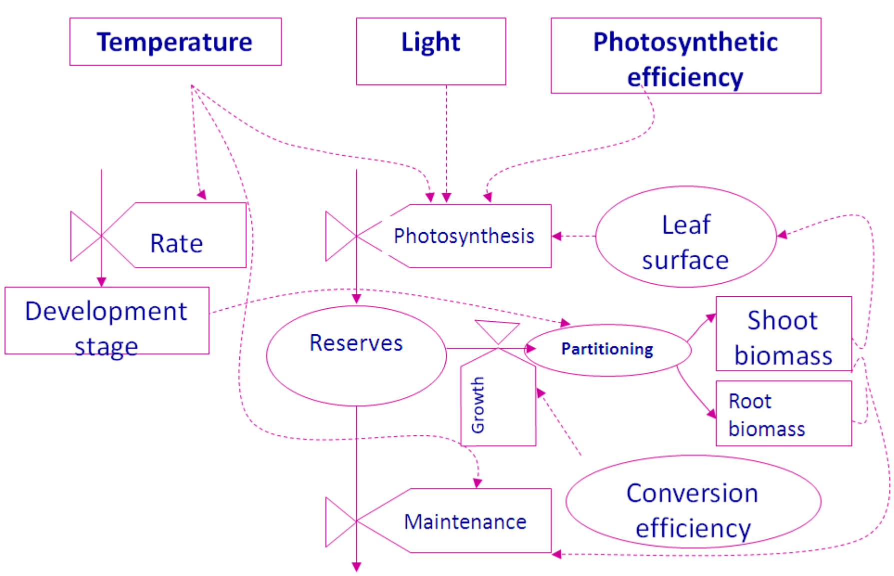
Introduction

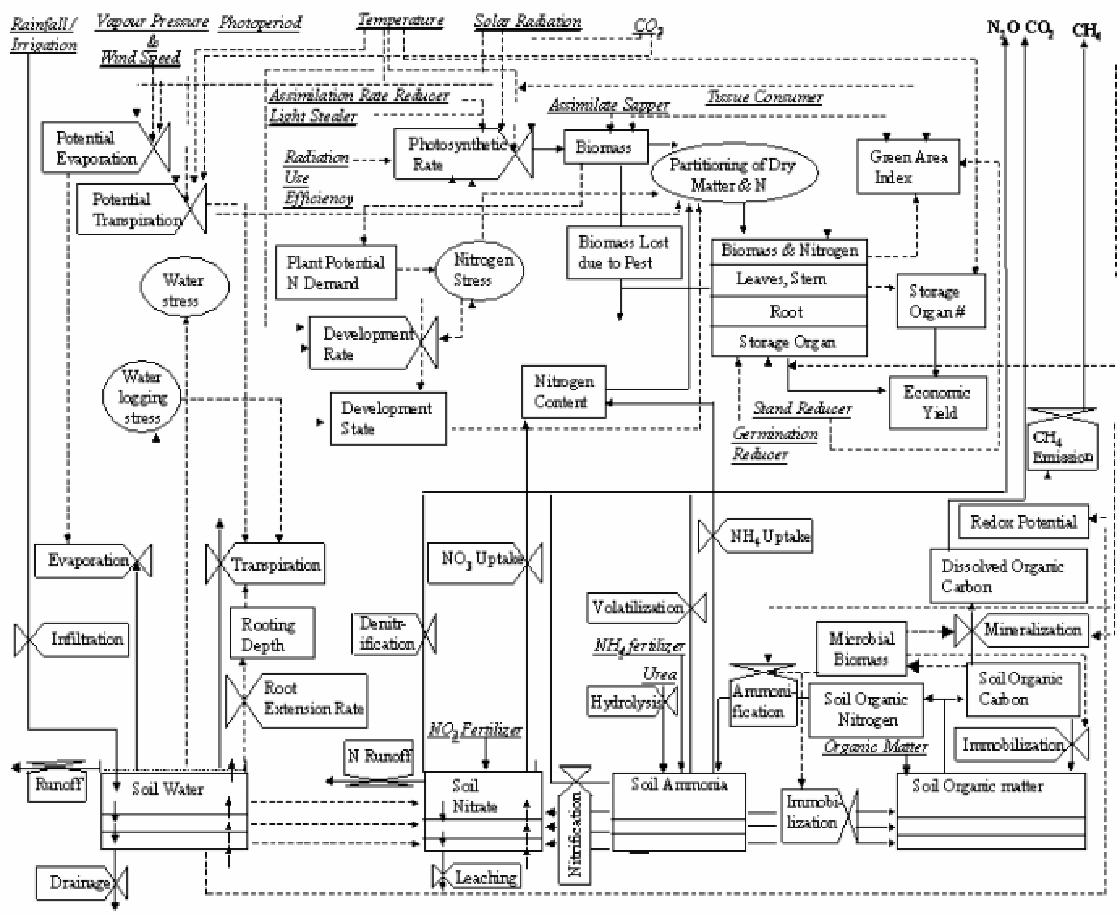
A model is a simplified representation of a complex system. Modelling of a crop has been done using approaches such as descriptive modelling, which is simple, or by explanatory modelling, which quantitatively describes the mechanisms and processes that cause the behaviour of a system. Crop growth simulation models, falling in the latter category, are based on quantitative understanding of the underlying processes, and integrate the effect of soil, weather, crop, and pest and management factor on growth and yield. The process could be crop physiological, meteorological, and soil physical, chemical or biological. Depending upon the objective, knowledge base of various agricultural disciplines can be integrated in a crop model. For instance simulating the crop-weather interaction forms the production level 1; while simulating growth rates determined by the availability of water apart from weather of a location gives production level 2. Inclusion of availability of factors such as nitrogen, other nutrients for crop growth provides production level 3é n. Addition of pests, diseases, weeds, etc. in simulating the crop growth and yield will further provide production levels more nearer to reality.

Fig 1: Relational diagram of a simulation model at production level 1



For simulating, the models need input data that mimic ógeneticsô of a crop/variety. Further, the response of variety to water, nutrient, pest limited or actual productivity, knowledge base of several additional disciplines are tapped and integrated into the model. Once the integration, calibration and validation is successful, crop simulation models can help us in analyzing the effect of various climatic factors on crop growth and yield considering the interaction with edaphic, biotic and agronomic factors. Such an analysis is normally not possible with conventional experimental methods. There have been over 120 crop models or compendium of models available across the world which can simulate 151 crops which include filed crops, horticultural crops, plantations, grasses, etc.

Fig 2: Simplified relational diagram of InfoCrop- a generic crop simulation model

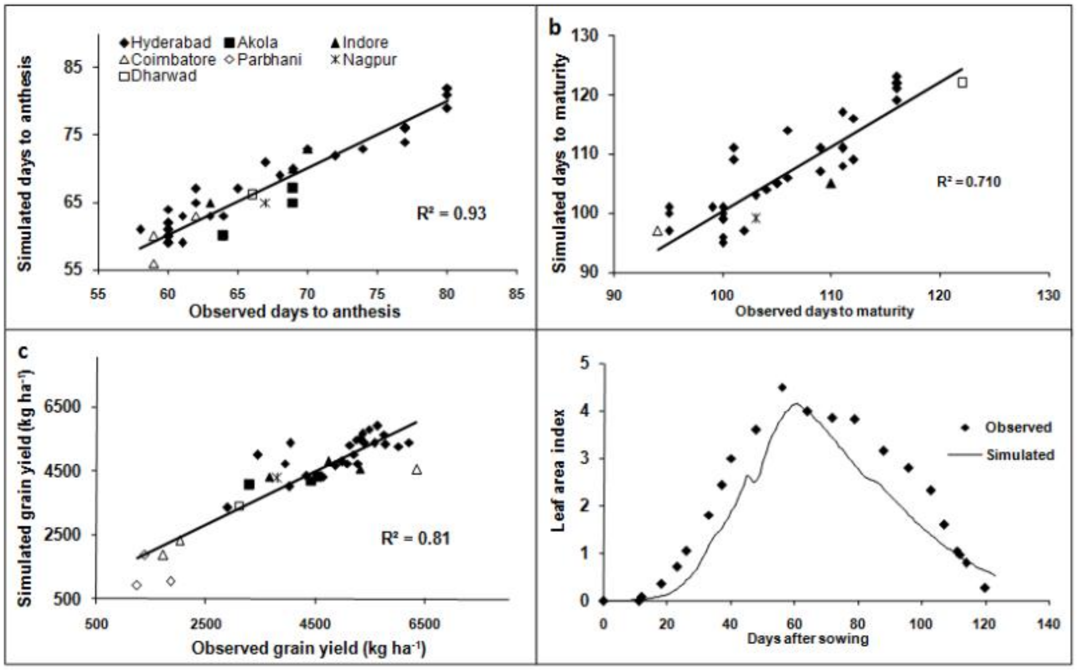


In recent years, agricultural system models have shifted from being mainly research oriented to tools for guiding resource management and policy-making. The linkage of these models to geographic information systems (GIS) and decision support systems has added dimensions to model applications. Agricultural system model have gone through more than 40 years of development and evolution. Prior to the mid-1980ǒs most of the modeling work focused on individual processes of agricultural systems, such as soil hydraulic properties, evapotranspiration, photosynthesis, plant growth and soil nutrients. The earlier models have served as a foundation for the development of agriculture system models in the last 20 years. Earlier examples of systems models have focused, for example, PAPRAN for pasture systems, CREAMS for soil, chemical and nutrient run off from cropping system, EPIC for soil erosion and soil productivity, CERES for crop growth, GLEAMS for ground water pollution, AquaCrop and CRPWAT for crop water requirement analysis and CENTURY for plant production, nutrient cycling and soil organic matter dynamics. Physiological growth and production models have shown to be very useful for guiding improvements in cropping systems of various annual crops. There have been several crop models and decision support systems available. Examples include DSSAT, InfoCrop, EPIC, APSIM, CROPSYST, etc.

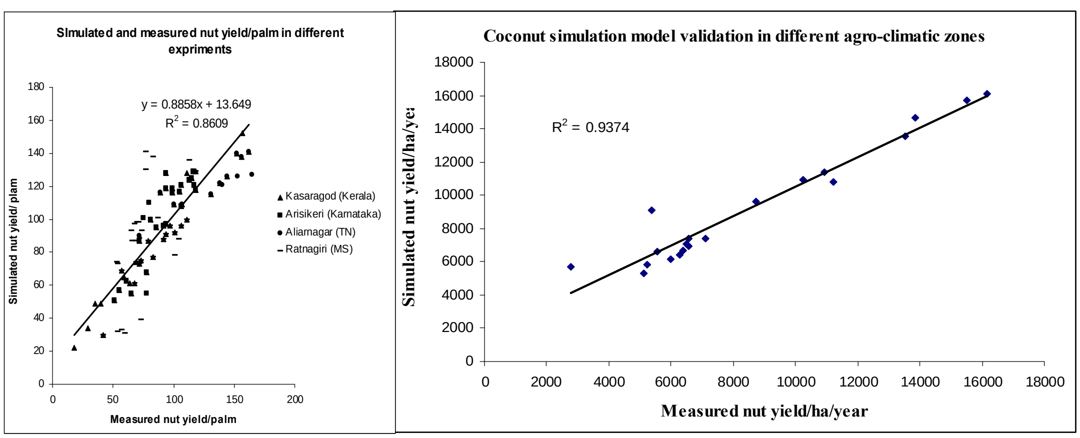
Calibration and validation of simulation models

Although the simulation models are flexible enough to perform under a variety of environments and farming conditions, calibration of model is necessary before running the model for study area. For this results from the detailed experiments on varietal performance can be made use of. The calibrated model can be used to simulate the crop growth performance in other set of experiments consisting of various treatments for validating the model performance under a range of conditions. This validated model can used for simulating impacts in that region. Model performance can be assessed through various statistical parameters viz., model bias error (MBE), root mean square error (RMSE), index of agreement (IA) and model efficiency (ME) among others.

Fig 3 : Examples of calibration and validation of model- essential steps before the application of any model



(source: Srivastava et al., 2010; Byzesh et al., 2010)



(source: Naresh Kumar et al., 2008)

Application of Crop Simulation models

Crop models are increasingly being used for environmental characterization and agro-ecological zoning, defining research priorities, technology transfer, estimating potential production, strategic and anticipatory decision making. In past 20 years crop simulation models are increasingly used for projecting the effects of climate change and climate variability. Recently, they have been used for quantifying the adaptation gains in climate change scenarios for prioritizing technology dissemination and also for identification of vulnerable areas.

Table 2 : Indicative use of models for several purposes and end uses

Purpose	Best used for
Decision support	Guiding current management options
Climate change impacts and / or adaptation	Climate change adaptation and mitigation guidance
Productivity / yield prediction or forecasting	Yield or productivity forecasting
Research for crop management improvement	Inter disciplinary research
Research for crop genetic improvement	Better understanding of processes, Improved crop breeding
Education / training	Improving training and education
Operations optimization	Policy development
Yield gap analysis	Improving agricultural management/ R&D policy development

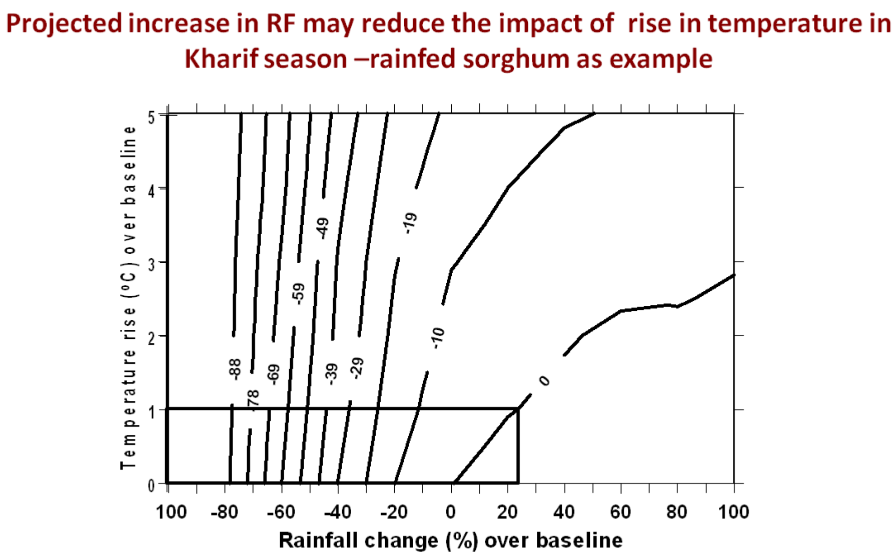
In a recently conducted global survey on use of crop simulation models (Rivington and Koo, 2010), it was found that the major purpose of the models are seen to be for decision support, analysis of climate change impacts and/ or adaptation, prediction or forecasting of productivity / yield and research for crop management improvement.

Crop simulation models are effective tools for the assessment of growth and yield of crops as well to suggest optimal resource management options (Kalra and Aggarwal, 1994; desired cultivar characteristics (Aggarwal *et al.,* 1997) performance evaluation of weather forecasters (Kalra and Aggarwal, 1996; Singh *et al.,* 1997). Apart from these, crop simulation models are now being seriously investigated as creditable tool for regional yield prediction (Nain *et al*., 2002) and integration of crop simulation model with remote sensing data for farm level wheat yield prediction (Nain *et al*., 2001).

Use of crop models in climate change studies

Analysis of impact of climate change on crop growth and yield can be carried out for individual and interaction effects of elevated temperature, rainfall, CO_2, etc. But these studies indicate the individual and interactional influence of various parameters irrespective of temporal scale. However, by using the climate scenarios, either derived from Global Climate Models (GCM) or from Regional Climate Models (RCMs), as inputs into the crop models, quantification of impacts on economic yields can be carried out for future climates. The adaptation analysis can be done by quantifying the response of different varieties, sowing time, nutrient management, water management, introduction of new crops, shift in cropping sequences, altered resource management and introduction of new technologies, etc. in various climate change scenarios so as to derive the best suitable technology package for reducing impacts of climate change at regional level then up-scaling to state and national level. These are called adaptation gains. The net different between impacts and adaptation gains is called net vulnerability of crop/system to climate change. Using the above approach, several studies have been conducted for quantifying the potential yields impacts, adaptation and vulnerability of coconut (Naresh Kumar et al., 2008; Naresh Kumar and Aggarwal, 2009), maize (Byjesh et al., 2010), sorghum (Srivastava et al., 2010) and also sensitivity of fragile ecosystems (Naresh Kumar et al., 2011).

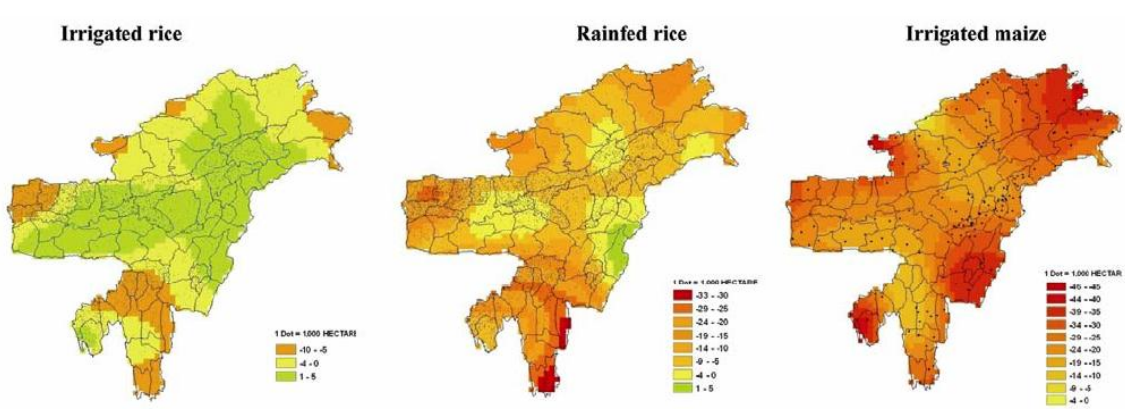
Fig 4: Sensitivity analysis on integration of two important factors influencing crop growthï point based simulations



(source: Srivastava et al., 2010)

Fig 5: Scenario based projections on impacts of climate change on crop productionï spatial integration

(source: Naresh Kumar et al., 2011)



Researchable issues

- Fine tune models based on updated thresholds of factors influencing major processes

- Fine tune/modify the models to best represent multiple stress impacts on crops in a season

References

Aggarwal, P.K., Kropff, M.J., Cassman, K.G. and Ten Berge, H.F.M. (1997). Simulating the genotypes strategies for increasing rice yield potential in irrigated tropical environments. *Field Crop Res.,* 51: 5-17.

Byjesh, K., S. Naresh Kumar and P. K. Aggarwal (2010). Simulating impacts, potential adaptation and vulnerability of maize to climate change in India. Mitigation and Adaptation Strategies for Global Change. DOI 10.1007/s11027-010-9224-3; 15:413-431.

Kalra, N. and Aggarwal, P.K. (1994). Evaluating water production functions for yield assessment in wheat using crop simulation models. In: ten Berge, H.F.M., Wopereis, M.C.S. and Shin, J.C. (Eds.), Nitrogen Economy of Irrigated Rice: Field of Simulation Studies, SARP Research Proceedings, AB-DLO, Wageningen, pp. 254- 266.

Kalra, N. and Aggarwal, P.K. (1996). Evaluating the growth response of wheat under varying inputs and changing climate options using wheat growth simulator ï WTGROWS. In: Abrol, Y.P., Gadgil, S. and Pant, G.B. (Eds.), Climate variability and agriculture. Narosa Publishing House, New Delhi, pp. 320-338.

