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Sorghum in the Semi-Arid Tropics: Agroclimatology, Physiology and Modelling*

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Summary

The climatic resources and the problems of sorghum production in different agroclimatic regions of the semi-arid tropics are highlighted, and the extent to which physiological knowledge can be applied to improve and stabilize sorghum yield is discussed. The effects of different environmental factors on crop processes during each growth stage need to be integrated for better understanding of genotype x environment interactions. A crop-growth simulation model (SORGF), calibrated for use in the tropics, is used to evaluate production potential in selected regions, and to demonstrate the effect of different agronomic practices on yield. Considering some problems in wide application of such simulation models, two simple schemes of analyzing crop productivity are suggested as alternatives, based on effective crop-growth duration and rate, and on the capture and utilization of limiting natural resources, such as solar radiation. In the near future, physiologists should concentrate on simple models, based on key integrating crop processes, which respond sensitively to the environmental and cultural characteristics of specific sorghum-growing regions. Such simple models, in turn, will be useful in improving the accuracy of complex simulation models. Both types of models will facilitate practical applications of current and future research on better adaptation of sorghum to the physical environment.

Introduction

Globally, sorghum [*Sorghum bicolor* (L.) Moench] ranks fifth in importance among cereals, and sixth among important dietary sources of energy for the world's population (Cock, 1985). Although tropical in origin, sorghum is widely distributed both geographically (between 35° N and 35°S) and ecologically (300 to 1400 mm annual rainfall, and 0 to 2250 m above sea level, etc.). Sorghum appears to occupy a niche between maize and pearl millet (Table 1), but its great genotypic diversity makes it adaptable to most regions where maize or millet can be grown.

Maximum harvested yields ≥ 15 t ha^{-1} in temperate regions, and ≥ 8 t ha^{-1} in regions of semi-arid tropics (SAT) have been demonstrated, but the average yields obtained by farmers in the SAT are about 0.8 t ha^{-1}, compared to 3.6 t ha^{-1} in high-technology, temperate regions. Effective cultural and genetic manipulation of crop for high and stable yields depends on a knowledge of its physiological and developmental characteristics, the environment in which it has to grow and reproduce, and the interaction between these two. In this paper, we briefly describe the agroclimatic regions where sorghum is grown in the SAT, and then consider salient features of sorghum physiology research for crop improvement. Next, we show the applica-

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Table 1. Comparison of maize, sorghum and pearl millet for world production, estimates of yields, and some physiological characteristics [generalized, and based on several sources quoted in ICRISAT (1984)]

	Maize	Sorghum	Pearl Millet
World annual production (10^6 t)	392	58	29
Grain yield (t ha $^{-1}$) in the tropics			
- High inputs*	4-6	4-6	2-4
- Low inputs*	1	1-1.3	0.6-0.8
Highest grain yields reported (in temperate regions) (t ha $^{-1}$)	20	15	8
Root system	Moderately deep, but less extensive	Deep and extensive branching	Shallow and spreading except on very sandy soils
Growing season length for best yields (days)	120-270	100-210	75-180
Seasonal water requirements (mm)	500-600	350-500	250-350
Temperature requirements (°C)			
- Optimum	25-30	32-36	30-36
- Mimimum	12-15	7-10	10-12
- Maximum	41-45	45-48	45-48
Nutrient demand (kg ha $^{-1}$) under high input* conditions:			
- Response to nitrogen	140-180	90-120	30-90
- Total N removed by crop	180-250	120-150	60-100

* = High input implies use of best adapted hybrid with adequate fertilizer and good growing conditions; low input implies use of local landrace with minimum monetary inputs and moderate level of crop management.

tion of a sorghum yield simulation model for making generalisations on crop production strategies and answering some questions about how sorghum crops respond to their environment. Finally, the need and scope for alternative simple models are discussed.

Agroclimatology

The agroclimatology of sorghum has been thoroughly reviewed by FAO (1979), ICRISAT (1984), and Sivakumar and Virmani (1982). In general, potential yields in the SAT are limited by the length of the growing season, which is primarily determined by the seasonal rainfall and the water-holding capacity of the soils. Total rainfall, the length of the season, the distribution of rain during the season, and rainfall intensity, especially during initial phase of vegetative development, may all be significant as they affect plant functions such as seedling emergence, early leaf and root growth, nutrient acquisition, and help to determine possibilities of biotic stress. When the water and nutrient supplies are adequate, other factors such as solar radiation may limit potential yield during part of the season.