Nain, A.S., Dadhwal, V.K. and Singh, T.P. (2002). Real time wheat yield assessment using technology trend and crop simulation model with minimal data set. *Curr. Sci.,* 82(10): 1255-1258.

Nain, A.S., Vyas, S.P., Dadhwal V.K., and Singh T.P. (2001). Farm level wheat yields prediction using remote sensing data. In: Proceedings of National Symposium on Advances in Remote Sensing with Emphasize on High Resolution Imageries, 11-13 December, 2001, ISRS, SAC, Ahmedabad, India.

Naresh Kumar, S., Kasturi Bai, K. V. Rajagopal V. and Aggarwal, P.K. 2008. Simulating coconut growth, development and yield using InfoCrop-coconut model. Tree Physiology, 28:1049ï 1058.

Naresh Kumar, S. and P. K. Aggarwal, 2009. Impact of climate change on coconut plantations. In Global Climate Change and Indian Agriculture-case studies from ICAR Network Project (PK Aggarwal ed.), ICAR, New Delhi Pub., pp.24-27.

Naresh Kumar, P. K. Aggarwal, Swaroopa Rani, Surabhi Jain, Rani Saxena and Nitin Chauhan (2011). Impact of climate change on crop productivity in Western Ghats, coastal and northeastern regions of India. Current Sci. 101 (3):33-42.

Rivington, M. and Koo, J. 2010. Report on the Meta-Analysis of Crop Modelling for Climate Change and Food Security Survey. CCAFS study. P 70.

Singh, K.K., Kalra, N., Mohanty, U.C. and Rathore, L.S. (1997). Performance evaluation of medium range weather forecast using crop growth simulator. *J. Environ. Syst.,* 25(4): 397-408.

Srivastava, A., S. Naresh Kumar and P. K. Aggarwal (2010). Assessment on vulnerability of sorghum to climate change in India. Agric. Ecosyst. Environ. Doi:10.1016/j.agee.2010.04.012; . 138:160-169.

Statistical tools for crop weather modeling

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Section of Design & Analysis

Linear Regression

Concept

- Regressionô is óstepping back or returning to the average valueö.
- Regression: measure of the average relationship between two or more variables in terms of the original units of the data.
- Regression analysis: estimates are made for a variable from knowledge of the values of one or more other variables.
- To study the functional relationship between the variables and thereby provide a mechanism for prediction or forecastingö.
- Regression analysis is an attempt to establish the ónature of the relationship between variables

Dependent vs Independent variables

- In regression analysis, there are two types of variables. The variable, which is used to predict the variable of interest, is called the independent variable and the variable we are trying to predict is called the dependent variable.
- In regression analysis independent variable is also known as regresser or predictor or explanatory while the dependent variable is also known as regressed or explained variable or criterion.
- The independent variable is denoted by X and dependent variable by Y. Changes in Y are assumed to be caused by changes in X. Relationship between X and Y is described by a linear function

Simple Vs Multiple Linear Regression

- Simple regression: Study of only two variables at a time

- But quite often the values of a particular phenomenon may be affected by multiplicity of factors.
- Multiple Regression: Studying more than two variables at a time

Correlation Vs Regression

- Correlation is only concerned with strength of the linear relationship. No functional relationship.
- No causal effect is implied with correlation.
- Non-directional.
- No units for Correlation co-efficient.
- Range is -1 to +1

Regression Equation

$$Y = \beta_0 + \beta_1 X + \varepsilon$$

- where Y is dependent variable
- X is independent variable

β_0 is intercept

β_1 is regression coefficient

ε is random error

Interpretation of Regression Coefficient

- Regression coefficient explains the impact of changes in an independent variable on the dependent variable.
- Say estimated value of β_0 is b_0. Then b_0 is the estimated average value of Y when the value of X is zero (if X = 0 is in the range of observed X values).
- Say estimated value of β_1 is b_1. Then b_1 measures the estimated change in the average value of Y as a result of a one-unit change in X.

$$b_1 = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (x_i - \bar{x})^2}$$

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_k X_{ki} + \hat{U}$$

$$b_0 = \bar{y} - b_1 \bar{x}$$

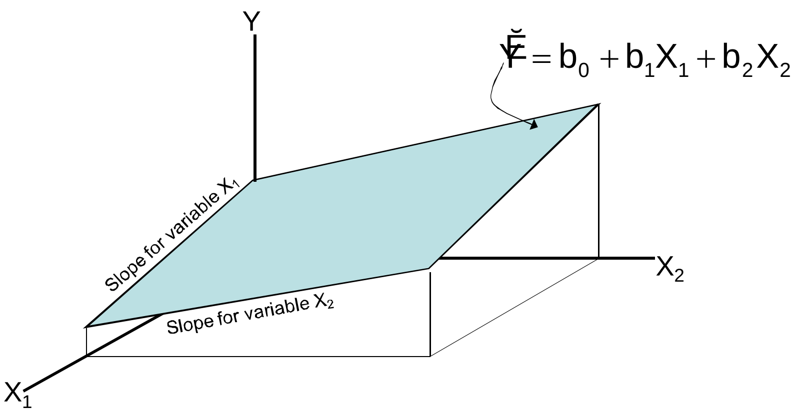
Where $\bar{x}$ and $\bar{y}$ are averages of X and Y variables, respectively.

Multiple Linear Regression Model

Multiple Regression Model with k Independent Variables will be

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_k X_{ki} + \hat{U}$$

Two variable model



F-Test for Overall Significance

H_0: $\beta_1 = \beta_2 = 0$

H_1: β_1 and β_2 not both zero

Test statistic $F = \frac{MSR}{MSE}$

Are Individual Variables Significant?

- Use t-test for individual variable slopes
- It tests if there is a linear relationship between the variable X_i and Y

Hypotheses:

H_0: $\beta_i = 0$ (no linear relationship)

H_1: $\beta_i \neq 0$ (linear relationship does exist between X_i and Y)

Test Statistic:

$$t = \frac{b_i - 0}{S_{b_i}}$$

(df = n − k − 1)

Step-wise Regression

Backward Regression:

Begins with all variables and drops variables one by one based on insignificance of regression coefficients

(Eg: Removal p>0.1)

Forward Regression:

Begins with most significant variable and adds one by one based on significance of regression coefficients (Eg: Entry p<0.05)

Cluster analysis

- Given a set of *p* variables $X_1, X_2, \ldots, X_p$, and a set of *N* objects, the task is to group the objects into classes so that objects *within* classes are more similar to one another than to members of *other* classes.
- Objects that are similar to one another should be in the same group, whereas objects that are dissimilar should be in different groups.
- All cluster analyses begin with measures of similarity/dissimilarity among objects (distance matrices)

Distance matrix

Objects that are closer together based on pairwise multivariate distances are assigned to the same cluster, whereas those farther apart are assigned to different clusters.

Some clustering distances

Distance metric	Description	Data type
Pearson	1- r for each pair of objects	quantitative
R^2	1 ï r^2 for each pair of objects	quantitative
Euclidean	Normalized Euclidean distance	quantitative
χ^2	χ^2 measure of independence of rows and columns on 2 X N frequency tables	counts
MW	Increment in SS_{within} if object moved into a particular cluster	quantitative

Scale considerations

Å In general, correlation measures are not influenced by differences in scale, but distance measures (e.g. Euclidean distance) are affected.

Å So, use distance measures when variables are measured on common scales, or compute distance measures based on standardized values when variables are not on the same scale.

Å Remove outliers in the data

Hierarchical clustering of objects

Å Begins with calculation of distances among all pairs of objectsé with groups being formed by agglomeration (lumping of objects)

Å The end result is a dendogram (tree) which shows the distances between pairs of objects.

Hierarchical joining algorithms

Å *Single (nearest-neighbour)*: distance between two clusters = distance between two closest members of the two clusters.

Å *Complete (furthest neighbour)*: distance between two clusters = distance between two most distant cluster members.

Å *Centroid :* distance between two clusters = distance between multivariate means of each cluster.

Å *Average*: distance between two clusters = average distance between all members of the two clusters.

Å *Median*: distance between two clusters = median distance between all members of the two clusters.

Å *Ward*: distance between two clusters = average distance between all members of the two clusters with adjustment for covariances.

K – means clustering

A method of partitioned clustering whereby a set of *k* clusters is produced by minimizing the *SSwithin* based on Euclidean distances.

In K ï means clustering, the objective is to partition a set of *N* objects into a number *k* *predetermined* clusters by maximizing the distance between cluster centers while minimizing the within-cluster variation.

Å Choose *k* ñseedò cases which are spread apart from center of all objects as much as possible.

Å Assign all remaining objects to nearest seed.

Å Reassign objects so that within-group sum of squares is reducedé

Å é and continue to do so until SS_{within} is minimized.

Principal Component Analysis

Most of the times, the variables under study are highly correlated and as such they are effectively ñsaying the same thingò.

Purpose of PCA

- Dimensionality reduction
  - Small number of uncorrelated hidden or underlying variables
  - Principal components are linear combinations of original set of variables
  - Decreasing order of importance
- To tackle with multi-colliniarity

Method

Let x1, x2, x3, . . . , xp be original variables, then first principal component may be defined as

$$z_1 = a_{11}x_1 + a_{12}x_2 + ... + a_{1p}x_p$$

such that variance of z1 is as large as possible subject to the condition that

$$a_{11}^2 + a_{12}^2 + ... + a_{1p}^2 = 1$$

This constraint is introduced because if this is not done, then Var(z1) can be increased simply by multiplying any a1jĉs by a constant factor.

The second principal component is defined as

$$z_2 = a_{21}x_1 + a_{22}x_2 + ... + a_{2p}x_p$$

such that Var(z2) is as large as possible next to Var(z1) subject to the constraint that

$$a_{21}^2 + a_{22}^2 + ... + a_{2p}^2 = 1$$

and cov(z1, z2) = 0 and so on.

- It is quite likely that first few principal components account for most of the variability in the original data. If so, these few principal components can then replace the initial p variables

Å An analysis of principal components often reveals relationships that were not previously suspected

An Introduction to APSIM Model

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1. Introduction

The Agricultural Production Systems Simulator (APSIM) has been used in a broad range of applications, including support for on-farm decision making, farming systems design for production or resource management objectives, assessment of the value of seasonal climate forecasting, analysis of supply chain issues in agribusiness activities, development of waste management guidelines, risk assessment for government policy making and as a guide to research and education activity.

APSIM has been developed by the Agricultural Production Systems Research Unit (APSRU), a collaborative group made up from CSIRO and Queensland State Government agencies. Development started with the formation of APSRU in 1991 and improvement or updation of the model has been continuing for the last two decades.

APSIM was designed at the outset as a farming systems simulator that sought to combine accurate yield estimation in response to management with prediction of the long-term consequences of farming practice on the soil resource (e.g. soil organic matter dynamics, erosion, acidification etc.).

The central concept of APSIM is ñthe soil provides a central focus, crop season and managers come and go, finding the soil in one state and leaving it in anotherò

2. Overview of the APSIM system and its components

The APSIM modelling framework is made up of;

a) a set of biophysical modules that simulate biological and physical processes in farming systems,

b) a set of management modules that allow the user to specify the intended management rules that characterise the scenario being simulated and that control the conduct of the simulation

c) various modules to facilitate data input and output to and from the simulation,

d) a simulation engine that drives the simulation process and controls all messages passing between the independent modules.

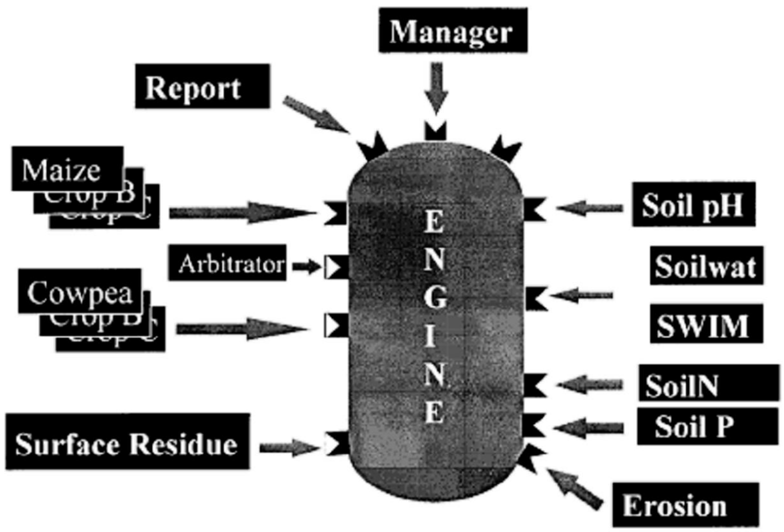

Fig. 1. Diagrammatic representation of the APSIM simulation framework with individual crop and soil modules, module interfaces and the simulation engine.

3. Details of APSIM components

3.1. Crop Modules

APSIM contains an array of modules for simulating growth, development and yield of crops, pastures and forests and their interactions with the soil. Currently crop modules are available for barley, canola, chickpea, cotton, cowpea, hemp, fababean, lupin, maize, millet, mucuna, mungbean, navybean, peanut, pigeonpea, sorghum, soybean, sunflower, wheat and sugarcane. Modules for forest trees, rice, forage grasses and lablab under development.

The plant modules simulate key underpinning physiological processes and operate on a daily time step in response to input daily weather data, soil characteristics and crop management actions. The crop modules have evolved from early versions for focus crops such as maize

(Carberry and Abrecht, 1991), peanut (Hammer et al., 1995), sorghum (Hammer and Muchow, 1991) and sunflower (Chapman et al., 1993).

Currently in APSIM, all plant species use the same physiological principles to capture resources and use these resources to grow.

Processes captured:

The seven important processes captured in this model are:

(1) Phenology

(2) Tillering and leaf area production

(3) Biomass accumulation and partitioning

(4) Root growth

(5) Crop water relations

(6) Crop nitrogen relations Senescence and plant death

Phenology Development:

Determinants of developmental changes are different. Germination is thermal time and soil water dependent while emergence is dependent on thermal time and depth. End of juvenile stage is influenced by thermal time and water and nitrogen stresses. Floral initiation, however, depends on thermal time, photo period and stresses due to nitrogen and water limitations. Stages from the start of grain fill to harvest stage are dependent on thermal time only.

Biomass accumulation:

In APSIM, biomass accumulation (DM) is simulated each day under both water limited and radiation limited conditions using the equations

DM = Soil water supply x transpiration efficiency (Under water limited conditions)

DM = Radiation use efficiency x radiation intercepts (Under radiation limited conditions)

Minimum value of the above estimates is taken as biomass accumulation of that day.

Biomass Partitioning:

Partitioning of biomass to various plant organs is based on following criteria

Partitioning based on stage-specific ratios/fractions:

- Root, leaf, stem, reproductive, grain
- Roots grown daily in stage-specific proportion to shoot
- Emergence to flowering: biomass partitioned to leaf & stem
- Start grain fill to maturity: grain +/- pod

Leaf area development:

It is calculated based on the formula

Leaf area/m2 (LAI) = plant density x axis no. x leaf no. per axis x area per leaf

- Leaf appearance driven by a variable thermal time rate
- Tiller appearance driven by leaf appearance or separate TT rate
- Lear area per leaf/node = f(Density, genotype, axis/tiller)
- Tiller senescence = f(age after FI, water depth)
- Leaf senescence rate = f(age, light competition, water stress, frost)

The routines in the library are structured in separate blocks corresponding to the crop model components of phenology, biomass, canopy, root system, senescence pools, water, nitrogen and phosphorus.

In APSIM there are modules for the two major modelling approaches that are commonly used for the soil water balance, namely cascading layer and Richardôs equation methods. SOILWAT (Probert et al., 1998c) is a cascading layer model that owes much to its precursors in CERES (Ritchie, 1972; Jones and Kiniry, 1986)

and PERFECT (Littleboy et al., 1989, 1992). It operates on a daily time step. The water characteristics of the soil are specified in terms of the lower limit (LL15), drained upper limit (DUL) and saturated (SAT) volumetric water contents of a sequence of soil layers.

* runoff which is calculated using a modified USDA curve number approach, that include effects of soil water content, soil cover both from crop and crop residue, and roughness due to tillage.

* evaporation which is based on potential evaporation (Priestly_ Taylor or Penman - Monteith) and modified according to the cover provided by surface residues or growing plant

* saturated flow which occurs when any layer ófillsô above DUL; a specified proportion (swcon) of the water in excess of DUL drains to the next layer

* unsaturated flow at water contents below DUL where gradients in soil water content occur between layers (e.g. in response to rainfall events or evaporation)

* movement of solutes associated with saturated and unsaturated flow of water are calculated using a ómixingô algorithm whereby existing and incoming solutes and water are fully mixed to determine the concentration of solute in the water leaving any layer.

4. MANAGER

The early recognition that all the possible management configurations required of the simulator could not be explicitly identified and addressed a priori, led to the development of the MANAGER module in APSIM. This module enables users to apply simple concepts of states, events, actions and conditional logic to build complex management systems whose scope goes well beyond anything envisaged by the early developers. The MANAGER must be present in all APSIM configurations and it provides control over individual components and the overall simulation. This module ómanagesô by issuing messages to other modules in the system, many of which are conditional upon states or events within the modules during simulation. It also allows the user to create their own variables and define these as a function of other variables within APSIM. The MANAGER script files are prepared by users defining the intended simulation and are compiled at runtime.

The APSIM MANAGER module can be used to invoke any action available by any module.

Possible actions include:

- Resetting individual module values.
- Reinitialising all data in modules to a given state.
- Sowing, harvesting or killing crops.
- Applications of fertiliser, irrigation or tillage to soil.

- Calculation of additional variables to track system state.

- Reporting of system state in response to events and/or conditional logic.

Reference

Carberry, P.S., Abrecht, D.G., 1991. Tailoring crop models to the semi-arid tropics. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics. CAB International, Wallingford, UK, pp. 157- 182.

Chapman, S.C., Hammer, G.L., Meinke, H., 1993. A sunflower simulation model: I. Model development. Agronomy J. 85, 725 - 735**.**

Hammer, G.L., Muchow, R.C., 1991. Quantifying climatic risk to sorghum in Australiaǿs semiarid tropics and subtropics: model development and simulation. In: Muchow, R.C.,

Bellamy, J.A. (Eds.), Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics. CAB International, Wallingford, UK, pp. 205 - 232.

Hammer, G.L., Sinclair, T.R., Boote, K.J., Wright, G.C.,Meinke, H., Bell, M.J., 1995. A peanut simulation model: 1. Model development and testing. Agronomy J. 87, 1085-1093.

Jones, C.A., Kiniry, J.R. (Eds.), CERES-Maize: a simulation model of maize growth and development. Texas A&M University Press, College Station 1986, p. 194.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., 1989. PERFECT*/A computer simulation model of Productivity Erosion Runoff Functions to Evaluate Conservation Techniques. Queensland Department of Primary Industries Bulletin, QB89005.

Probert, M.E., Robertson, M.J., Poulton, P.L., Carberry, P.S., Weston, E.J., Lehane, K.J., 1998a. Modelling lucerne growth using APSIM. Proceedings of the Ninth Australian Agronomy Conference, Wagga Wagga, pp. 247 - 250.

Probert, M.E., Carberry, P.S., McCown, R.L., Turpin, J.E., 1998b. Simulation of legume-cereal systems using APSIM. Aust. J. Agric. Res. 49, 317 - 328.

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C., Strong, W.M., 1998c. APSIMôs water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56, 1 - 28.

Ritchie, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204- 1213.