In the Sahel and Sudan Savanna vegetation zones of the African SAT (10-16° N; northern fringes of Senegal, Mali, Burkina Faso, etc.), the growing season is only about 90 days long, but it increases to 270 days towards the equator (southern Guinean Savanna; 6-8° N; southern regions of Ghana, Nigeria, and Sudan). South of the equator, the growing season is generally shorter (around 90 days in Botswana, Zimbabwe, Mozambique, etc.), but there are exceptions, e.g., in parts of Tanzania. The soils of Africa, especially in the west, are mostly poor in nutrients (especially phosphorus), and have a low water-holding capacity (generally Alfisols with low clay content).

In the sorghum-growing regions of India, the length of the growing season ranges between 90 and 180 days (Table 2). In some marginal areas such as Jodhpur, Rajasthan (arid) where the season is shorter, sorghum is grown mainly for fodder. Sorghum-growing areas in India fall mostly under Vertisols (about 80% of area cropped annually) or Alfisols, fertile enough to sustain modest yields except where there are acute deficiencies of nitrogen, phosphorus or zinc. One distinct feature of sorghum production in India is cultivation during the post-rainy season; some 40% of the total sorghum area is accounted for by sorghum grown solely on stored moisture in the Vertisols of the Deccan region.

Low temperature at high altitudes, drought, and acid soils are the three salient features of sorghum-growing environment of Latin America, where average yields are much higher than in the rest of the SAT.

Table 2. Rainfall and soil moisture characteristics, and actual and simulated yields of sorghum crops under low and high crop management levels at five SAT locations in India. Measured yields are for the 1954-1970 period, simulated yields are from climatic data for individual years during 1941-1970, using the modified SORGF model (Huda 1987)

Location	Jodhpur	Anantpur	Hyderabad	Dharward	Indore
Annual rainfall (1941-70):					
Mean (mm)	382	527	792	889	1001
CV (%)	42	25	20	22	27
probability (%) of receiving annual rainfall (mm):					
> 400 mm	50	90	96	98	97
> 800 mm	4	10	65	60	83
> 1200 mm	0	0	0	8	18
Soil type	Aridisol	Alfisol	Vertisol	Vertisol	Vertisol
Soil water-holding capacity (mm)	100	50	150	150	150
Length of the the growing season (approx. days)	90	120	150	180	200
Probability of stored soil-water >120 mm at the end of rainy season (%)	0	0	52	37	62
Farmers yield recorded for 1954-1970:					
Mean (t ha^{-1})	0.1	0.4	0.5	0.6	0.7
CV (%)	128	26	28	28	29
Simulated yields:					
- Low management:					
Mean (t ha^{-1})	1.1	0.9	1.4	1.9	2.0
CV (%)	34	32	5	9	3
- High management :					
- Mean (t ha^{-1})	3.1	2.6	4.6	5.7	6.4
CV (%)	39	39	6	14	3

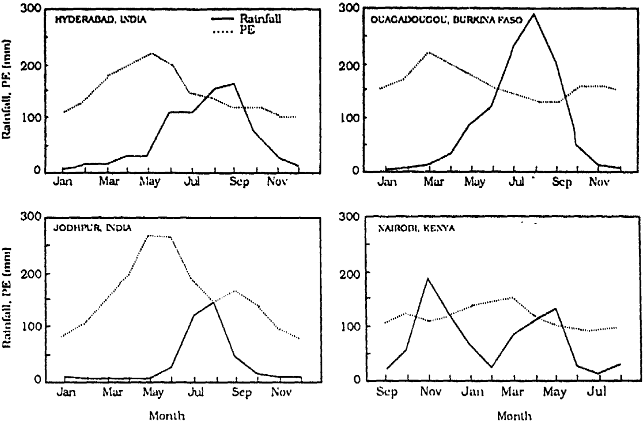

Fig. 1. Monthly rainfall and potential evapotranspiration (PE, mm; calculated based on Penman equation) at four locations in the semi-arid tropics.

Solar radiation (between 17 and 21 MJ m^{-2} day^{-1}) is generally adequate during the growing season in the SAT. Temperature extremes are more critical in determining crop growth and yield (Peacock and Wilson, 1984). It is difficult to generalize on cardinal temperatures since they differ substantially between genotypes (see below), and perhaps even for different plant processes. For example, the optimum temperature for photosynthesis is close to 40°C, while for growth it is in the range of 30-35°C (Eastin, 1983). The adaptation range is immense. Some cultivars grown at high altitude can tolerate temperatures just above freezing for several weeks (nevertheless they take a long time to mature). The maximum temperature in sub-saharan Africa during the season can exceed 45°C. Low temperature stress is important in the highlands of Ethiopia and Kenya, and in some countries of southern Africa and Latin (mainly Central) America. High air and soil temperature at the beginning of the season may impede crop establishment if rains are inadequate. Temperature may also impede crop establishment if rains are inadequate. Temperature may also increase at the end of the season, especially during years when the rains end early; this may lead to severe terminal drought stress. Although the temperature during vegetative growth may be high in some regions/ years, it seems to be less critical than that at either early or late stages, especially if roots have access to water.

This discussion suggests that the diversity of sorghum-growing environments is mainly attributable to the differences in the amount and distribution of rainfall in relation to the potential evaporation (PE; calculated using Penman equation), followed by the differences in temperature. Rainfall, in turn, is correlated with solar radiation, air and soil temperature, and saturation vapour pressure deficit (SD) of the atmosphere in the SAT (Squire *et al.*, 1987). The monthly rainfall and PE at three locations in the SAT, and an arid location (Jodhpur) is shown in Figure 1. While the rainfall in Hyderabad and Ouagadougou exceeds the PE for three months, at Jodhpur it does not exceed the PE for any month. Nairobi has biomodal rainfall; during the first peak of rain, rainfall can exceeds for about one month only. Production problems in each of these regions distributed across continents are different (Table 3), and different sorghum genotypes and management strategies are required to produce high and stable yields in each of these regions.

Physiology Research for Crop Improvement

Physiological research on sorghum has been reviewed recently by Eastin (1983), Krieg (1983), Norman *et al.* (1984), and Peacock and Wilson (1984). As other authors in this volume have discussed specific physiological aspects of sorghum, we will confine ourselves to some general issues relating to the use of physiological knowledge for crop improvement.

In temperate regions, cereals are grown in highly managed agricultural systems, almost exclusively for feed-quality grain. Short, early, and high-yielding hybrids, responding to high levels of fertilizer and water, are used. The objectives of research in this region are: tolerance to low temperature at the beginning and escape from frost at the end of the season, tolerance to high temperature around flowering, and, in some cases, drought tolerance during reproductive growth. Shorter vegetative periods, with high potential seed number during panicle development, and with longer grain-filling periods coupled with greater assimilation during grain-filling periods are regarded as physiological means to increase potential grain yields (Eastin, 1983). Potential yields, however, have been static for nearly two decades. Any further increase in yield will need resources and inputs exceeding the current levels (already high).

Table 3. Sorghum production problems in each of the three different agroclimatic areas in the semi-arid tropics

Problems in near optimum rainfall areas

- Soil-related constraints:
    - 0 Crusting in Alfisols
    - 0 Water-logging in Vertisols
    - 0 Mineral Toxicity in highly leached soils
- Disease (grain mold)

Problems in marginal rainfall areas

- Short growing season
- Intermittent or terminal drought
- Sand blasting
- Crop establishment
- High temperature stress

Problems in bimodal rainfall areas

- Crop establishment
- Mid-season drought
- Low temperature stress at high altitude

In the SAT, on the other hand, climatic and soil constraints are more severe, and the resource-base of the farmer is generally poor. Crops are grown with minimal inputs of energy, inorganic fertilizer, and water Besides food-quality grain, crop residue is also valued for various uses, such as fodder, fuel, and fencing. Sorghum cultivation is characterized by medium to tall cultivars, low to medium population density, and inter-or mixed-cropping with legumes or other cereals. Seed saved from the previous crop is sown on relatively dry soil, using simple implements, at the beginning of rains in summer. Poor crop establishment restricts yields, especially in areas prone to crusting and high temperature, such as in West Africa. Research is aimed mainly at producing genotypes for moderate and stable yields with low inputs. This is achieved by reducing the crop maturity and the height of tall and late local landraces. Because the abrupt termination of rains is common, as is the delay in its onset, cultivars with specific local adaptations (e. g., with high photoperiod sensitivity) are still widely grown. Grain size is almost as important as grain number in these traditionally high-stress, low-yield environments.