Fundamentals of DSSAT Model

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Crop modeling enables researchers to integrate knowledge from different disciplines in a quantitative way. That, in turn, helps researchers to understand the underlying processes that determine the behavior of complex agricultural systems. Mathematical models are caricatures of systems made from mathematical equations. Integrating and solving the equations enables a numerical description of the system to be produced. During the first phase of a modeling exercise, the modeler seeks to give names, magnitudes and units to the component parts of the problem. In the second phase of modeling a problem, the processes are described as mathematical functions. In the final phase, 'what if' questions can be asked about the functioning of a system and numerical answers provided. Mathematical models that contain no clear logical link with the basic processes governing the relationship between the system inputs and outputs are unlikely to contribute much of significance to any debate concerning strategic decisions in relation to research management.

Models at different levels of detail are developed to meet different objectives, ranging from a thorough understanding of an existing system to the prediction of crop production in untested conditions. Four types of crop production systems can be distinguished.

1. Potential production, where production is determined by solar radiation, temperature, and crop and varietal characteristics.
2. Water-limited production.
3. Water- and N-limited production.
4. Water-, N- and other nutrient-limited production.

Going from type one to type four, production generally decreases and the variables that determine system behavior increase. At all levels, growth-reducing factors such as insects, pathogens, and weeds can be introduced. Models for all production levels can be developed. Models at the first level are further developed than models at the others.

Well-developed models that simulate the growth of a crop in relation to its dynamic environment can be used to help prioritize research. Crop modeling combined with geographic information systems (GIS) analysis enables researchers to distinguish agro ecological zones and to quantitatively rank the technical constraints to agricultural production within them. These models allow the impact of new technology on agricultural production to be assessed before the technology is introduced. The GIS database can link the models directly with socioeconomic aspects.

Crop simulation models have many uses. Models can be used as a research tool and to support problem solving, risk assessment, and decision making. They can guide researchers in prioritizing their research and in integrating quantitative knowledge from different disciplines. Also, models can be used as a framework for training. Further, models can be used to extrapolate research findings over broad regions and extended time, since the models account for crop-environment interactions. Using long-term weather data, yield probabilities can be simulated.

An aspect that is beginning to gain more importance is the use of models to set breeding goals. The physiological attributes that contribute significantly to crop production in a given environment lend themselves to definition by crop modeling. Through modeling, the optimum timing of seeding or transplanting, irrigation and fertilization can be determined for a given environment.

Modeling is especially useful in yield gap analysis, a method for identifying constraints to agricultural production in different agroclimatic zones. From yield gap analysis, constraints that can be reduced can be identified. Researchers then concentrate on ameliorating those factors that contribute to the gap between farm yield, potential farm yield, and potential experiment station yield

DSSAT model

The decision support system for Agrotechnology transfer (DSSAT) was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project to facilitate the application of crop models in a systems approach to agronomic research. Its initial development was motivated by a need to integrate knowledge about soil, climate, crops, and management for making better decisions about transferring production technology from one location to others where soils and climate differed. The systems approach provided a framework in which research is conducted to understand how the system and its components function. This understanding is then integrated into models that allow one to predict the behavior of the system for given conditions. After one is confident that the models simulate the real world adequately, computer experiments can be per- formed hundreds or even thousands of times for given environments to determine how to best manage or control the system. DSSAT was developed to operationalized this approach and make it available for global applications. The DSSAT helps decision-makers by reducing the time and human resources required for analyzing complex alternative decisions. It also provides a framework for scientific cooperation through research to integrate new knowledge and apply it to research questions.

The DSSAT is a collection of independent programs that operate together; crop simulation models are at its center (Fig. 1). Databases describe weather, soil, experiment conditions and measurements, and genotype information for applying the models to different situations. Software helps users prepare these databases and compare simulated results with observations to give them confidence in the models or to determine if modifications are needed to improve accuracy.

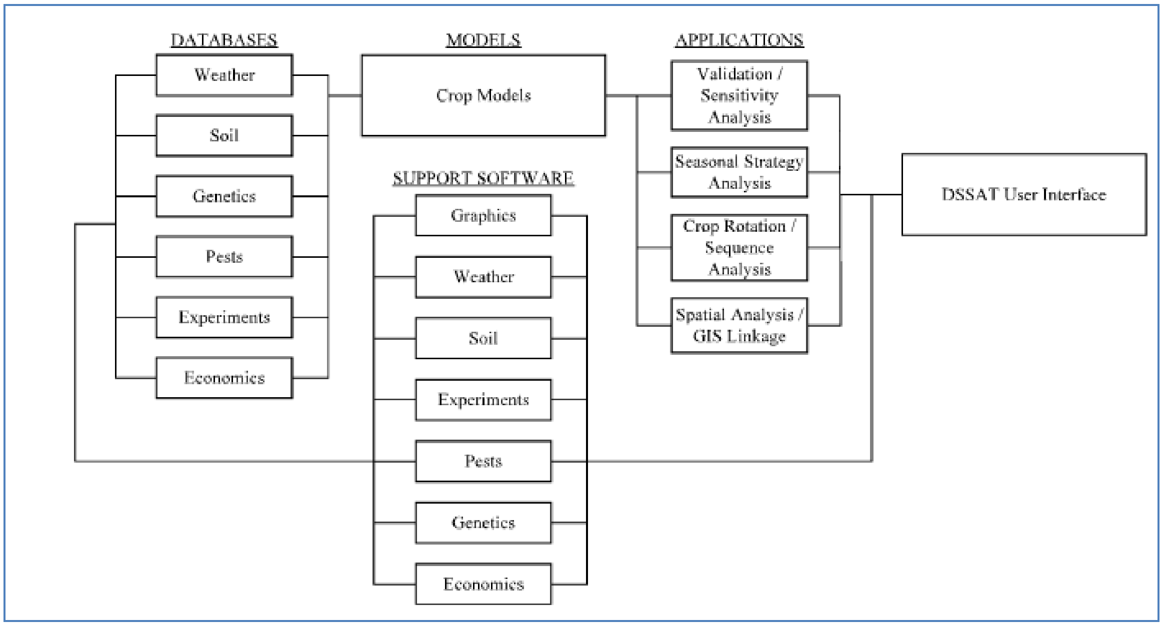

Fig.1: Basic Structure of DSSAT model

Different types of applications are accomplished in DSSAT modal by using different modes to call the land unit module on a daily basis; the mode is specified as a command line argument when the model is run. The basic mode provides for inter- active sensitivity analysis and comparison of simulated vs. observed field data. A second mode of operation simulates crops over a number of years of weather using the same soil initial condi- tions. This mode allows one to evaluate the effects of uncertain future weather conditions on deci- sions made when all soil initial conditions are known. A third mode operates the cropping system modules to simulate crop rotations over a number of years, and soil conditions are initialized only at the very start of the simulation. A fourth mode operates the CSM to simulate one or more crops over space (i.e. for precision agriculture, land use management or other spatial-based applications). One can also completely replace the main driver for other applications, thereby providing a highly flexible approach for development of additional applications and user interfaces without having to modify code for any other module (fig.2).

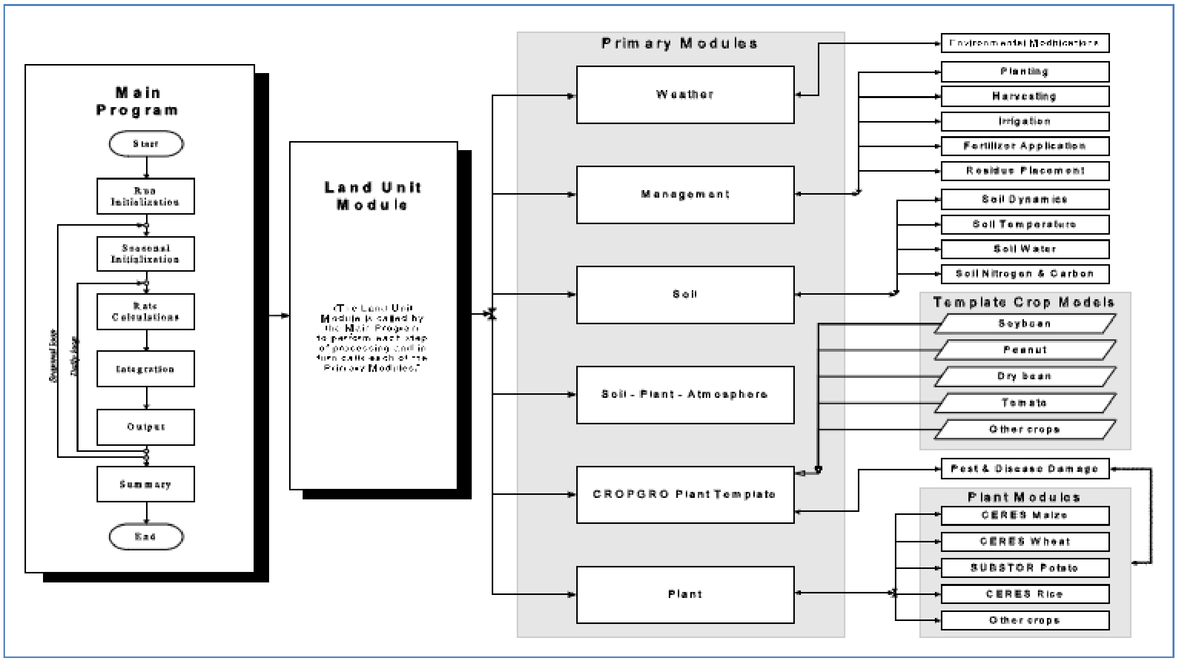

Fig.2: Overview of components and modules in DSSAT

The primary and sub modules currently used in the CSM and summarizes their functions are given in table 1.

Table.1: Summary description of modules in the DSSAT — CSM

Modules	Sub modules	Behavior

Main program (DSSAT ð CSM)		Controls time loops,, determines which modules to call based on user input switches, controls print timing for all modules
Land unit		Provides a single interface between cropping system behavior and applications that control the use of the cropping system. It serves as a collection point for all components that interact on a homogenous area of land
Weather		Reads or generates daily weather parameters used by the model. Adjusts daily values if required, and computes hourly values
Soil	Soil dynamics	Computes soil structure characteristics by layer. This module currently reads values from a file, but future versions can modify soil properties in response to tillage, etc
	Soil temperature module	Computes soil temperature by layer
	Soil water module	Computes soil water processes including snow accumulation and melt, runoff, infiltration, saturated flow and water table depth. Volumetric soil water content is updated daily for all soil layers. Tipping bucket approach is used
	Soil nitrogen and carbon module	Computes soil nitrogen and carbon processes, including organic and inorganic fertilizer and residue placement, decomposition rates, nutrient fluxes between various pools and soil layers. Soil nitrate and ammonium concentrations are updated on a daily basis for each layer
SPAM		Resolves competition for resources in soil ð plant ð atmosphere system. Current version computes partitioning of energy and resolves energy balance processes for soil evaporation, tran- spiration, and root water extraction
CROPGRO Crop Template	module	Individual plant growth modules

CERES-Maize; CERES-Wheat; CERES- Rice; SubStor-Potato; Other plant models	Computes crop growth processes including phenology, photo-synthesis, plant nitrogen and carbon demand, growth partition- ing, and pest and disease damage for crops modeled using the CROPGRO model Crop Template (soybean, peanut, dry bean, chickpea, cowpea, faba bean, tomato, Macuna, Brachiaria, Bahiagrass) Modules that simulate growth and yield for individual species. Each is a separate module that simulates phenology, daily growth and partitioning, plant nitrogen and carbon demands, senescence of plant material, etc	
Management opera- tions module	Planting	Determines planting date based on read-in value or simulated using an input planting window and soil, weather conditions
	Harvesting	Determines harvest date, based on maturity, read-in value or on a harvesting window along with soil, weather conditions
	Irrigation	Determines daily irrigation, based on read-in values or automatic applications based on soil water depletion
	Fertilizer	Determines fertilizer additions, based on read-in values or automatic conditions
	Residue	Application of residues and other organic mMaterial (plant, animal) as read-in values

MINIMUM DATA SETS

The DSSAT models require the minimum data set for model operation. The contents of such a dataset have been defined based on efforts by workers in IBSNAT and ICASA. They encompass data on the site where the model is to be operated, on the daily weather during the growing cycle, on the characteristics of the soil at the start of the growing cycle or crop sequence, and on the management of the crop (e.g. seeding rate, fertilizer applications, irrigations) (Table.2)

Contents of minimum data sets for operation and evaluation of the DSSAT ð CSM

(a) For operation of model

Site	Latitude and longitude, elevation; average annual temperature; average annual amplitude in temperature
	Slope and aspect; major obstruction to the sun (e.g. nearby mountain); drainage (type, spacing and depth); surface stones (coverage and size)
Weather	Daily global solar radiation, maximum and minimum air temperatures, precipitation
Soil	Classification using the local system and (to family level) the USDA-NRCS taxonomic system
	Basic profile characteristics by soil layer: in situ water release curve characteristics (saturated drained upper limit, lower limit); bulk density, organic carbon; pH; root growth factor; drainage coefficient
Initial condi-tions	Previous crop, root, and nodule amounts; numbers and effectiveness of rhizobia (nodulating crop)
	Water, ammonium and nitrate by soil layer

Management Cultivar name and type

Planting date, depth and method; row spacing and direction; plant population Irrigation and water management, dates, methods and amounts or depths

Fertilizer (inorganic) and inoculant applications

Residue (organic fertilizer) applications (material, depth of incorporation, amount and nutrient concentrations) Tillage

Environment (aerial) adjustments

Harvest schedule

(b) For evaluation of models

Date of emergence

Date of flowering or pollination (where appropriate)

Date of onset of bulking in vegetative storage organ (where appropriate) Date of physiological maturity

LAI and canopy dry weight at three stages during the life cycle

Canopy height and breadth at maturity

Yield of appropriate economic unit (e.g. kernels) in dry weight terms

Canopy (above ground) dry weight to harvest index (plus shelling percentage for legumes) Harvest product individual dry weight (e.g. weight per grain, weight per tuber)

Harvest product number per unit at maturity (e.g. seeds per spike, seeds per pod) Harvest product number per unit at maturity (e.g. seeds per spike, seeds per pod) Soil water measurements vs. time at selected depth intervals

Soil nitrogen measurements vs. time

Soil C measurements vs. time, for long-term experiments

Damage level of pest (disease, weeds, etc.) infestation (recorded when infestation first noted, and at maximum) Number of leaves produced on the main stem

N percentage of economic unit

N percentage of non-economic parts

In addition to research applications, the DSSAT and its crop models have been used in teaching, both in continuing education courses and in formal university courses at graduate and under- graduate levels (Tsuji et al., 1998). There also have been attempts to use these models in advising farmers (through extension services and the pri- vate sector). In one application, described by Welch et al. (2002), an agricultural company has implemented versions of three of the DSSAT v3.5 models in a comprehensive farmer support soft- ware package that is being used by private consultants. This software package, called PCYield, includes CROPGRO-Soybean, CERES- Maize and CERES-Wheat models. PCYield is available to clients of the company via the Internet along with daily weather data for specific farm locations. It has a very simple user interface to allow private crop consultants to operate them for any of their farmer clients (http://www.mPower3. com).

MODEL USES AND LIMITATIONS

Models are developed by agricultural scientists but the user-group includes the latter as well as breeders, agronomists, extension workers, policy-makers and farmers. As different users possess varying degrees of expertise in the modelling field, misuse of models may occur. Since crop models are not universal, the user has to choose the most appropriate model according to his objectives. Even when a judicious choice is made, it is important that aspects of model limitations be borne in mind such that modelling studies are put in the proper perspective and successful applications are achieved.

Agricultural systems are characterized by high levels of interaction between the components that are not completely understood. Models are, therefore, crude representations of reality. Wherever knowledge is lacking, the modeler usually adopts a simplified equation to describe an extensive subsystem. Simplifications are adopted according to the model purpose and / or the developerꞌs views, and therefore constitute some degree of subjectivity.

Models that do not result from strong interdisciplinary collaboration are often good in the area of the developerꞌs expertise but are weak in other areas. Model quality is related to the quality of scientific data used in model development, calibration and validation

When a model is applied in a new situation the calibration and validation steps are crucial for correct simulations. The need for model verification arises because all processes are not fully understood and even the best mechanistic model still contains some empirism making parameter adjustments vital in a new situation.

Model performance is limited to the quality of input data. It is common in cropping systems to have large volumes of data relating to the above-ground crop growth and development, but data relating to root growth and soil characteristics are generally not as extensive. Using approximations may lead to erroneous results. Large variations in wheat yields (4.5 to 8.0 t ha-1) attributable to within-field soil heterogeneity were reported by Russell and Van Gardingen (1996). Hence, the use of average values of soil characteristics as model inputs could lead to some errors in simulated output.

Most simulation models require that meteorological data be reliable and complete. Meteorological sites may not fully represent the weather at a chosen location. In some cases, data may be available for only one (usually rainfall) or a few (rainfall and temperature) parameters but data for solar radiation, which is important in the estimation of photosynthesis and biomass accumulation, may not be available. In such cases, the user would rely on generated data. At times, records may be incomplete and gaps have to be filled. Using approximations would have an impact on model performance. Nonhebel (1994) has reported that simulated wheat yield was overestimated under potential conditions and underestimated under water-limiting conditions when generated meteorological data were used with SUCROS87 (Spitters et al. 1989).

At times, model developers may raise the expectations of model users beyond model capabilities. Users, therefore, need to judiciously assess model capabilities and limitations before it is adopted for application and decision-making purposes.

Generally, crop models are developed by crop scientists and if interdisciplinary collaboration is not strong, the coding may not be well-structured and model documentation may be poor. This makes alteration and adaptation to simulate new situations difficult, specially for users with limited expertise. Finally, using a model for an objective for which it had not been designed or using a model in a situation that is drastically different from that for which it had been developed would lead to model failure

Further details and complete information on DSSAT functionality read the paper

ñ J.W. Jones et al. 2003.The DSSAT cropping system model, Europ. J. Agronomy 18 (2003) 35 ð   265ò

Predicting cotton production using Infocrop-cotton simulation model, remote sensing and spatial agro-climatic data

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A methodology is described to predict cotton production on a regional basis using the integrated approach of remote sensing (RS), geographic information system (GIS) and a crop simulation model, i.e. Infocrop-cotton model. This model is based on an indigenous crop growth simulator called Infocrop. The Infocrop-cotton model was calibrated and validated to simulate the effect of diverse weather, soil, and agronomic management practices on growth, development and yield of cotton varieties and hybrids using results of several diverse field experiments (60 datasets). These experiments were conducted during 2000–01 to 2004–05 in major cotton-producing states of India across locations spreading from Hisar (29°10′N, 75°46′E) to Coimbatore (11°00′N, 77°00′E) with varying management practices, weather and soil. The model satisfactorily simulated the trends in leaf area, dry matter growth, days to flowering and seed cotton yield. The simulated time to flowering and maturity varied between 54 and 80 days as well as 136 to 193 days, with an RMSE value of 3 and 8.5 days respectively. Total biomass and seed cotton yield showed an accuracy of 86 and 89% respectively. The model also precisely simulated water deficit and N stress, the two important abiotic constraints for dryland cotton production.

The Infocrop-cotton model was used in conjunction with RS and GIS techniques for developing an integrated approach for deriving cotton production estimates. Resourcesat-1 LISS III data of October/November months corresponding to peak vegetative stage of cotton crop were used to derive spatial distribution of cotton crop. The study area was classified as polythesian polygons based on pedo-climatic variables, namely soil type, soil depth and rainfall pattern using GIS. Cotton yields for each of these polygons were simulated using the crop model and were aggregated to determine the total production of the district. The prediction of cotton production was more accurate to the partially irrigated or irrigated districts and not for the rainfed districts. The utility of the integrated approach in prediction of cotton production at the regional level has been discussed.

Keywords: Cotton, crop simulation model, production, remote sensing.

COTTON is an important commercial crop and a widely traded commodity across the world. Its yield is sensitive to weather, soil as well as management practices. India and China, where cotton is predominantly cultivated under dryland conditions, are two of the five largest cotton-producing countries in the world accounting for 42% of the world's cotton production[1]. In these countries, abiotic and biotic constraints such as declining soil fertility, frequent water and nutrient stresses, outbreaks of insect pests, uncertainties in rainfall and other environmental hazards cause large year-to-year fluctuation in yield[2]. The present production estimations by different agencies based either on the crop area sown, crop-cutting experiments or market arrivals show wide variability because of their inability to capture the indeterminate nature of the crop and its response to weather conditions. The unreliability and delay in the present production estimations are posing serious problems to planners to take timely import–export decisions. Reliable prediction methods are therefore needed to help planners and policy makers take strategic decisions to safeguard national interest.

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Crop simulation models, which account for daily variation in weather, are being used to predict the year-to-year fluctuation in yield[3,4]. However, crop simulation models, when run with input data from a specific field site, produce a point output. Their scope can be extended to a regional scale by providing spatially varying inputs (soil, weather, crop management practices) using a geographic information system (GIS). The interfacing of models with GIS facilitates the temporal and spatial analysis of yield on a regional scale as crop behaviour has a spatial dimension and simulation models produce a temporal output[5]. Recent developments in GIS technology allow capture, storage and retrieval, and visualization and modelling of geographic data. Earlier there were few attempts to integrate crop models with GIS. In the European Union, the WOFOST model has been integrated with GIS for operational yield forecasting of important crops[6]. The crop growth monitoring system (CGMS) of the MARS (monitoring agriculture with remote sensing) integrates crop growth modelling (WOFOST), relational database ORACLE and GIS with the system's analytical part for yield forecasting[7]. In India, simulation model WTGROWS was integrated with GIS to simulate potential and water-limited wheat yields for 219 weather locations[8].

With the availability of multi-spectral (visible, near infrared) sensors on polar orbiting earth observation satellites, remote sensing (RS) data have become an important tool for crop-yield modelling[9–11]. In indeterminate crops like cotton, the poor relationship between leaf area index (LAI) and vegetation indices (VI) is one of the constraints for direct adoption of this approach for cotton-yield modelling[12]. However, remote sensing technology has immense potential for estimation of pre-harvest crop acreage and its distribution. The spatial distribution of the crop can be integrated with different pedo-climatic variables using GIS. The crop yield under different pedo-climatic variables can be estimated using crop simulation models. Thus, integration of crop simulation models with RS and GIS is useful for crop monitoring, modelling and forecasting of crop production.

A simple generic model, Infocrop, has been found to satisfactorily simulate the growth and yield of rice and wheat[3] and a number of other crops such as potato, pearl millet, soybean, maize and sorghum in the tropical and sub-tropical environments[13]. It simulates the effects of weather, soil, agronomic management practices (planting, nitrogen, residues and irrigation) and major pests on crop growth, yield, soil carbon, nitrogen, water and greenhouse gas emissions. Because of its simplicity, requirement of a limited number of easily measurable/available plant and soil parameters, and easy availability of the source code, it is found to be amenable for integration with GIS and RS. This article describes the results of our study on the calibration and validation of Infocrop to simulate the growth and yield of cotton, and a methodology to predict cotton production on a regional basis by integrating RS, GIS and Infocrop-cotton simulated yields. The detailed methodology is illustrated for Nagpur District and the results of other cotton-growing districts are also given.

Material and methods

Model description

Infocrop is a generic model to quantify the interactions of weather, variety, soil, N, water and pests on crop growth and yield. The basic model is written in Fortran Simulation Translator programming (FST/FSE; Graduate School of Production Ecology, Wageningen, The Netherlands), a language also adopted by the International Consortium for Agricultural Systems Applications (ICASA) as one of the standard languages for systems simulation[14]. A user-friendly version of the model has also been developed to expand its applications in agricultural research and development by the stakeholders not familiar with programming. The user-interface of this software is written using Microsoft.Net framework, while the back-end has FSE models and databases in MS-Access[13].

In Infocrop, the basic crop growth and yield processes follow Penning de Vries *et al.*[15] and Aggarwal *et al.*[16]. It simulates crop development, growth, yield and N accumulation in response to temperature, photoperiod, soil water and N supply. It uses a daily time-step, and is designed to predict yield, crop biomass, crop nitrogen uptake and partitioning within the crop. Brief descriptions of some of the well-established genetic coefficients which were used in the model development[17–22], are presented in Table 1. Details about the basic crop model are given by Aggarwal *et al.*[3].

Model calibration

Data collected from field experiments conducted during the season of 2002–03 at the Central Institute for Cotton Research (CICR), Nagpur farm on a fine, smectitic hyperthermic Typic Haplusterts were used to calibrate the model. The treatments involved were three sowing dates (15 June, 2 and 20 July) and three nitrogen doses (0, 45 and 90 kg ha^{-1}) arranged in a split-plot design with dates of sowing as main plots and fertilizer levels as sub-plot treatments. A long-duration intra-hirsutum hybrid, NHH 44 and a popular variety, LRA 5166 were grown at a spacing of 60 × 60 cm. Each treatment was replicated three times in plots of size 10 m × 8 m. Half dose of N and complete dose of P_2O_5 and K were applied 20 days after sowing. Rest of the N was applied in two equal splits at squaring and flowering. Plots were weeded manually and intercultural operations were done at regular intervals in the early growth stages until the canopy was closed. Insecticides

Table 1. Genetic coefficients set for the model calibration of a hybrid and a variety

Genotypic constant	Units	Hybrid	Variety	Reference
Base temperature	°C	15	15	4
Thermal time for				
Germination	Degree-days	70	70	Field experiments
Germination to anthesis (range)	Degree-days	800–900	700–800	
Anthesis to maturity (range)	Degree-days	1600–1900	1500–1700	
Optimum temperature (°C) for seedling emergence, squaring, flowering and boll development	°C	28	28	4, 17
Specific leaf area (SLA)	$dm^2\ mg^{-1}$	0.0022	0.0020	Field experiments
Relative growth rate of leaves during early stage	$(°C\text{-}d)^{-1}$	0.0095	0.009	3, field experiments
Radiation use efficiency (range)	$g\ MJ^{-1}\ day^{-1}$	1.5–1.8	1.4–1.6	18
Extinction coefficient of leaf at flowering	ha soil ha^{-1} leaf	0.80	0.70	3, 18
Contribution of bracts and capsules to photosynthesis	Per cent	15	15	19
Potential boll weight	mg $boll^{-1}$	5000	4000	Data from All-India
				Coordinated Cotton
Potential boll load	Million bolls/ha	1.4–1.6	1.2–1.4	Improvement Project
Root extension growth rate	mm day^{-1}	12	12	20
Biomass partitioning				
At emergence seed biomass in				
Root	Fraction	0.6	0.6	4
Above ground		0.4	0.4	
At early seedling				
Root		0.35	0.35	4
Above ground		0.65	0.65	
Squaring				
Leaf		0.7		Field experiments
Stem		0.3		
Flowering				
Leaf		0.4		
Stem		0.6		
Early boll development				
Leaf		0.1		
Stem		0.2		
Seed rate	kg/ha	2.5	5.0	Recommended
Sensitivity to flooding (between scale 1.0 and 1.2)		1.0	1.0	21
Index of greenness of leaves (between scale 0.8 and 1.2)		1.0	1.0	Field experiments
Photosensitivity	–	Commercially grown cultivars are photoinsensitive		4, 22

were used according to the recommendations to control sucking pests, *Helicoverpa armigera* and *Pectinophora gossypiella*. Sampling was done at every 15-day interval. Plants from 1 m^2 area were cut above the soil surface from the inner four rows of each plot. Each sample was partitioned into leaf (lamina), stem (including petioles), squares, green bolls and open bolls. Leaf area of a few representative leaves was measured using leaf area meter (LICOR-3000, Lincoln, USA) and their dry weight was recorded. Using this area : weight relation the leaf area of the whole plant at each of the sampling dates was calculated for all the treatments. The shed plant parts such as leaves, squares, flowers and bolls were collected at regular intervals and added to the weight of the respective plant parts.

Before sowing, the soil profile was examined and horizon-wise soil samples were analysed for texture, soil reaction, EC, bulk density, soil moisture constants, saturated hydraulic conductivity, organic carbon, $CaCO_3$, exchangeable cations, CEC, initial ammonical N, nitrate N, available P and available K.

Model parameters such as radiation use efficiency (RUE), light extinction coefficient, root growth rate and mobilization of reserve carbohydrate of cotton, which are relatively stable, were obtained from the literature. With the incorporation of the above weather, soil and crop parameters, the model was run to simulate the phenology, growth and yield of normal and late-sown hybrid and variety at different 'N' levels.

Model validation

Datasets collected from similar experiments as described above (involving date of sowing and nitrogen level) conducted under the Technology Mission on Cotton Project funded by the Government of India were utilized for model validation. Field experiments were conducted dur-

Table 2. Experiments and their details used for model validation under water-limited and nitrogen-limited environments. Treatments differed in location, genotypes, irrigation, date of sowing and nitrogen levels

Location	Latitude/ Longitude	Agro-eco region	Year	Genotype	Hybrid or variety	Sowing in Julian days		N level (kg/ha)	No. of treat-ments	Temperature range (°C)		Solar radiation (MJ m²/day)*	Rain-fall (mm)*
						Rainfed	Irrigated			Maxi-mum	Mini-mum		
Coimbatore	11°00′N, 77°00′E	Hot semiarid	2003	LRA 5166	Variety	–	221, 231, 261	0, 60, 90, 120	12	26.5–34.7	14.0–25.0	22.1–28.8	500–700
Dharwad	15°27′N, 75°05′E	Hot semiarid	1996	Abadhita	Variety	178, 198,	–	90	3	22.8–31.9	10.9–21.5	8.2–22.1	400–600
			1997	Abadhita	Variety	218, 198,	–	90	2				
			1997	Abadhita	Variety	216, 218	–	90	1				
Nagpur	21°09′N, 79°09′E	Hot dry sub-humid	2001	NHH 44	Hybrid	187, 202, 217	–	90	3	23.8–40.5	12.2–28.4	6.4–19.0	700–900
			2002	NHH 44	Hybrid	166, 183, 201	–	0, 45,	12				
							–	90, 135					
			2003	NHH 44	Hybrid	175, 191	175, 191	90	4				
				LRA 5166	Variety	175	175	60	2				
			2004	NHH 44	Hybrid	192	192	90	2				
Surat	21°12′N, 72°52′E	Hot semiarid	2001	GCOT Hy 10	Hybrid	–	183, 198, 213	120, 240, 360	9	24.7–39.0	12.5–28.0	9.5–26.5	700–900
			2002	GCOT Hy 10	Hybrid	–	182	120, 240	2				
			2003	GCOT Hy 10	Hybrid	171, 191	171, 191	240	4				
Hisar	29°10′N, 75°46′E	Hot typic arid	2001	H 1098	Variety	–	132	40, 80,	3	25.4–45.5	11.9–32.5	10.0–28.0	
			2002	H 1098	Variety	–	123, 141, 156	120 80	3				

*Values are ranges during the crop growth period.

ing 2000–01, 2002–03, 2003–04 and 2004–05 seasons in different cotton-growing states of India, spreading from Hisar (29°N) in the north to Coimbatore (11°N) in the south (Table 2). There was a wide variation in temperature, solar radiation and rainfall across these regions. Cotton was grown under rainfed conditions at Nagpur and Dharwad, and irrigated condition at Coimbatore and Hisar. At Surat, one or two protective irrigations were given. At each location the popular variety or the hybrid was selected for the experiment (Table 2).

Digital analysis of satellite data

Standard digital analysis technique employing complete enumeration approach using in-season ground truth information was followed for deriving information on spatial extent of cotton crop in Nagpur, Dharwad, Bharuch and Sirsa districts. The IRS LISS-III satellite data of 24 m resolution of October/November months corresponding to the optimal bio-window of cotton crop was used in the study. In-season ground truth information on land use/land cover was collected and marked on LISS-III false colour composite prints. Based on the ground truth, training areas for different agricultural land use/ cover classes were defined and signatures were generated in terms of mean, variance and co-variance matrices. These signatures were used in the classification of satellite data employing supervised maximum likelihood algorithm to derive the spatial distribution of cotton crop of the district by overlaying the administrative boundary.

Spatial integration of crop, soil and weather parameters with Infocrop simulation model

The distribution of cotton crop derived from satellite data was spatially integrated with pedo-climatic variables, viz. soil type, soil depth and rainfall using GIS techniques. The soil map 1 : 50,000 scale developed by the National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur[23] was digitized in an Arc GIS environment. This shape file was further integrated with soil parameters, viz. soil depth (six classes – extremely shallow, very shallow, shallow, moderately shallow, moderately deep and deep) and six textural classes (fine clay, clay, fine loamy, loamy, coarse loamy and loamy skeletal). Using long-term rainfall data of 14 rain gauges located in Nagpur District, nine homogenous thessien polygons were identified. Unified soil maps (depth and texture) were overlaid to identify homogenous units for running the model. Similar exercise was undertaken for Dharwad (Karnataka), Bharuch (Gujarat) and Sirsa (Haryana) districts. The district maps were prepared from the soil re-

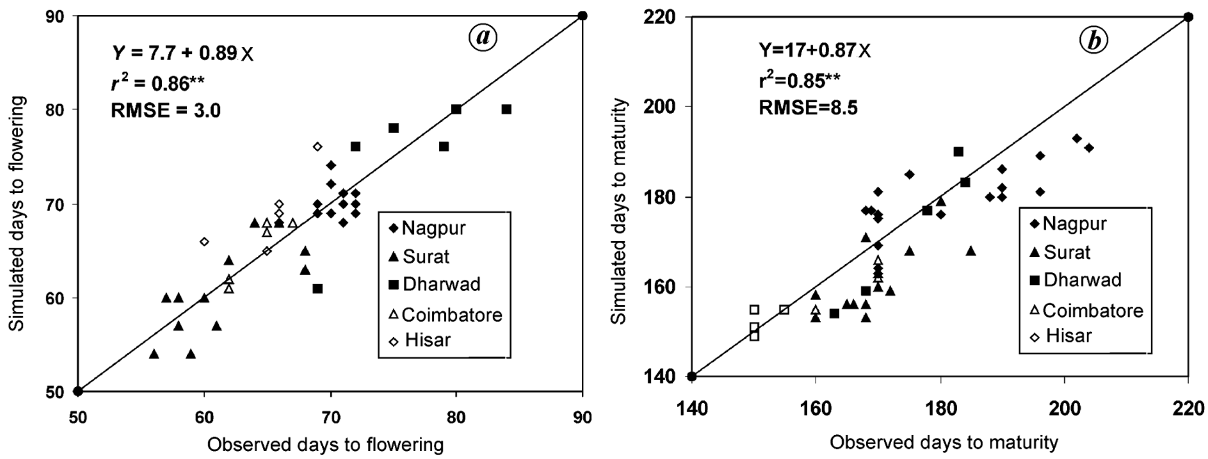

Figure 1. Simulated and measured duration to (*a*) flowering and (*b*) maturity across datasets varying in location, year, season, weather, N management, sowing date and genotype. The 1 : 1 line is also presented.

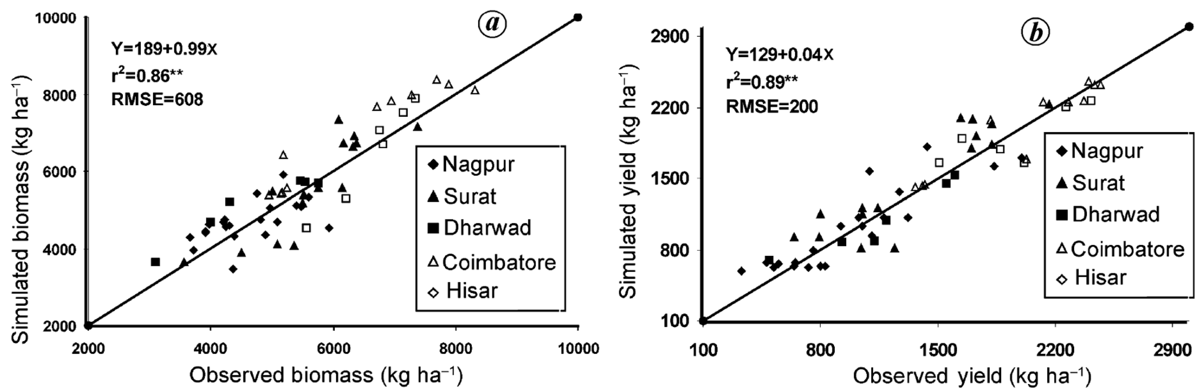

Figure 2. Simulated and observed (*a*) biomass and (*b*) seed cotton yield across datasets varying in location, year, season, weather, N management, sowing date and genotype. The 1 : 1 line is also presented.

source maps (1 : 50,000) of Karnataka[24], Gujarat[25] and Haryana[26].

The cotton crop map in vector format was integrated with soil map for estimating the proportion of cotton crop cultivated under different soil depth and texture classes for each of the nine-thessien polygons. For each polygon class, the Infocrop model was run and the yield was computed for two sowing dates (20 and 30 June) for different soil depth and soil texture combinations using daily weather data. The mean yield (over sowing dates) was multiplied with the area under cotton in each polygon (the chosen polygon is unique, with uniform soil depth and texture parameters) to provide the production at disaggregated level.

Statistical analysis

Data from the field experiments were analysed using split-plot design. Comparisons were made between the simulated (Y) and observed (X) data with regression analyses of the form $Y = a + bX$. Measures of accuracy were made with the adjusted coefficient of determination (r^2) and the root mean squared error (RMSE) between simulated and observed values.

Results and discussion

Model validation

Phenology: In the datasets used for model validation, large variation was seen for time to flowering and maturity. The former ranged from 56 to 84 days, whereas the latter ranged from 150 to 204 days. Year-to-year fluctuation was more under rainfed compared to irrigated condition. The simulated time to flowering ranged between 54 and 80 days, with an RMSE value of 3 days (Figure 1 *a*), whereas time to maturity ranged between 136 and 193 days with an RMSE of 8.5 days (Figure 1 *b*). In most parts of India, cotton at early growth stages suffers from intermittent drought, waterlogging and insect attack and at later stages, owing to its indeterminate growth habit produces multiple flushes of squares and bolls. This complicates the determination of exact time to physiological maturity, causing poor relationship between phenology and heat unit under adverse conditions. This might partially explain the discrepancies between observed and simulated phenology[27,28].

Biomass and yield: Data depicted in Figure 2 *a* and *b* indicate that there was a close relationship between the simulated and observed biomass, and seed cotton yield across all treatments comprising location, season, genotype, sowing date and N level. Measured biomass and seed cotton yield ranged from 3096 to 8319 kg ha^{-1} and 590 to 2466 kg ha^{-1} respectively. Though there is a good correlation between vegetative growth and fruit load in cotton[29], this is offset by the loss of fruiting forms caused by biotic and abiotic factors under rainfed condition. Despite the above complexities the model-simulated yield showed an accuracy of 89%, with an RMSE of 200 kg ha^{-1}. Simulated biomass on the other hand, showed 86% accuracy with an RMSE value of 608 kg ha^{-1}. The difficulty in recording of biomass lost as litter (leaves, squares and bolls) between observations could partly explain the relatively larger variance between simulated and observed biomass.