Further increase in harvest index as a measure of yield potential, without understanding the development of yield *per se*, may be of little value in improving the yields of tropical sorghums (Peacock and Wilson, 1984). The increasing trend in whole-plant utilization of sorghum calls for continued attention to overall growth and biomass productivity, rather than merely to efficient partitioning into the grains. As the supplies of natural resources needed for crop production are both low and erratic, their efficient capture and utilization by both genetic and agronomic means should be emphasized. Study of the edaphic environment and of roots, including crop-growth regulation originating from roots themselves, needs greater attention. Rapid establishment of an efficient canopy, and its longevity to suit local conditions, needs to be studied in relation to water and nutrient supply patterns during crop growth.

Physiologists have been largely studying crop processes and yield constraints in isolation. But, in the future, more attempts are needed to integrate the effects of individual factors and processes. The sorghum crop is a managed ecosystem in which environmental factors, especially stresses, interact significantly; more studies should be pursued to combine individual effects from a combination of stresses during critical phases of development (e. g., water x temperature, temperature x photoperiod, nitrogen x water, etc.). These studies should be selected for relevance to target regions. In areas with recurrent droughts, more research is needed on crop establishment, survival during early dry and hot periods, recovery after the revival of rains, and ability to fill grain and resist lodging under terminal stress.

Yield maximization in a given environment can be effective only when the genotype, environment and the consequent developmental pattern are correctly matched. Our knowledge of how developmental processes limit yield is coming into focus. However, this knowledge has yet to be applied to tropical environments. The need to match crop maturity to the length of the growing season is well recognised in the SAT, but there is a tendency to overlook the fact that *all* developmental components of maturity, including yield, are strongly directed by those genes that govern the magnitude of the photoperiod-temperature response of flowering. Lack of quantitative understanding of the flowering behaviour of genotypes is a limitation both to crop simulation modelling, and to effective global germplasm exchange and utilization. The delay in flowering, caused in the SAT by severe nutrient, temperature and water stresses, deserves special study.

Despite much research, we lack sufficient understanding of how physiological processes are related to the developmental processes which determine yield components. The stability of yield, rather than realization of potential yields, is of major concern in the SAT. Most physiological work, therefore, has been directed towards identifying efficient management practices and genotypes for yield stability. But the application of existing knowledge for applied sorghum breeding has been both inadequate and difficult; selections are often based on single physiological traits, which are rarely adequately related to final yields measured in the field. To be helpful to breeders, physiologists must distinguish between tests for the presence of a trait (or efficiency of a process) associated with stress resistance, and the field tests that finally demonstrate the stress resistance of cultivars in the target environments.

Modelling

Crop simulation modelling offers several advantages for assessing the crop's potential in different regions, and as a decision-making tool for crop management and deployment of suitable crop cultivars for a region. For illustration, we have used SORGF, the sorghum growth and development model developed by Arkin *et al.* (1976), and modified and calibrated for tropical conditions by Huda (1987). In Table 2, the actual yields (from crop-cutting experiments of the Government of India Statistical Service) and simulated yields are summarised for five SAT locations in India (Huda and Virmani, 1987). The simulation includes both low levels of management (landrace grown with moderate plant density and low fertilizer levels) and high levels (hybrid with high plant density and adequate fertilizer). First, the yield data show the the ranking of these locations for production potential is independent of the level of technology, with a single exception: the actual yields at Jodhpur are less than at Anantapur, but the reverse is the case with predicted yields. Jodhpur is on the fringe of the sorghum-growing region with a short season, and the local forage landraces are not intended for grain production. Secondly, Indore and Dharwad are zones of high productivity, while Anantapur and Jodhpur are in the zones of low productivity. Hyderabad is intermediate. Variability in measured or simulated yields is also low at Indore and Dharwad, and high at Anantapur and Jodhpur.

Thus crop simulation models can provide results which rank environments in a similar fashion as actually measured yields. Simulated yields in Table 2 are much higher than the measured yields, as no biotic stresses are considered, and higher levels of technology are assumed. However, models can predict how the crop would respond to management alternatives so that, for example, the profitability of applying specified amounts of fertilizer can be assessed. The feasibility of inter- or sequential cropping can be estimated from the residual soil moisture after rainy-season cropping. In our present analysis, water left in the profile at the end of the rainy-season cropping is inadequate for growing a second crop at Jodhpur and Anantapur (Table 2). At Indore, however, the scope for intercropping sorghum with a long-duration legume crop (e. g., soybean) or raising an additional crop in the post-rainy season is apparent, but at Dharwad only intercropping seems to be appropriate. Extreme case analysis of simulated yields can expose the nature of catastrophic events such as pollen wash caused by storms, or panicle blasting or leaf firing in unusually hot weather. However, appropriate subroutines are not yet incorporated in the current version of the model.