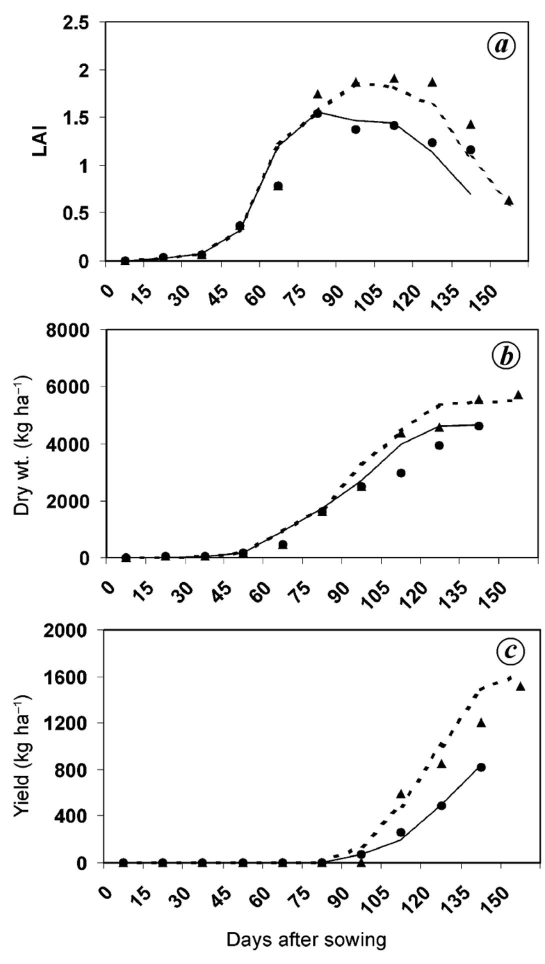

Figure 3. Observed (symbols) and simulated (line) (*a*) LAI, (*b*) biomass and (*c*) seed cotton yield in a dryland (observed (•) and simulated (–)) and irrigated (observed (▲) and simulated (-----)) experiment with intra-hirsutum hybrid (NHH 44) sown on 22 June 2004 on a vertisol at CICR Farm, Nagpur.

Effect of water stress: Water deficit is an important constraint in dryland cotton production. Cotton crop which is sown with the onset of monsoon, experiences intermittent drought owing to uneven distribution of rainfall, or terminal drought because of its early cessation. Figure 3 depicts the capability of the model to simulate the water-deficit effects on cotton (cv. NHH44) sown in 2004 at CICR farm, Nagpur without irrigation. In this experiment, the crop experienced a terminal drought and a single irrigation at early boll development significantly increased the LAI, biomass and seed cotton yield. The response to irrigation depicted in Figure 3 shows that the model could capture increased growth and yield with irrigation. The model also precisely simulated the crop duration, which was extended (as seen in Figure 3 with irrigation), with the application of irrigation.

Spatial distribution of cotton crop in Nagpur District: The classified Resourcesat-1 LISS-III satellite data showing spatial distribution of cotton crop are given in Figure 4, with cotton crop depicted in green colour and area of cotton crop estimated as 72,587 ha. Cotton crop in Nagpur District is mostly concentrated in the western part, as indicated in red colour on the satellite data. The integrated soil and crop analysis showed that about two-third of cotton crop in Nagpur District is grown in deep soils. Though very shallow soils are not congenial for cotton cultivation[30], about 22% of cotton is being cultivated in such soils (Figure 4 *a*). Similarly, about two-third of cotton cultivation is on fine-textured clayey soils and nearly 20% is distributed on coarse textured soils (Figure 4 *b*). Area of cotton crop under different soil depth and soil type regimes, individually and across all combinations for each of the nine-polythesian triangles of Nagpur District is presented in Table 3. A unique polygon id was given for a unique combination of station, soil type and soil depth, thus generating about 58 unique polygons. The number of unique polygons may vary from year to year based on the distribution of the cropped area.

The rainfall in different polygons during 2004 ranged from 510 to 763 mm and this was received over 35–43 rainy days (days with > 2.5 mm rainfall). Considerable

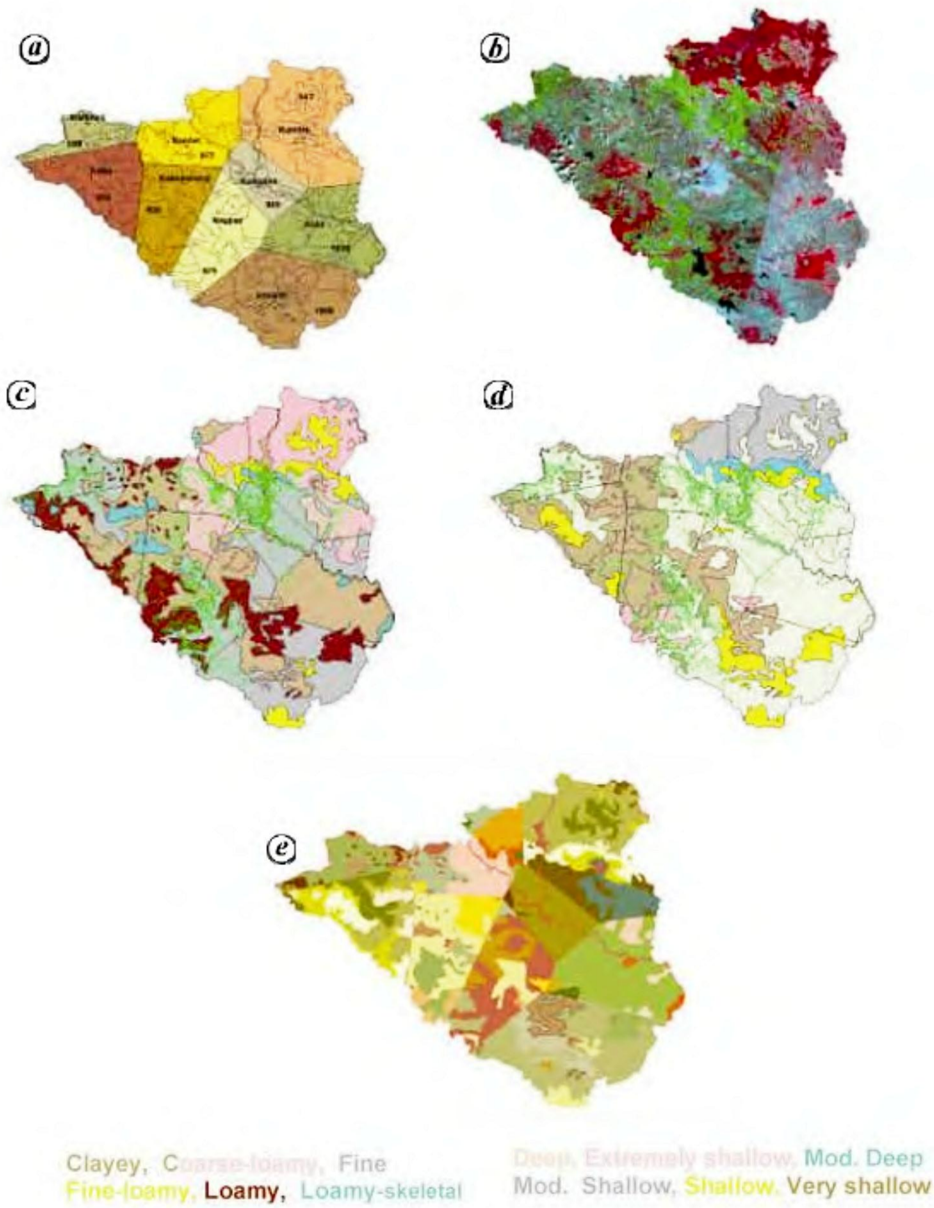

Figure 4. ***a***, Unified soil resource map with rain gauge network. ***b***, Classified crop map showing spatial distribution of cotton crop in Nagpur District (green colour). ***c***, ***d***, Soil texture map and soil depth map of Nagpur District with distribution of cotton overlaid. ***e***, homogenous polygons with station, soil type and soil depth.

variation was observed in simulated productivity (Table 3) and this could be assigned to differences in the soil (depth and texture) and rainfall distribution pattern across stations. The integrated approach offers details on productivity estimates across stations combined with soil type and depth, which can be examined for further improvement in productivity. The integrated approach has been validated to a few more years at Nagpur District and other cotton-growing districts of Dharwad, Bharuch and Sirsa (Table 4). RS estimated cotton area at an accuracy of above 95% to the above cotton-growing districts, except Dharwad where cotton is grown both in kharif and rabi seasons; in this observation, RS captured only kharif cotton. The prediction of cotton production using the integrated approach was found to be more accurate in the irrigated cotton belt of Sirsa District and the partially irri-

Table 3. Polygon features and estimated area, production and productivity of cotton in Nagpur District

Polygon	Rainfall (m) June–December	Rainy days (no.)	Composite soil unit (no.)[a]	Dominant soil unit	Area (ha)	Area under dominant soil unit (ha)[b]	Productivity (kg/ha)[c]	Production (bales)*
On station basis								
Kalmeshwar	751	42	6	Clay, 18 cm	9693	4728 (49%)	361	20,587
Kamptee	742	35	4	Fine clay, 120 cm	9483	8996 (95%)	497	27,723
Katol	540	36	5	Clay, 18 cm	4412	1494 (34%)	397	10,307
Kuhi	590	38	6	Fine clay, 120 cm	759	404 (53%)	473	2940
Nagpur	672	39	6	Fine clay, 120 cm	11745	6883 (58%)	313	21,653
Narkhed	533	37	4	Fine clay, 120 cm	7950	6396 (80%)	392	18,326
Ramtek	750	37	7	Fine clay, 120 cm	11004	4728 (43%)	630	40,749
Saoner	737	42	9	Coarse loamy, 120 cm	14587	9458 (65%)	577	49,480
Umred	763	43	7	Fine clay, 120 cm	2956	2627 (89%)	441	7659
Total					72589		465	198,594

[a]Soil depth and texture combination; [b]Percentage of total area in polygon; [c]Simulated yield (mean over 170 and 180 Julian days).
*Bale = 170 kg lint fibre.

On soil-type basis

Soil type	Area (ha)	Productivity (kg/ha)	Production (bales)
Clay	11244	150	9941
Coarse loamy	16220	698	66,553
Fine	33192	482	94,084
Fine loamy	3729	729	15,982
Loamy	8014	249	11,724
Loamy skeletal	188	281	311

On soil-depth basis

Soil depth (cm)	Area (ha)	Productivity (kg/ha)	Production (bales)
18	18,890	188	20,854
45	1629	363	3476
60	749	463	2039
90	2049	643	7754
120	49,271	567	164,471

gated Bharuch District, while the discrepancies between the official and estimated values were high in the rainfed tracts of Nagpur and Dharwad. In most cases the integrated approach over-estimated productivity because at this juncture the model did not account for the loss due to insect pests. At Sirsa and Bharuch cotton is mostly monocropped. However, nearly 20% of cotton area under Nagpur District is intercropped with pigeon pea. In Dharwad also cotton is intercropped with onion and chillies in replacement series and the actual area planted under cotton is less. If the above losses and discrepancies were accounted for in the model, the predicted yield would be more accurate with the observed yield in Nagpur as well as Dharwad districts. Since the difference is considerable, there is need for a closer look at the official estimates (large discrepancy between Ministry of Textiles and State Government estimates) as well as simulated productivity values. A calibrated and validated model like the one described above, would offer a better choice than the black-box approach of official estimates, which does not furnish information on productivity at a lower level than a district. Thus there is little scope to verify the simulated productivity estimates across rainfall stations within a district. One possible solution could be to carry out a sample survey for productivity estimates across soil types and stations, and compare the same with the simulated values. Further, the model-based estimates can be made available before the end of the crop season. The integrated approach offers an insight into the production potentials within a district for crop production, considering the available resources.

Conclusion

This article reports a crop-simulation model for cotton, a widely cultivated commercial crop in the tropics and subtropics. Infocrop, a generic model was used to simulate cotton growth and yield under rainfed as well as irrigated conditions by modifying certain genetic coefficients based

Table 4. Cotton area, production and productivity estimated by the integrated approach, official values and their deviation for Nagpur, Dharwad, Bharuch and Sirsa districts

District	Year	Area (ha)		Percentage deviation	Productivity (kg/ha)		Percentage deviation	Production ('000 bales)		Percentage deviation
		Estimated	Official		Estimated	Official		Estimated	Official	
Nagpur	2003–04	78,410	74,300	5	220	264	–20	101.00	115.40	–14
	2004–05	72,587	75,300	–4	465	235	49	198.00	104.30	47
	2005–06	78,490	73,300	7	540	229	58	249.00	98.80	60
	2006–07	68,435	–	–	589	–	–	237.00	–	–
Dharwad	2004–05	159,018	86,480	46	184	139	24	172.00	70.95	59
Bharuch	2004–05	131,526	129,700	1	478	439	8	409.00	335.00	18
	2005–06	138,439	148,000	–7	530	499	6	431.00	485.00	–13
	2006–07	130,233	149,300	–15	495	435	12	379.00	381.00	–1
Sirsa	2005–06	192,000	190,000	1	550	581	–6	622.00	649.00	–4
	2006–07	198,116	194,000	2	535	620	–16	624.00	707.00	–13

on the physiology of the crop. The model was calibrated and later validated using datasets generated through multi-location experiments conducted under diverse climate, soil and management conditions. Despite the relatively simple approach employed, the model gives good predictive capability for cotton phenology, leaf area, biomass, seed cotton yield under diverse growing conditions (dryland and irrigated), cultivars (varieties and hybrids) and management conditions (date of sowing, fertilizer level, irrigation). Since the model is simple and had shown good predictions, it was interfaced with GIS and RS data for the prediction of cotton production in Nagpur, Dharwad, Bharuch and Sirsa districts. The integrated approach prediction of cotton production was found to be more accurate in the irrigated cotton belt of Sirsa and the partially irrigated Bharuch districts, while the discrepancies between the official and estimated values were high in the rainfed tracts of Nagpur and Dharwad. Though the non-inclusion of pest component and the mixed cropping systems could explain the above discrepancies, it still calls for a closer look at the official estimates as well as simulated productivity values.

1. Anon., Cotton world statistics. In Bulletin of the International Cotton Advisory Committee, Washington DC, USA, September 2006.
2. Sinha, S. K., Singh, G. B. and Rai, M., Is decline in crop productivity in Haryana and Punjab a myth or reality? Indian Council of Agricultural Research, New Delhi, 1998, p. 89.
3. Aggarwal, P. K., Kalra, N., Chander, S. and Pathak, H., Infocrop: a dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. *Agric. Syst.*, 2006, **89**, 1–25.
4. Reddy, K. R., Hodges, H. F. and McKinion, J. M., Crop modelling and applications: a cotton example. *Adv. Agron.*, 1997, **59**, 225–289.
5. Hartkamp, A. D., White, J. W. and Hoogenboom, G., Interfacing Geographic Information system with agronomic modelling: a review. *Agron. J.*, 1999, **91**, 764–772.
6. Meyer-Roux, J. and Vossen, P., The first phase of the MARS Project, 1988–1993; overview, methods and results. In Proceedings of the Conference on the MARS Project; Overview and Perspectives. Commission of the European Communities, Luxembourg, 1994, pp. 33–85.
7. Bouman, B. A. M., van Dipen, C. A., Vossen, P. and van Der Wal, T., Simulation and systems analysis tools for crop yield forecasting. In *Application of Systems Approaches at the Farm and Regional Levels* (eds Teng, P. S. *et al.*), Kluwer, Dordrecht, The Netherlands, 1997, vol. 1, pp. 325–340.
8. Aggarwal, P. K., Agro-ecological zoning using crop growth simulation models: characterization of wheat environments of India, In *Systems Approaches for Agricultural Development* (eds Penning de Vries, F. W. T., Teng, P. and Metselaar, K.), Kluwer, Dordrecht, The Netherlands, 1993, vol. 2, pp. 97–109.
9. Maas S. J., Using satellite data to improve model estimates of crop yield. *Agron J.*, 1988, **80**, 655–662.
10. Mali, P., Hara, C. O. and Anantharaj, V., Consideration and comparison of different remote sensing inputs for regional crop yield prediction model. In American Society of Photogrammetry and Remote Sensing, Annual Conference, Reno, Nevada, 1–5 May 2006.
11. Reynolds, C. A., Yitayew, M., Slack, D. C., Hutchinson, C. F., Huete, A. and Peterson, M. S., Estimating crop yields and production by integrating the FAO crop specific water balance model with real time. Satellite data and ground based ancillary data. *Int. J. Remote Sensing*, 2000, **21**, 3487–3508.
12. Perumal, N. K. *et al.*, Canopy spectral reflectance in cotton in relation to yield. *Indian J. Plant Physiol.*, 1999, **4**, 63–64.
13. Aggarwal, P. K., Joshi, P. K., Ingram, J. S. I. and Gupta, R. K., Adopting food systems of the Indo-Gangetic plains to global environmental change: Key information needs to improve policy formulation. *Environ. Sci. Policy*, 2004, **7**, 487–498.
14. Jones, J. W., Keating, B. A. and Porter, C. H., Approaches to modular model development. *Agric. Syst.*, 2001, **70**, 421–443.
15. Penning de Vries, F. N. T., Jansen, D. M., Ten Berge, H. F. M. and Bakema, A., Simulation of ecophysiological processes of growth in several annual crops. *Simulation Monographs 29*, 1989, Pudoc Wageningen.
16. Aggarwal, P. K., Kalra, N., Singh, A. K. and Sinha, S. K., Analyzing the limitations set by climatic factors, genotype, and water and nitrogen availability on productivity of wheat. I. The model documentation, parameterization and validation. *Field Crops Res.*, 1994, **38**, 73–91.
17. Hesketh, J. D., Baker, D. N. and Duncan, W. G., Simulation of growth and yield in cotton: II. Environmental control of morphogenesis. *Crop Sci.*, 1972, **12**, 436–439.
18. Sadras, V. O., Cotton responses to simulated insect damage: radiation use efficiency, canopy architecture and leaf nitrogen content

as affected by loss of reproductive organs. *Field Crops Res.*, 1996, **48**, 199–208.
19. Wullschleger, S. D., Oosterhuis, D. M. and Rutherford, S. A., Importance of bracts in the carbon economy of cotton. *Arkansas Farm Res.*, 1990, **39**, 4.
20. Pace, P. F., Harry, T., Cralle, Sherif, H. M., Halawany, El.-J., Cothren, T. and Senseman, S. A., Drought-induced changes in shoot and root growth of young cotton plants. *J. Cotton Sci.*, 1999, **3**, 183–187.
21. Hebbar, K. B., Effect of long duration waterlogging on growth and yield of *G. hirsutum* and G. *arboreum* genotypes of cotton at early seedling and flowering stages. *Indian J. Agric. Sci.*, **73**, 172–174.
22. Bhatt, J. G., Growth of cotton under rain fed conditions. In *Cotton Physiology* (eds Sundaram, V. and Rao, S. B. P.), Cotton Monograph Series, Indian Society for Cotton Improvement, Mumbai, 1996, pp. 26–37.
23. Challa, O., Vadivelu, S. and Sehgal, J., Soils of Maharashtra for optimizing land use. Report, NBSS&LUP Publ. 54b, NBSS&LUP, Nagpur, 1995, p. 6.
24. Shivaprasad, C. B., Lal, T., Rana, K. P. C., Sehgal, J. and Velayutham, M., Soils of Karnataka for optimizing land use. Report, NBSS&LUP Publ. 47b, NBSS&LUP, Nagpur, 1998, p. 111.
25. Sharma, J. P., Shyampura, R. C. and Sehgal, J., Soils of Gujarat for optimizing land use. Report, NBSS&LUP Publ. 29b, NBSS& LUP, Nagpur, 1994, p. 73.
26. Sachdeva, C. B., Lal, T. and Sehgal, J., Soils of Haryana for optimizing land use. Report, NBSS&LUP Publ. 44, NBSS&LUP, Nagpur, 1995, p. 59.
27. Krieg, D. R. and Hicks, S. K., Cotton lint yields response to accumulated heat units and soil water supply. *Field Crops Res.*, 1989, **19**, 253–262.
28. Hebbar, K. B., Venugopalan, M. V., Rao, M. R. K., Gadade, G. D., Chatterji, S. and Mayee, C. D., Effect of sowing dates and fertilizer levels on phenology, growth and yield of cotton. *Indian J. Plant Physiol.*, 2002, 7, 380–383.
29. Hearn, A. B., The growth and performance of rain-grown cotton in a tropical upland environment. II. The relationship between yield and growth. *J. Agric. Sci.*, 1972, **79**, 137–145.
30. Sehgal, J. L. and Yadav, S. C., Soil site suitability criteria for cotton. *J. Indian Sci. Cotton Improv.*, 1995, **20**, 60–65.