The greatest advantage of modelling is the ability to answer 'what if' questions. For example, a breeder may want to know what would happen if he replaces one cultivar with another maturing two weeks earlier. At Jodhpur, the yield will increase, as the growing season is very short (Table 2), and the average number of weeks receiving at least 20 mm of rain is only 11. At Anantapur, yield will decreases as the rainfall is most uncertain for about 2 months following the beginning of the season (or sowing), and soils are shallow. Early cultivars are likely to flower before the 2-week period of assured rain in October, resulting in lower yields. In other locations, an increase in time to maturity will also increase high yield potentials. Howeve grain mold will become a serious problem for early-maturing lines at these location, as the grain will mature during the wet periods.

The second example will illustrate how modelling can help to guide decisions on crop management practices. In India, receding soil moisture and low temperatures are two major constraints of sorghum yields during the post-rainy season (as discussed). Early sowing is not always possible because Vertisols are difficult to work when they are wet. Using the SORGF, we predicted yield reductions from delayed sowing for comparison with records of actual yield reduction from a serial sowing experiment. As figure 2 show, predictions and measurements agreed quite well. Yields were closely related to (simulated) soil moisture levels at sowing in these crops, grown on stored water. In another study, the model was shown to be useful in developing an irrigation strategy to maximize water-use efficiency in a drought-prone area (Huda *et al.*, 1986).

When not properly calibrated, models may lead to misleading conclusions, however, such as when cultivars grown in the field have genotypic coefficients different from those used in the model. For example, although the base and optimum temperatures for seed germination are nearly the same for a set of six sorghum genotypes, both the ceiling (maximum) temperature and the rate of germination were substantially different (D. J. Flower, ICRISAT Centre; personal communication). IS 17605, a heat-resistant landrace from Egypt, showed at least 5°C higher ceiling temperature, and germinated nearly twice

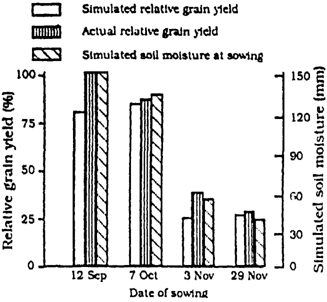

Fig. 2. Effect of date of sowing on relative simulated and measured yields, and the simulated soil moisture at sowing. (Measured yield of crop sown on 12 Sep., and simulated yield for that crop were considered as 100%; based on Huda *et al.*, 1986).

as fast as ICSV 213, a heat-susceptible variety. Thus, unless the subroutine dealing with germination takes into account significant differences between genotypes, the prediction of time of emergence will not be accurate. Under high temperature stress, the crop stands will be drastically different for these two genotypes, which will result in a significant discrepancy between actual and measured yields.

Even a sophisticated and complex model like the SORGF is incomplete with regards to some physiologically based subroutines. This model requires leaf number and the area of individual leaves as inputs. Leaf area is among the most dynamic crop growth variables, and its study can be a powerful tool for assessing the response of plants to their environment (Seetharama *et al.*, 1982). Leaf growth is basically driven by temperature. Leaf-extension rate in a hybrid CSH 8R increased by 0.26 mm h^{-1} with an increase of 1.0°C, but it decreased when neither nitrogen nor water was applied (Table 4). Similar responses were recorded for leaf senescence but, unlike leaf expansion, drought had more effect than nitrogen stress. Besides leaf area, crop phenology is also altered. Generally, mild drought increases developmental rate before flowering, but severe drought slows it down (Seetharama *et al.*, 1984; Table 4). Nutrient stresses always delay development. Drought after flowering enforces early maturity (Table 4). These effects are not yet incorporated in the current version of the model.

Models, being merely tools, are limited by our incomplete understanding of the behaviour of sorghum in its ecosystem. Simple models, relating effective crop-growth rates and durations during the growing season (Monteith and Scott, 1981), are quite useful. Such an analysis of rates and durations can be related to specific weather or management factors, or genotypes; it provides a useful basis for summarizing otherwise complex dynamic interactions between crops and environments, as illustrated by Monteith and Scott (1981). In Table 4, for example, though the nitrogen stress and, to a small extent even drought increased the effective crop-growth duration (period of linear rate of dry-matter accumulation), the growth rate was substantially lower under stress conditions than that of the control crop supplied with both water and fertilizer. Similarly, the acquisition and efficiency of utilization of natural resources (water, radiation, etc.) are also useful for comparing environments, and genotypes. This is illustrated by the data on seasonal radiation interception and the efficiency of its use in Table 4. The radiation-use efficiency value in the control crop (receiving adequate nitrogen and water) was much lower than the value of 2.7 g MJ^{-1} reported by Sivakumar and Huda (1985) for the rainy-season crop (warmer and more humid than during post-rainy seasons). It is imperative that such seasonal effects be considered while building and refining large simulation models, such as SORGF.

Conclusions

The large diversity of ecological conditions of sorghum-growing environments is matched by a parallel diversity in sorghum

Table 4. Effect of nitrogen and water levels on phenology, biomass and grain yields, and selected physiological characteristics of sorghum hybrid CSH 8R Vertisols, ICRISAT Center, 1981 post-rainy season

Observations	Added nitrogen			
	80 kg ha^{-1}		0 kg ha^{-1}	
	Irrigation treatment [S]			
	Wet	Dry	Wet	Dry
Time to flower (d)	67	66	76	81
Time to maturity (d)	107	101	119	115
Biomass (t ha^{-1})	9.1	5.6	3.8	2.8
Grain yield (t ha^{-1})	5.0	2.5	1.5	1.1
Leaf-extension rate at 25 °C (mm h^{-1})[SS]	3.7	2.6	1.9	1.8
Max. crop growth rate (g m^{-2} day^{-1})	14.4	9.0	4.3	3.2
'Effective' growth duration (days)	48	52	62	63
Seasonal intercepted radiation (MJ m^{-2})[SSS]	465	442	400	240
Radiation - use efficiency (g MJ^{-1})	1.96	1.26	1.25	1.14

S 'Wet' treatment received two irrigations at 30 and 60 days after sowing. 'Dry' treatment refers to a totally stored-moisture environment.

SS Estimated from the regression of hourly extension rate vs air temperature.

SSS Photosynthetionally active radiation (PAR)

adaptation. Substantial progress has been made during the last two decades in understanding component traits of various processes, and in elucidating genotypic differences in stress tolerance, especially those related to yield formation. However, this information cannot yet be used confidently in crop improvement programs because complex interactions between factors and processes are not adequately treated at the whole-plant and crop levels. Pressure on scientists to become experts in relatively narrow areas of plant physiology involves the risk that research on whole plants may be considered less sophisticated or less important than narrow specialization. Modelling offers physiologists an opportunity to synthesize their knowledge of processes on different levels of organization, and to test it for practical applications. Even failures' from such exercises are useful in identifying critical areas of research. Modelling, like crop breeding, is a continuous exercise. In the past, physiologists have attempted to model individual crop processes under controlled sets of conditions, but in the future they need to emphasize modelling crop growth and grain yields under well-quantified field conditions.

Considering the diversity of sorghum-growing environments, substantial resources for interdisciplinary research will be needed to make a single, complex physiological model capable of effectively serving the needs of a range of environments. Such efforts should be aimed at developing and refining different subroutines of the model and particularly at determining genotypic coefficients.

While such simulation models provide generalized answers to broad questions, they tend to indicate the need for additional research more often than they provide practical answers to problems at specific production sites within a reasonable time. Simple models, which respond to well-defined climatic and edaphic factors and to the agronomic needs of target regions, can be more effective as a practical tool, especially in the short run. Holistic and integrative studies of the impact of the environment on crop growth (e.g., Squire *et al.*, 1987) should be pursued at benchmark locations in the tropics, to help integrate knowledge of physiological processes and environmental characteristics. These can be a basis for building simple models which, in turn, can also form the basis of large ones that can be used for the specific applications discussed. The full benefits of modelling can be realized only when the traditional boundaries between disciplines are removed. Interactions between the physical environment, biotic stresses and genotypes are beyond the scope of this review, but they must receive adequate attention by modellers in the future.

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