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MODELING INSECT POPULATIONS

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1.0 INTRODUCTION

Modeling insect populations is important for understanding and predicting their population dynamics. Insect pests are influenced by both macro and micro-weather parameters: temperature, rainfall, humidity, sunshine hours, wind speed and direction. The rates at which insects complete their life cycles depend mainly on temperature, so that the times of activity of a given pest insect can vary greatly both from region to region and from year to year. In addition to influence of weather, insect pest appearance and regulation of numbers are governed by other interactions with the availability of susceptible plant hosts and their natural enemies such as parasitoids and predators. Parameters along with the type of influence they exert on insect abundance are given in Table 1.

Table 1. Parameters influencing insect abundance

Category	Parameter	Type of influence on insects
Weather	Temperature (maximum and minimum)	Insect developmental rate, diapause
	Humidity (morning and evening)	Oviposition, egg hatch
	Rainfall (amount and distribution)	Adult emergence, oviposition, wash-out
	Bright sunshine hours	Oviposition
	Wind speed and direction	Dispersal and migration
	Microclimatic parameters (canopy temperature, humidity, leaf wetness, soil temperature)	Development and rate of spread
Crop attributes	Genotype	Rate of development, foci of infestation
	Phenology	Pest appearance and intensity
	Crop stand	Dispersal
	Nutrition	Fecundity
	Time of sowing	Pest onset
	Cropping system/alternate hosts/previous crop	Off-season survival, carry over
Pest attributes	Life stages and their duration	Generation number and duration
	Conditions for stage transfer	Diapause
	Timing of reproduction	Pest onset
	Fecundity	Pest abundance
	Mortality factors	Pest regulation

2.0 INSECT POPULATION MODELING – APPROACHES

Important points for consideration in any model development are: the level of detail at which a given model is to be developed as the level of detail is linked to the objective and data availability to develop and run the model. Models can range from strictly empirical to most complex and sophisticated descriptive models. A model may be discrete or continuous, static or dynamic, and deterministic or stochastic.

2.1 EMPIRICAL APPROACHES

Empirical approaches involve estimating pest and disease incidence and intensity through experimentation and surveys on crops not subjected to control interventions and establishing relationships with concurrent, prevailing weather and/or past weather factors. The studies could be conducted at single stations in which the emphasis is on delineation of differences in meteorological conditions in epidemic and non-epidemic years or multi-station studies in which the emphasis is on delineation of meteorological conditions leading to changes in periods and intensity of infestations. A multi-station study is preferred as it facilitates corroboration of the general surmises and leads to maximization of data in a short period if observations are recorded on crop stands sown at periodic intervals at a number of stations (Venkataraman and Krishnan, 1992). It should be noted that findings from empirical field studies can straight away be applied in climatologically analogous areas but can give misleading results when applied to other areas.

Development of an empirical forecast model is not an end in itself. Even the simplest model must be tested to be proven, but validation over a wide range of conditions will be most important for models based on empirical rather than biological and physical processes, or where there is insufficient understanding and quantification of how interactions change under varying environmental conditions. Any type of forecast model needs to be fully described for running the model, correct interpretation of the output and its effective dissemination and operational use. Synthesis of model elements into a computer program would be an ideal logical step to make available a product for operational use in agro-advisories.

Many empirical models use various types of pest/disease incidence data (trap catches, population counts and crop damage assessments). Many research articles published on pest-weather relationships used pest monitoring data from light traps (for example yellow stem borer in rice), pheromone traps (for American bollworm) and sticky traps (for whitefly) apart from population counts and damage assessment data. Long-term data is preferable as it better captures the patterns in relationships. These models also require access to weather and climate data, in addition to pest and plant data. Models usually require as inputs, measurements of temperature, rainfall and humidity, although other variables may be required either as direct inputs or in computing values for variables not measured. Weather variables need to be measured at the field level, at regional stations, or on a broader scale depending on the need. For many farm management actions, data representative of the field conditions are expected and hence data is taken from automatic weather stations or the nearest observatory.

2.2 INSECT PHENOLOGY MODELS

Insect phenology modeling is based on insect life cycles. These models are developed using temperature data to forecast timing of insect activity. Insects have different development stages, the developmental durations of which are based on temperature above a lower developmental threshold known as base temperature. Different insect stages can have different lower thresholds (Table 2). A day-degree is defined as one degree of average temperature above a base temperature over a 24 h period. The duration of the insect stage is expressed in day-degrees. Once the required day-degrees are completed, the insect moves into the next stage in its development. Hence, expression of insect development in day-degrees gives it a mathematical expression and is better than using calendar days. Relatively crude methods of computing day-degrees are sufficient for many applications. Most forecasting models on diurnal variation rely on approximations using sine waves. Degree days are accumulated from a start date known as 'bio-fix'. These start dates are generally based on the first adult trap catch using pheromone traps or first notice of eggs in field or planting date etc. The degree day approach allows the prediction of the biological events in the insect development using temperature data. The stage-specific thermal constants are arrived at by studying insect development at several constant temperatures. Often the lower threshold is an approximation by extrapolating the linear portion of the development rate curve. Day-degree forecasts, in general, cannot readily predict insect populations that have overlapping generations in a year. In this case day-degree approach may be restricted to the first or second generation of the pest. In temperate countries with clear start and end of cropping seasons, insect modeling is majorly through insect phenology models, However, in the tropics where cropping is year-round and winter is not very severe (except in North India), phenology models can be accurately be applied mostly to insect pests with one or few distinct generations in a year.

Table 2: Threshold temperatures and degree days for completion of different life stages of Groundnut leaf miner life cycle

Life stage	Temperature threshold (^{0}C)	Degree Days	Development duration (days) at 30^{0}C constant temperature	Development duration (days) at variable temperatures (30^{0}C MaxT and 24^{0}C MinT)
Egg	12.4	60	3.4	4.8
Larva	11.3	327	17.5	23.9
Pupae	14.7	72	4.7	7.0
Adult	3.0	202	7.5	9.2

2.3 DATA MINING APPROACHES

Many times when statistical correlations and regressions are attempted through step-wise regression or multiple regression models and applied to pest data and corresponding weather data from several years, it is observed that in different years different weather parameters show significant influence. The criteria for best fit model selection is based on the Co-efficient of determination (R^2) which explains the extent of variability in the insect population explained with the independent factors (weather parameters) chosen. The R^2 values in many models are low and hence poor explain the variation and instill low confidence in the model for prediction purposes. Data mining is a useful technique to bring out patterns in when long-term data has been collected on pests, crops, their sowing times, cultivars, cropping pattern, insecticide use along with weather factors. Similar to regression models, data mining technique also gives two measures which help in fine tuning the assumptions or association rules made. One is the measure of support and another is the measure of confidence. For example, we applied data mining technique to study yellow stem borer population relationship with weather parameters. An association rule was developed as ñWhen rainfall is less than 8 mm and sunshine hours greater than 8 hrs, possibility of moth catch greater than 100 has got a support of 40.2 percent and confidence of 75.4 per centò. In other words, nearly forty per cent of the cases in the data set supported total weekly moth catches of more than 100, when the prevailing total rainfall in that particular week was less than 8 mm and mean sunshine hours were more than 8 h. The high confidence value (75.4%) showed that YSB adult emergence was strongly influenced by rainfall and sunshine hours. Neural network model was developed by training the network with weekly moth catch data and corresponding lag weather data from 1975 to 1996. Validation of neural network model was carried out with the data of subsequent years i.e. 1997, 1998, 1999 and 2000 for *kharif* (Fig.1) and 1998, 1999 and 2000 for *rabi*. The time of occurrence of peaks and trend in pest dynamics was well predicted in all the four years of study though the intensity of peaks was not estimated accurately. This information could be very useful to forewarn peak moth emergence activity of yellow stem borer in rice for the specific location.

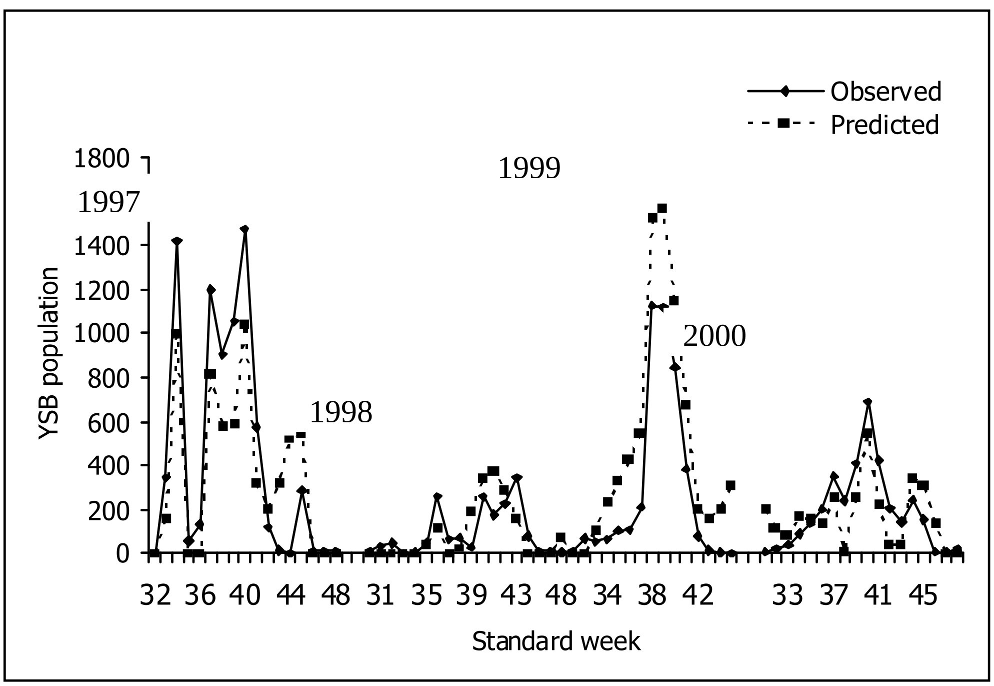

Fig.1. Validation of neural network model on rice YSB in kharif season

2.4 MODELING SOIL MOSITURE FOR ESTIMATING SOWING TIMES AND INFLUENCE ON INSECT POPULATIONS

A soil-moisture model was adopted for estimation of leaf miner severity in Karnataka (Gadgil *et al.*, 1999). In the model it is assumed that leaf miner populations are always present at a low level. Whenever favorable weather conditions occur in the appropriate growth stage of the crop, population builds up rapidly. However, if a drenching shower (> 2 cm/day) occurs in the first 14 leaf miner days (starting 35 days after sowing), it is assumed that the leaf miner is eliminated. A leaf miner day has been defined as a non-rainy day with dry soil (< half of the available soil moisture). In this model the loss in crop yield due to leaf miner incidence is taken to depend upon the number of leaf miner days. The soil moisture model estimates the sowing dates in a given region based on rainfall and soil data and then estimates the leafminer days 35 days after sowing based on model assumptions.

2.5 PROCESS BASED MODELING OFINSECT POPULATIONS – DYMEX SOFTWARE

A review of research articles that were published in pest forecasting related aspects since 1980 within and outside India in rice and cotton, two crops of global importance, was undertaken. A significant percentage of research effort has been directed towards studies on monitoring and seasonal occurrence followed by studies that establish insect pest relationships with weather in India in both the crops (Prasad, 2005). Despite the availability of a variety of information that can become input to building reliable process forecast models, the trend reflects a lack of concerted and directed research to develop process based models and decision support systems in India vis-à-vis the trend abroad particularly in crops like cotton and rice where pesticide use is still the highest in the country. The main limitation is the availability of appropriate indigenous software packages that can consider dynamics of animal and plant populations that are influenced by many factors, and understanding the response of a population to a multitude of external factors can be very difficult.

Simulation models are a powerful means of representing such systems and allowing users to interact with them. These models help to summarize our understanding of a speciesô population dynamics, identify gaps in knowledge and enable rapid evaluation of management options. Building population models, however, can be expensive in time, and may require specialist programming skills. The DYMEX package is designed to overcome the bottleneck caused by inadequate computer programming resources and modeling expertise. DYMEX enables the user to build a class of ecological models referred to as mechanistic or process-based models, without the need to know a computer programming language. It is a modular modelling software package that consists of two parts: a *Builder* and a *Simulator*. The *Builder* is used to create and modify the model, while the *Simulator* is used to run a completed model, and display the results of simulations.

DYMEX is a computer software package that enables you to interactively build and then run models of fluctuating populations of organisms in changing environments. Models are structured around lifecycles, which in turn consist of the stages that individuals pass through during their life. A DYMEX lifecycle describes cohorts of individuals and the processes that affect the size, age and number of individuals in the cohort (individuals of same stage and age). Models created within DYMEX consist of a series of modules, with each module responsible for a particular task. Modules use information from other modules as input, and supply information to other modules. DYMEX comes with a library of modules that can be incorporated into any model constructed with the Builder. Each module performs a specific function (for example, MetBase is used to read a standard set of meteorological variables from a file). Models created in the *Builder* can be opened in the *Simulator* within which simulations can be run. The results of these simulations can be displayed in tables, graphs and maps as well as exported to other programs. Models will normally be developed around one or more Lifecycle modules. Other modules provide data to the lifecycle modules, or manipulate lifecycle output in some way. Many modules have multiple uses (e.g. Function module) and may be used in several places in a model, while others are more specialised (e.g. the Soil Moisture module). Most modules receive input fromanother module or from an outside source.

3.0 DECSION SUPPORT SYSTEMS AND AGROMETEOROLGOICAL NETWORKS FOR PEST FORECAST AND ADVISORY SERVICES

East Germany began developing forecasting procedures for the occurrence of important crop plant diseases and insect pests by designing simulation models (system PROGEB) (Gutsche, 2001) in the 1980ǿs. Later after the German re-unification the project was run under the name PASO which resulted in introduction of a number of forecasting models in practice throughout Germany. To ensure stable operation of the forecast and decision support system by the state crop protection service an keep the system open for innovations, the federal states set up a ŏCentral Service for Decision Support Systems and Programmes in Crop Protectionô which is successfully being operated since 1998.

The Slovenian plant protection forecasting service runs an agrometeorological network of 94 uniform weather stations in 7 centres to collect meteorological information (temperature, humidity, precipitation and leaf wetness) automatically by radio. The data is analysed at the central data collection facilities to determine pest risk and other farm operations. In addition to weather station measurements, information from field monitoring, insect and spore traps, observations of crop phenological phases was used in forecasting models for pests and diseases processed by software (AgroExpert, ProPlant). The warnings were disseminated to growers by a variety of means (Knapic et al, 2001)

In Norway, a web-based warning system called VIPS has been developed which calculates warnings for than 70 weather stations for several pests and diseases in selected fruits, vegetables and cereals. Warnings are site specific with validated meteorological data from an authorized station and validated biological data necessary to run the models supplied by the extension service (Folkedal and Brevig, 2001).

Yonow *et al*., (2004) developed a cohort-based life cycle model for the population dynamics of the Queensland fruit fly using DYMEX model (Maywald et al., 1999), a process-based, modular modelling software package that contains a library of modules. The model is primarily driven by weather variables, and so can be used at any location where appropriate meteorological data are available. DYMEX model helped to improve the understanding of fruitfly population dynamics and relative abundance, and in so doing, identify critical gaps in knowledge.

Using climatic modeling, risk of establishment of invasive species has been successfully defined *a priori* in Europe (Sutherst *et al*., 1991). Samways *et al*., (1999) used the CLIMEX model (Sutherst *et al*., 1995, 1999) and itôs associated ôMatch Climatesö, climate-matching algorithm to make their predictions of species geographical ranges. The CLIMEX model is a simulation model of moderate complexity for inferring the responses of a species to climate from its geographical distribution. Once response functions have been fitted, the model can be run with meteorological data from other parts of the world to estimate the species response to new climatic environments. The potential range, as determined by climate, can then be estimated. The model parameter values constitute the hypotheses on the climatic factors that determine the species population growth, and survival during adverse seasonal conditions, and so limit the geographical distribution. Alternatively, the meteorological data base can be manipulated to create scenarios of climate change.

Decision support systems are widely accepted in the Australian cotton industry for assisting with integrated pest management, crop nutrition and other aspects of information transfer. Uses of EntomoLOGIC, part of the CottonLOGIC software suite, select sample areas in their cotton fields and collect information on the types of beneficial and pest insects present, their stage of development and quantity. The hand held electronic device facilitates data entry process, running models of pest development, generates in-field reports of pest status, access to historical data on insects and crops. The software is then used to predict future pest numbers, using weather data, and indicates when pest numbers are over defined economic thresholds for crop managers to decide on appropriate pest management interventions (Bange *et al*., 2004).

CONCLUSIONS

Modeling insect populations requires adequate understanding of their life cycles and the multitude factors that affect their population dynamics. Empirical models developed from long term data capture the fluctuations in populations over seasons and years better than short period data. These models are highly location specific and generally cannot be applied to other locations except those which are climatologically and ecologically analogous. In contract models based on insect life cycles such as phenology models are simple to construct and once established can be run with temperature data. However, their application is limited to monocyclic pests and regions which have distinct cropping seasons such as those in temperate regions. Simulation models that are again based on life cycles and also take into account several factors along with weather data are generally costly to develop. However, once developed they can be used across locations for modeling the timing and intensity of pest attack.

REFERENCES

Bange M. P., Deutscher S.A., Larsen.D,.Linsley. D, Whiteside.S. 2004. A handheld decision support system to facilitate improved insect pest management in Australian cotton systems. *Computers and Electronics in Agriculture* **43**: 131-147

Folkedal, A. and Brevig, C. 2001. VIPS ï a web-based decision support system for crop protection in Norway. In Proceedings of European Federation for Information

Technology in Agriculture, Food and the Environment (EFITA) Congress 2001, Montpellier, France (*http://www.effita.net*)

Gutsche, V. 2001. From mathematical models to decision support systems ï the development of the German plant protection forecasting sysem PASO. In Proceedings of European Federation for Information Technology in Agriculture, Food and the Environment (EFITA) Congress 2001, Montpellier, France (*http://www.effita.net*)

Knapic, V., Zmrzlak, M., Simoncic, A., Miklavc, J., Zezlina, I. and V. Skerlavaj. 2001. Agrometeorological network and computer aided forecasting of plant protection in Slovenia. In Proceedings of European Federation for Information Technology in Agriculture, Food and the Environment (EFITA) Congress 2001, Montpellier, France (*http://www.effita.net*)

Maywald, G.F., Sutherst, R.W., Zalucki, M.P. 1999. DYMEX Professional: Modelling Natural Systems Version 1.0. CSIRO Publishing, Melbourne

Prasad, Y.G. 2005. Pest forecasting: Trends and development in India. In: *Gleanings in Entomology* (V.V. Ramamurthy, V.S. Singh, G.P. Gupta & A.V.N. Paul eds). Division of Entomology, IARI, New Delhi. pp. 145-168.

Samways, M. J., Osborn, R., Hastings, H. and Hattingh, V. 1999. Global climate change and accuracy of prediction of species geographical ranges: establishment success of introduced ladybirds (Coccinellidae, *Chilocorus* spp.) worldwide. *Journal of Biogeography* **26**: 795ï 812

Sutherst, R.W., Maywald, G.F. & Skarratt, D.B. 1995. Predicting insect distributions in a changed climate. Insects in a changing environment (eds R. Harrington and N.E. Stork), Academic Press, London pp. 59ï 91

Sutherst, R.W., Maywald, G.F., Yonow, T., Stevens, P.M. 1999. CLIMEX: Predicting the effects of Climate on Plants and Animals. CD ROM and User Guide. CSIRO Publishing, Melbourne pp. 90

Venkataraman, S. and Krishnan, A. 1992. Weather in the incidence and control of pests and diseases. **In**: Crops and Weather (Ed. Venkataraman, S. and Krishnan, A.) Publications and Information Division, Indian Council of Agricultural Research. pp: 259-302

Yonow, T., Zalucki, M.P., Sutherst, R.W., Dominiak, B.C., Maywald, G.F., Maelzer, D.A. and Kriticos, D.J. 2004. Modelling the population dynamics of the Queensland fruit fly, *Bactrocera* (Dacus) *tryoni*: a cohort-based approach incorporating the effects of weather. *Ecological Modelling* **173**: 9ï 30

Fifty Years of Dryland Agricultural Research in India
H.P. Singh, Y.S. Ramakrishna, K.L. Sharma and B.Venkateswarlu (eds.), 1999
Central Research Institute for Dryland Agriculture, Hyderabad, India.

CHAPTER 21

SIMULATION MODELLING AND GEOGRAPHIC INFORMATION SYSTEMS - NEW TOOLS IN DRYLAND AGRICULTURAL RESEARCH

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Climatic variability is the principal source of fluctuations in dryland production and price of agricultural commodities. It also affects global strategic food supplies and food security especially in the semi-arid tropics (SAT). In India out of 142 million ha of total net area cultivated, dryland agriculture constitutes about 92 million ha and contributes around 44% food and supports 40% of India's burgeoning population of 960 million people (Katyal et al., 1996a). Dryland agriculture is characterized by constant demand for water (seasonal evapotranspiration) and a highly variable supply of water (seasonal rainfall). India receives 400 mh-m of rainfall annually but only 29% of it is utilized and the rest is lost as runoff to sea causing unrestricted erosion of fertile top soil.

The challenge for sustaining crop production in dryland agriculture is to identify proper land surface management and crop production strategies which can minimize the impact of climatic variability. These strategies must not sacrifice crop output as demands for food will continue to increase as population increases. The research and development (R&D) of dryland agriculture until now generally follows a crisis management technique rather than following a risk management strategy. Risk management strategy involves utilization of newer approaches. Currently dryland agricultural R&D is inundated with site-specific crop management technologies (dates of sowing and rates of fertilizer application to crops) and factors that affect these technologies. The capability to use these site-specific information to predict crop performance in other sites and years and for different climatic conditions is lacking. Systems analysis and simulation models are modern techniques of information and are designed for use to achieve this purpose.

Systems analysis techniques are widely used in industries to optimize resources for a given task (Weinberg, 1975). This approach tries to solve complex problems involving iterative process of problem definition, identification of alternatives, and evaluation of alternatives using a simulation model (Robertshaw et al., 1978). In dryland R&D, a new era of using systems management techniques is starting wherein the outcome of selected management options can be evaluated using simulation models before they can be tried out in real crop growing situations. The systems analysis involving process-oriented crop simulation models renders the simulation results to a particular environment. The input data for simulation models can be changed to investigate crop response to different management regimes

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at another site. Thus the simulation results will be a point source in a field and extrapolation as such on a spatial scale is not possible. However, agricultural decision making in dryland agriculture R&D needs information on a regional scale where there may be a wide mix of soil types and weather conditions.

Geographic Information Systems (GIS) is a computer-based technique that combines geographic and cartographic analysis with a capacity for relative database management. The GIS allows input, storage, manipulation, spatial analysis, and display of data as thematic maps. Data from different sources (soil type, vegetation, landuse, and topography) and infrastructures (roads, drains, and political divisions such as major revenue divisions and towns) may be integrated in the GIS databases. There are three levels at which GIS approach can be used for resource management (Harrison and Sharma, 1992). The first level provides a simple inventory of current resources and their characteristics in a region. The second level deals with data management from a wide variety of sources housed within a single framework. At this level integration of different types of data such as three maps of a region showing soils, ratio of actual to potential evapotranspiration, and topography, might be used to examine potential production of a crop in that region. The third and more advanced level involves a combination of spatial analysis and crop simulation models. This involves interlinking process-oriented crop simulation with spatial analysis of GIS. It allows answering of a question such as what will be the regional yield response of a crop cultivar "X" in response to a management treatment [such as application of nitrogen (N) fertilizer], compared to another cultivar "Y". This combine approach provides two major benefits (Singh et al., 1993).

- A framework where outputs for a region from wide variety of sources (from complex biophysical or socioeconomical models) can be entered into a relational database and manipulated, integrated, analyzed, and mapped.
- Outputs enable non-technical users to see the results of technical and complex analysis in a thematic map form to help understand the interrelationships between many different factors.

In this review, some examples where simulation models and GIS technology have been used in dryland R&D are presented.

Assessing Climatic Potential for Crop Productivity

In view of enormous variability in rainfall both temporally and spatially, it is important to quantify the relation between climate and potential crop production. This will assist in determining the opportunities in an agroecological zone. In late 1980s climatologists from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) began to use crop simulation models to assess climatic potential for sorghum productivity. The SORGF model has been in use since long. Results reveal that in 14 out of 20 years simulated yields were 2.2 t ha^{-1} at Anantapur, 4.5 t ha^{-1} at Hyderabad, 5.5 t ha^{-1} at Dharwar, and 6.2 t ha^{-1} at Indore. The results indicated that potential productivity increased with increase in rainfall. More recently Monteith and Virmani (1991) using a simplified RESource CAPture (RESCAP) model and 20 years of climatic data assessed climatic potential for Hyderabad and Solapur. The mean growing season rainfall at Hyderabad was 500 mm compared to 390 mm at Solapur. The corresponding rainfall after crop maturity was 220 mm at Hyderabad and 290 mm at Solapur, so the annual rainfall at the two sites differed by less than 5%. At low input level, the characteristic of dryland farming is that grain yield in most of the years fall in a narrow range (1.4 to 1.8 t ha^{-1} at Hyderabad and 1.4 to 1.6 t ha^{-1} at Solapur). When simulations were run with slightly better input conditions, the range of yield was narrow at Hyderabad (2.5 to 3.0 t ha^{-1} between 25% and 75% probability). In contrast at Solapur the range of yield was wide (0.8 to 2.8 t ha^{-1} between 25% and 75% probability) indicating the increased risks to sorghum production at Solapur.

The groundnut model PNUTGRO was used and production potential was quantified at eight locations in India. The groundnut production potential was high in Ludhiana and Solapur mainly due to high radiation regimes; high productivity at Hebbal was due to cold temperature that induced longer crop duration. Low production potential at Coimbatore, Anand, Patancheru, Anantapur, and Pune were due to cloud cover and low radiation level. This analysis distinguished locations in terms of production potential. Locations with assured rainfall need more attention for managing soil fertility, whereas in low rainfall locations more attention was needed to manage water and its use efficiency.

Simulation of Nitrogen Dynamics and Risks Involved in Nitrogen Fertilizer Application for Sorghum Production

The post-green revolution yield increases have taken place in irrigated agriculture. Such dramatic increase in yield are generally not encountered with the SAT agriculture. The productivity in SAT agricultural system is influenced by both temporal and spatial variability of rainfall. The response to N fertilizer in sorghum was highly variable and dependent on rainfall. Because of the risks involved for dependable crop production and the increased cost of fertilizers, dryland farmers do not generally use fertilizers. However, the conservatism about the fertilizer use in the Vertisols of the SAT is changing progressively. Crop simulation models when coupled with stochastic weather generators, can be used to evaluate the climatic risks involved.

Alagarswamy et al. (1990) used CERES Sorghum model and risk analysis procedures to quantify climatic risks to sorghum production and risks involved to the use of N fertilizer in Vertisols and Alfisols of the Indian SAT.

In Alfisols simulation studies during 25 years indicated that in wet environments fertilizer use efficiency is often limited by losses of N associated with leaching of N. Studies indicated that where leaching losses were high, such as in Hyderabad, there was an advantage to splitting of fertilizer application. In drier environments the recovery of applied fertilizer was low in general and the median recovery was approximately 25%. Comparison of N fertilizer use strategies for shallow Alfisols indicated that in 1 out of 4 years there was no response to applied fertilizer above 30 kg ha^{-1}. Even under similar Vertisol soil series risks associated with fertilizer application was variable and related to variable moisture environments.

In fertile Vertisols (initial mineral N content is 36 kg ha^{-1}; available water storage capacity is 172 mm), a basal application of 30 kg N ha^{-1} could boost yields to over 4.5 t ha^{-1}, indicating a response of 53 kg grain kg^{-1} of N fertilizer applied. Economic response (1 kg N produced 5 kg grain) is obtained up to 90 kg N ha^{-1}. However, in Alfisols, a much higher level of N fertilizer was required to obtain comparable higher yields. The efficiency of fertilizer N utilization (ratio of kg N to kg additional grain produced) was much lower in Alfisols compared to Vertisols. The results indicated that the practice of applying 30 kg N ha^{-1} at sowing can safely be extended to sorghum growing areas in the Vertisols where annual rainfall exceeds 700 mm and the risks in applying fertilizer seem to be minimum. This proposition seems to be appropriate for marginal dryland farmers who generally are risk averse and have limited means to bear higher risks.

Alagarswamy and Virmani (1996) used CERES Sorghum model and risk analysis as a research tool to quantify climatic risks involved in the use of N fertilizer in selected sorghum-growing areas of peninsular

India. When no fertilizer was used, in many years there was crop failure and the yield variation was very high (CV 125%). However, an application of 30 kg N ha^{-1} conferred stability in yield even in years of crop failure (CV 30%). Substantial response to applied N fertilizer up to 60 kg ha^{-1} was noted from probability distribution for gross monetary returns. The gross and net monetary returns were maximum at 60-90 kg N ha^{-1}. At Hyderabad with dependable growing season rainfall the risks associated with N fertilizer application was minimal. In contrast, at Akola, Parbhani, and Pune there was an increased level of risk associated with fertilizer use. In all four locations an application of 30 kg N ha^{-1} was less risky than no fertilizer application. This conclusion supports that in dryland agriculture the economic optimum N rate is lower than biological optimum level of N fertilizer (Venkateswarlu, 1984).

Characterizing Yield Gap of Sorghum Production in Vertisols

The difference between the agroecological potential of a crop and what farmers realize in a given region is termed as "yield gap". It is a popular way of characterizing the "untapped" potential and defining the opportunity that can be exploited if all constraints are removed. With the robust CERES Sorghum model the agroecological potential of sorghum crop in selected Vertisol benchmark sites in the major sorghum-growing agroecological subregions of peninsular India, was estimated.

In the rainy season agroecological subregions even though the rainfall is adequate and improved sorghum cultivars are used by farmers, the yield gap was large. As a first step, the research portfolio management in these agroecological subregions should be directed to explore the causes for existence of such a large yield gap before launching any research program.

The yield gap is < 1 t ha^{-1} in the core postrainy season agroecological subregion. Potential yield estimates demonstrate that even with the improved technology coupled with any improved cultivars might not change the existing low yield in these subregions so long as water resources are not properly developed. These results show a way to integrate crop simulation models with GIS which would then serve as a powerful tool for research priority setting in the years to come.

Impacts of Climate Change on Sorghum Productivity

The prospects of changes in earth's climate due to greenhouse gas effects and consequent global warming stimulated various researchers to predict how crop production will be influenced. The climate change influenced increase in carbon dioxide gas from present level of 350 parts per million, considered to increase crop growth and yield mainly through its effect on crop photosynthetic process. Increase in temperature through global warming, on the other hand, generally decrease crop yield by speeding up development of plants. Simulation models coupled to climate change models offer an opportunity to examine the climate change impact on crop productivity.

The annual rice production in the main cropping season in India was predicted to increase through beneficial effects of elevated carbon dioxide. However, in the second cropping season, which is not the main season, large decrease in yield was predicted due to decrease in crop maturity on account of increase in the ambient temperature (Mohandass et al., 1995). Gangadar Rao and Sinha (1994) showed the impact of climate in change in wheat crop. They indicated that wheat yields are likely to be reduced due to adverse effect of elevated temperature during grain maturity. The impact of climate change in sorghum productivity was studied by Gangadar Rao et al. (1995) using CERES Sorghum model and climate change models. The simulation study was carried out using historical weather data for Hyderabad (20 years), Akola (30 years), and Solapur (31 years). The results of simulation study indicated a marginal decline in sorghum productivity during rainy season regardless of soil types in response to climate change. The sorghum productivity was mainly controlled by availability of nutrients and water. Unlike in wheat and rice which are very sensitive to temperature changes during maturity, sorghum productivity is influenced only marginally by climatic changes.

Modelling of Soil Management Effects

Soil erosion induced by rainfall reduces crop productivity by decreasing soil depth and available soil moisture, removing soil nutrients, and altering physical properties resulting in less infiltration and root penetration. Littleboy et al. (1996) used PERFECT (Productivity, Erosion, Runoff Functions to Evaluate Conservation Techniques) to estimate effects of soil erosion on production of sorghum on an Alfisol in semi-arid India. Their results indicated that on average, soil depth decreased by 0.91 cm year^{-1} at Hyderabad for a 10% slope, 80 cm soil depth, shallow tillage at planting, and no surface amendment. The rates of soil removal by erosion and subsequent yield reduction was more severe in shallow soils with steeper slopes and if land management practice provided less surface cover. Application of at least 3.5 t ha^{-1} rice straw at planting is required to protect these lands from erosion induced ill effects and can maintain productivity of this type of soil for at least 90 years. This study enabled to identify regions with a high risk of degradation from soil erosion and estimate the impact of various land management options on long-term sustainability. Models provided basis to focus research and a means of assessing alternate management strategies to preserve long-term production.

GIS and Crop Simulation Models For Regional Productivity Analysis

Regional productivity analysis involves evaluating spatial soil and weather variability, identifying optimum crop management practices, and predicting productivity of the region under different climatic and management scenarios. These analysis can help regional planners and policymakers in delineating acreage and distribution of areas with high productivity and developing management recommendations for different crops. Lal et al., (1993) extended the scope of applicability of site-specific crop simulation models such as DSSAT to regional planning productivity and policy analysis by combining their capabilities with ARC/INFO (AEGIS). In this combined system, simulation models predict information on yield and other crop related outputs for different homogeneous soil and weather combinations, and GIS aggregates information from individual units, displays maps, and also presents results in tabular format for the study region.

Lal et al. (1993) used this system of analysis for three sites having considerable soil and weather variability. To generate yield databases for AEGIS several thousands of simulations are to be made using DSSAT for a variety of management combinations for different soil and weather conditions in the study regions. The input for this type of study includes soil maps, soil survey reports, daily, precipitation, daily maximum and minimum temperatures, and solar radiation values. The results of the study by Lat et al. (1993) indicate considerable variation in optimum planting dates and yield levels under rainfed conditions. Their study successfully demonstrates the scope of applicability of site-specific models to regional planning and productivity analysis by combining their capabilities with GIS. Singh et al. (1993) demonstrated the use of GIS to investigate N fertilizer efficiency in Maharashtra state, using sorghum crop simulation model coupled with a GIS. The spatial databases of the GIS contain information on soils, weather, and other inputs needed by the sorghum model. The system allows regional analyses and the output can be in terms of maps. Hence these combined tools can be used for characterizing the region, locating high yielding and problematic areas and estimating their productivity under different management strategies.

GIS and Hydrologic Modelling

Crop planning based on watershed as a unit is very important for optimizing the use of limited water resources to maximize and sustain the productivity under rainfed conditions. Geographical information systems have been successfully integrated with distributed parameter, single event, water quality models such as AGNPS (Agricultural Non Point Source) and ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation). These aspects are very well discussed by Garg (1994). Other widely used models include EPIC (Williams et al., 1983), CREAMS (Knisel, 1980), and SWRRB (Arnold et al., 1990). The amount of time, expertise and cost required for acquiring input data to run the models are greatly increased. For example, a simple model such as USLE requires only six inputs, while a spatially distributed, single event model such as AGNPS requires 22 inputs for each cell or grid within a study area. The need can vary significantly between and within models, depending on the questions to be answered, thereby tremendously increasing the cost, time, and complexity of analyzing results. The integration of GIS with distributed parameter models can eliminate many of the limitations associated with the use of these models particularly for input data preparation. Srinivasan and Engel (1991) integrated the AGNPS model to display and facilitate analysis of model output. Rewerts and Engel (1991) integrated the ANSWERS model with the GRASS GIS to build inputs to run the model. Both AGNPS and ANSWERS are single-event-distributed-parameter models that require a watershed to be divided into square grids and resample like a raster-based GIS where the data are sorted in a grid-like array. There are significant differences between the single-event and continuous-time distributed models, both in methods of extracting inputs and methods of analyzing and displaying outputs, due to time component involved in continuous-time modelling.

Continuous-time, distributed-parameter models consider the basin or watershed divided into sub-basins based on topography, soil, and landuse and thus preserve the spatially-distributed parameters and homogeneous characteristics within a sub-basin. Collection of inputs for such models is often difficult due to the level of aggregation and the nature of spatial distribution. To overcome this problem Srinivasan and Arnold (1994) developed a GIS interface to automate inputs to a continuous-time, distributed-parameter model called the Soil and Water Assessment Tool (SWAT). Digital elevation model (DEM) created in GIS is an important input to this model. Given an input surface such as DEM, the hydrologic modelling tools can be used to generate grids that encode the flow direction and flow accumulation for each cell or grid representing local and natural watersheds and drainage network.

SWAT (Arnold, 1992) was developed to predict the effect of alternative management practices on water, sediment, and chemical yields from ungauged rural basins. The model was developed by modifying the SWRRB (Simulator for Water Resources in Rural Basins) model (Williams et al., 1983) for application to large, heterogeneous rural basins. SWAT model (a) allows simultaneous computations on several hundred sub-watersheds (the upper limit is 2500 sub-basins); and (b) simulates lateral flow from the soil profile (0-2 m), groundwater flow from the shallow aquifer (2-25 m), reach routing transmission losses, and sediment and chemical movement through ponds, reservoirs, streams, and valleys. SWAT operates on a daily time step and is capable of simulating 100 years or more. Major components of the model include surface hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, groundwater and lateral flow, and agricultural management. Further, GIS ILWIS (Integrated Land and Water Information System) was used to predict average soil loss through USLE (Universal Soil Loss Equation) model.

GIS and Crop Simulation Models for Predicting Yield at Farm Level

Field experiments are generally conducted in some statistical design which helps to infer the results based on statistical significance tests. The unaccounted variability called experimental error is attributed to uncontrollable environmental factors. On the other hand computer-based decision support systems such as DSSAT are developed to understand the interaction between various crop management options and environment. Hoogenboom et al. (1993) used DSSAT models at research farm level by using IAGIS software to interface with ARC/INFO GIS for various spatial databases. The first objective of their study was to expand the use of crop simulation models through a linkage with GIS and spatial soil databases. The second objective was to apply this system to study the distribution of yield, water use, and other agronomic variables as a function of soil spatial variability on a farm level. The strength of a GIS is that we can create various spatial database layers for topology, elevation, soil depth, soil type, weather, landuse, and any other related information using GIS. One could, for instance, digitize a soil map to provide the basic map layer and develop an attribute database for soil type, soil family, soil association, pH, slope and other soil physical and chemical characteristics. Each layer can be overlaid to create polygons, each with unique characteristics based on the classification of each layer. The GIS crop-model system can then be used to simulate crop growth and development for each polygon or field with different characteristics. The results of the study by Hoogenboom et al. (1993) for the crops grown under rainfed conditions showed a strong spatial variation. Hence, it may be possible to capture the variability in crop yields adequately by overlaying many soil characteristics using GIS and appropriate analytical models.

Geographical Information Systems and crop simulation models are powerful tools for regional productivity only when they are properly validated for the representative locations. It can be concluded that linkage of spatial databases, and analytical and simulation models with GIS is an ideal way to study spatial variation and distribution of crop yield, water use, and other agronomic variables as a function of soil and weather conditions and management strategies. Further, GIS is an ideal tool for crop planning on watershed basis since digital elevation models (DEM) created in GIS can be integrated with other spatial information including landuse pattern obtained from remote sensing data from time to time. As mentioned earlier, GIS greatly reduce the processing time for data preparation as the amount of input information needed to execute these simulation models is tremendously increased. Unlike in irrigated system, there exists considerable soil spatial variation with respect to crop growth and behaviour even at micro level under dryland conditions. Hence, GIS is an ideal tool for capturing this variability and understanding crop growth and behaviour under dryland conditions for critical and varied analysis.

GIS for Spatial Resource Inventory, Characterization, Analysis and Mapping

Mapping temporal and spatial dynamics of trends in area and productivity of rainfed crops

Measuring agricultural growth has been one of the most extensively researched areas. Time series data at national level, state level, or at district levels is being considered for this purpose. Creating this database in vector GIS such as ARC/INFO has many advantages in understanding not only temporal trends in agricultural growth but also spatial pattern of growth. Further GIS will be useful as a tool for mapping these trends indicating resource characterization. For example Katyal et al. (1996b) and Katyal and Narayana Reddy (1997) studied the changes in area and productivity of rainfed crops such as sorghum, pearl millet, pigeonpea, and chickpea by linking the time series district-wise data to the district map of India. Further agroecoregions were overlayed (Sehgal et al., 1992).

These maps reveal the spatial trends in area and productivity of rainfed crops in different agroecoregions apart from temporal trends. For example from the study of Katyal and Narayana Reddy (1997), sorghum is grown in agroecoregion (AER) numbers 2, 5, 6, 7, 8, 9, and 10. The concentration is more in AER 6 followed by that of 5 and 7. Their study emphasized the need to revitalize the efforts on stabilizing and accelerating the productivity levels even in AER 6, which is the major sorghum area. Various steps involved in this analysis are shown in Figure 1.

In recent years GIS has proved to be an efficient tool for natural resource inventory, characterization, and mapping. Satellite remote sensing digital data is an useful source for characterizing the rainfed regions accurately at grass-root level. By importing this data to GIS the spatial distribution of rainfed regions can be mapped. This will enable to overlay other natural resources and socioeconomic aspects and monitoring the changes over time.

Creation of research resource inventory

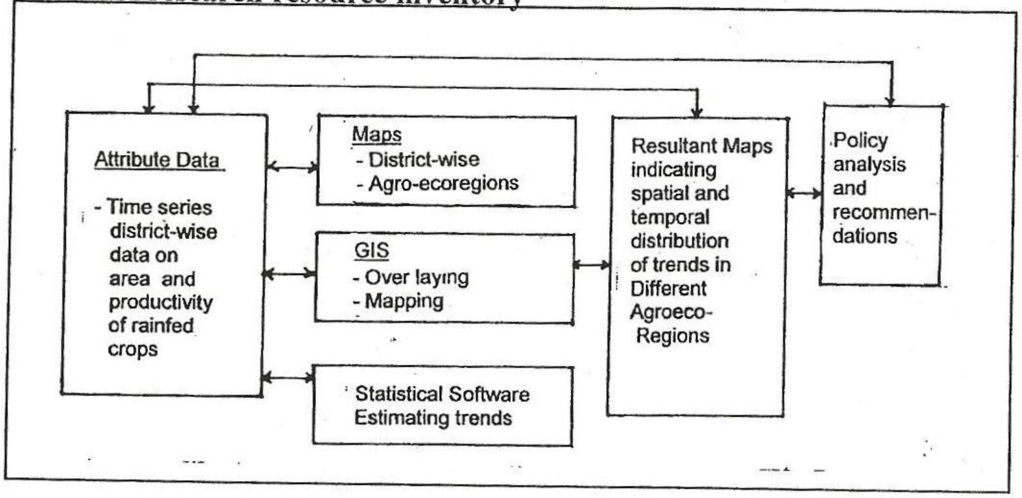

Figure 1. Flow chart for preparing maps on spatial and temporal dynamics of rainfed crops

Huge amount of data is being generated at various locations through field experiments and surveys on various aspects of rainfed agriculture. For example there are 22 cooperating centres of the All India Coordinated Research Project for Dryland Agriculture (AICRPDA). GIS can be used for maintaining this data with its geographical identity. This will help in arriving at optimum and timely action area plans regarding the technology adoption by integrating with bio-physical and socioeconomic factors.

References

Alagarswamy, G. and Virmani, S.M. 1996. Risk analysis of rainfed sorghum production at various levels of nitrogen fertilizer rate with the CERES Sorghum crop simulation model. Pages 603-615 *in* Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics (Ito, O., Johansen, C., Adu-Gyamfi, Katayama, K., Kumar Rao, J.V.D.K., and Rego, T.J. eds. Japan). Japan International Research Center for Agricultural Sciences.

Alagarswamy, G., Virmani, S.M., Godwin, D.C., and Singh, U. 1990. Evaluating fertilizer use strategies for sorghum - a systems approach. Pages 71-81 *in* Technology Blending and Agrarian Prosperity (Verma, J.P., and Varma, A., eds). New Delhi, India: Malhotra Publishing House.

Arnold, J.D. 1992. Spatial scale variability in model development and parameterization. PhD Thesis, Purdue University, West Lafayette, Indiana, USA. 183 pp.

Arnold, J.D., Williams, J.R., Nicks, A.D, and Sammons, N.B. 1990. SWRRB - A basin scale simulation model for soil and water resources management. Texas A&M Press, College Station, Texas, USA. 255 pp.

Gangadar Rao, D., Katyal, J.C., Sinha, S.K., and Srinivas, K. 1995. Impacts of climate change on sorghum productivity in India: Simulation study. Pages 325-337 *in* Climate Change and Agriculture: Analysis of Potential International Impacts. ASA Special Publication No. 59. Madison, Wisconsin, USA: ASA.

Gangadar Rao, D. and Sinha, S.K. 1994. Impact of climate change on simulated wheat production in India. Pages 1-17 *in* Implication of Climate Change for International Agriculture: Crop Modelling Study (Rosenzweig, C. and Iglesias, I., eds.). USEPA230-B-94-003. Washington, D.C., USA: USEPA.

Garg, P.K. 1994. Geographical information system as a tool for distributed hydrologic modelling. GIS, India, Vol. 3. pp 27-31.

Harrison, S.R. and Sharma P.C. 1992. GIS and economic models as information systems for sustainable development. Presented at IDS conference, Calcutta, India, January 1992.

Hoogenboom, G., Lal, H., and Gresham, D.D. 1993. Spatial yield prediction. An ASAE meeting presentation paper No. 93-3550. Hyatt Regency, Chicago, Illinois, USA: ASAE.

Katyal, J.C., Kaushalya Ramachandran, Narayana Reddy, M., and Rama Rao, C.A. 1996a. Indian Agriculture - Profile of land resources, crop performances and prospects. Proceedings of South Asia Regional Workshop on Regional Land Cover Changes, Sustainable Agriculture and their Interactions with Global Change. 16-19 December, 1996, Madras, India. COSTED, ICSU and UNESCO.

Katyal, J.C. and Narayana Reddy, M. 1997. Remote sensing and GIS to address certain issues related to dryland agriculture. NNRMS Bulletin, Vol. 20, January, pp. 4-15.

Katyal, J.C., Narayana Reddy, M., and Virmani, S.M. 1996b. A case study on the spatial and temporal dynamics of area and productivity of sorghum and pigeonpea in India through GIS. The World Bank - NARP Report on "Resource Characterization of Rainfed Farming Systems in Peninsular India". Hyderabad, India: CRIDA.

Knisel, W.G (Ed.) 1980. CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. USDA Conservation Research Report No. 26. USA: USDA. 643 pp.

Lal, H.G., Hoogenboom, J.P., Calixte, Jones, J.W., and Beinroch, G.H. 1993. Using Crop Models and GIS for Regional Production Analysis. Transaction of ASAE 36(1):177-184.

Littleboy, M., Cogle, A.L., Smith, G.D., Rao, K.P.C., and Yule, D.F. 1996. Soil management and production of Alfisols in the semi-arid tropics. IV. Simulation of decline in productivity caused by soil erosion. Aust. J. Soil Res. 34:127-138.

Mohandass, S., Kareem, A.A., Ranganathan, T.B., and Jeyaraman, S. 1995. Rice production in India under current and future climates. Pages 165-181 *in* Modelling the Impact of Climate Change on Rice Production in Asia (Mathews, R.B., Kropff, M.J., Bachelet, D., and van Laar, H.H. eds.). Wallingford, Oxford, UK: CAB International.

Monteith, J.L. and Virmani, S.M. 1991. Quantifying climatic risk in the semiarid tropics: ICRISAT experience. Pages 183-204 *in* Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics (Muchow, R.C., and Belamy, J.A., eds.). Wallingford, Oxford, UK: CAB International.

Rewerts, C.C. and Engel, B.A. 1991. ANSWERS on GRASS: Integrating a Water Simulation with a GIS.

ASAE Paper No. 91-2621. Michigan, USA: ASAE.

Robertshaw, J.E., Mecca, S.J., and Rerick, M. 1978. Problem solving: A Systems Approach. New York, USA: Petrocelli Books Inc. 272 pp.

Sehgal, J.L., Mandal, D.K., Mandal, C., and Vadivelu, S. 1992. Agro-Ecological Regions of India. National Bureau of Soil Survey & Land Use Planning (ICAR), Nagpur. New Delhi, India: Oxford & IBH Publishing Co. Pvt. Ltd.

Singh, U., Brink, J.E., Thornton, P.K., and Christianson, C.B. 1993. Linking crop models with geographic information system to assist decision making: A prototype for the Indian semiarid tropics. Paper series - IFDC P-19. Muscle Shoals, Alabama, USA: 39 pp.

Srinivasan, T. and Arnold, J.D. 1994. Integration of a basin-scale water quality model with GIS. Water Resources Bulletin, 30:453-462.

Srinivasan, T. and Engel, B.A. 1991. GIS estimation of runoff using the CN Technique. ASAE Paper No. 91-7044. Michigaon, USA: ASAE.

Venkateswarlu, J. 1984. Nutrient management in drylands with special reference to cropping systems and semi-arid red soils. Project Bulletin No. 9. Hyderabad, India: AICRPDA. 56 pp.

Weinberg, G.M. 1975. Introduction to General Systems Thinking. New York, USA: Wiley-Interscience Publ.

Williams, J.R.K., Renard, G., and Dyke, P.T. 1983. EPIC - A new model for assessing erosion's effect on soil productivity. J. Soil Wat. Conserv. 38(5):381-383.

Concept of Genetic coefficients and their estimation

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Introduction:

Genetic coefficients are integral components of all the crop growth simulation models. Lack of knowledge on genetic coefficients and their non-availability in the crops of interest in India is posing a problem for use of crop simulation models for evolving better agricultural management practices.

Definition Genetic coefficients:

Genetic coefficients are mathematical constructs that are designed to mimic the phenotypic outcome of genes under different environments. Each simulation model is driven by cultivar, ecotype and species coefficients all known as Genetic coefficients.

Cultivar coefficients: They define traits that differ among cultivars

Ecotype coefficients: They define traits for groups of cultivars

Species coefficients: They define traits specific to any crop or crop species.

Genetic coefficients for each variety are affected by processes or factors *viz.,* life cycle, photosynthesis, sensitivity to day light (photo period), leaf area, partitioning, remobilization, seed growth, seed composition, seed fill duration, Vernalization, growing degree days accumulation etc.

Cultivar coefficients:

Cultivar coefficients govern life cycle and reproduction growth rate of the crop cultivars. The definition of cultivar coefficients is located on cultivar files of all crop simulation models.

Genetic coefficients of some crop:

Genetic coefficients for the DSSAT CERES-Maize, Wheat and Barley models

(A) Maize	
P1	Degree days (base 8 °C) from emergence to end of juvenile phase
P2	Photoperiod sensitivity coefficient (0–1.0)
P5	Degree days (base 8 °C) from silking to physiological maturity
G2	Potential kernel number
G5	Potential kernel growth rate mg/(kernel d)
PHINT	Degree days required for a leaf tip to emerge (phyllochron interval) (°C d)
(B) Wheat and barley	
P1D	Photoperiod sensitivity coefficient (% reduction/h near threshold)
P1V	Vernalization sensitivity coefficient (%/d of unfulfilled vernalization)
P5	Thermal time from the onset of linear fill to maturity (°C d)
G1	Kernel number per unit stem + spike weight at anthesis (#/g)
G2	Potential kernel growth rate (mg/(kernel d))
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)
PHINT	Thermal time between the appearance of leaf tips (°C d)

Genetic coefficients of Sorghum and Millet

Variety	Definition	Units	Typical Range
P2O	Critical photoperiod or the longest day length (hours) at which development occurs at a maximum rate. At values higher than P2O, the rate of development is reduced	Hr	12.5-16.0
P2R	Extent to which phasic development leads to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O	GDD	1-300

G1	Scaler for relative leaf size (used in place of SLA)		0-20
G2	(Sorghum) Scaler for partitioning assimilates to the panicle		1-8
G4	(Millet) Scaler for partitioning assimilates to the panicle		0-1.0

Ecotype coefficients:

Most CERES models now have ecotype coefficients and library of ecotype coefficients are also defined in the models. All the ecotype coefficient files will have extention of ôECOö. They are traits that are common across many cultivars. Temperature responses of vegetative and reproductive periods, radiation use efficiency and growing degree days to emergence are some of the ecotype coefficients to name.

Species coefficients:

All CERES models now have species traits, although these traits are not consistent among the crops. Species traits are characteristics that define difference between plant species. These species traits include (i) temperature response (ii) CO_2 response (iii) water stress response and (iv) Tissue composition etc. Temperature response in case of development is defined in terms of base temperature, Temperature optimum 1 and 2 and maximum temperature. Temperature response on Crop Growth Rate (CGR) and photosynthesis are also some of the species coefficients. Response of Radiation Use Efficiency (RUE) to CO_2 in both C_3 and C_4 type of crops also serve as species coefficients.

Genetic coefficients in cropping system model:

In cropping system model (CSM-CERES) maize, wheat/Barley and rice contain 6, 7 and 8 cultivar coefficients, respectively. In CSM-CROPGRO models, cotton, tomato, cabbage and green bean crops have 18 cultivar coefficients and potato contain 6 cultivar coefficients.

Cultivar coefficients for CROPGRO:

The cultivar coefficients in CROPGRO models and their definition are illustrated in following tables:

Cultivar coefficients for CROPGRO ï Phase Modifiers

Name	Value	Definition
CSDL	13.40	Critical Short Day Length below which repr. Development progresses with no day length effects (hours)
PPSEN	0.285	Slope of the relative response of development to photoperiod with time (1/hour)

Cultivar coefficients for CROPGRO ï Life Cycle Duration

Name	Value	Definition
EM-FL	19.0	Time between plant emergence and flower appearance (R1) (PD)
FL-SH	6.0	Time between first flower and first pod (R3) (PD)
FL-SD	14.0	Time between first flower and first seed (R5) (PD)
SD-PM	33.2	Time between first seed (R5) and beginning maturity (R7) (PD)

Cultivar coefficients for CROPGRO ï Vegetative

Name	Value	Definition
FL-LF	26.0	Time between first flower (R1) and end of leaf expansion (PD)
LFMAX	1.030	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, & high light (mg CO2/m2-s)
SLAVR	375	Specific leaf area of cultivar under standard conditions (cm2/g)
SIZLF	180	Maximum size of full trifoliate (3 leaflets) (cm2)

Cultivar coefficients for CROPGRO ï Reproductive

Name	Value	Definition
XFRT	1.00	Maximum fraction of daily growth that is partitioned to seed + shell
WTPSD	0.19	Maximum potential weight per seed (g)
SFDUR	23.0	Seed filling duration for pod cohort at standard growth conditions (PD)
SDPDV	2.20	Average seed per pod under standard growth conditions (#/pod)

PODUR	10.0	Time required to reach final pod load under optimal conditions (PD)

How to obtain and determine genetic coefficients:

Genetic coefficients can be obtained by querying DSSAT or ICASA experts, calibrating to the measured data and gene based estimation.

Measuring specific traits:

It can be achieved in environment control chamber experiments but they are expensive and also the conditions inside the chambers will differ from those in experimental or farmers fields.

The most commonly used method for estimating cultivar coefficients is through the use of field data. It is also referred as ōInverse Modelingô or ōFitting Coefficientsô or ōCalibratingô in some cases.

If you have model and do not have cultivar coefficients you can estimate them with the help of field data having carefully measured traits.

The objective criteria for determining the coefficients values is by fitting the observed and simulated data in to statistical regression.

Fitting coefficients to field data:

Data needed (minimum data set):

- Frequent observations of timing of vegetative and reproductive events
- Growth analysis data
- Final yield, yield components
- Weather data (essential)

Multiple environments (locations, years, dates)

- Yield trials (Plant Breeders)
- Multiple planting dates are very useful
- Extreme (non-commercial) dates or locations
- Especially helpful to predict phenology

Estimating Coefficients: Trial and Error

Initial values from ōbest guessesô

Phenology coefficients

- Data are observations of flowering, maturity and other stages
- Simulate available experiments, varying genetic coefficients (e.g., P1, P2 and P5 in maize)
- Criteria for selection
    - Visual closeness of simulated to observed data
    - Statistical measures (OLS, RMSE, Likelihood function, correlation, model efficiency, Wilmott (1981) D-index, é) *Wallach et al., 2006*

Growth, partitioning and yield coefficients

- Yield, yield component data (also growth analysis data?)
- Simulate available experiments many times, varying genetic coefficients (e.g., G2 and G5 in maize)
- Criteria for selection
    - Visual closeness to simulated to observed data
    - Statistical measures (OLS, RMSE, Likelihood function, correlation, model efficiency, Wilmott (1981) D-index, é) *Wallach et al., 2006*

óFittingô Coefficients can be done through software (Gencalc2) in DSSAT v4.5 óRulesô file with information on target traits, controlling coefficients, number of simulations and step size for each coefficient. Other software such as gradient search or Monte Carlo methods. GLUE: General Likihood Universal Estimation available in DSSAT v4.5.