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Problems and Prospects in Modeling Pearl Millet Growth and Development: A Suggested Framework for a Millet Model

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Abstract

Physical environment plays an important role in determining crop duration, water availability, the occurrence of pests and diseases, and thereby the ultimate yield. Knowledge of the influence of environmental factors on pearl millet growth and development will thus be helpful in devising the means to increase and stabilize pearl millet production. Simulation modeling is an effective approach to integrating various processes involved in crop growth and development. Currently no simulation model for pearl millet is available in the literature, but because of the similarity in some of the growth and development processes between pearl millet and sorghum, the suitability of adapting certain subroutines of the existing sorghum model (SORGF) is examined. The difficulty in modeling the tillering habit of pearl millet is recognized. However, the effects of temperature and daylength on the duration of growth stages and tillering habit of the selected pearl millet genotypes are discussed. The total dry matter computed from the amount of light intercepted by the canopy, and partitioning of dry matter to different plant parts are dealt with. Based on the available information, a framework for developing a pearl millet model is suggested.

Résumé

Problèmes et perspectives de la modélisation de la croissance et du développement du mil; proposition d'un cadre pour la modélisation du mil : Le milieu physique exerce une forte influence sur le cycle de croissance, la disponibilité en eau, ainsi que l'incidence des ravageurs et des maladies, donc le rendement d'une culture. Une compréhension de l'influence des éléments environnementaux sur la croissance et le développement du petit mil permettra d'établir des méthodes visant à augmenter et à stabiliser la production de petit mil. Des modèles simulés permettent d'intégrer les différents processus impliqués dans la croissance et le développement des cultures. Actuellement il n'existe pas de tels modèles pour le petit mil. Cependant, compte tenu des ressemblances entre les différents processus physiologiques du sorgho et du petit mil, il conviendrait d'examiner l'adaptabilité au petit mil de composantes du modèle utilisé pour le sorgho (SORGF). Le processus de tallage chez le petit mil pose un problème particulier. Les auteurs discutent l'effet de la température et de la durée du jour sur la durée des différentes phases de croissance et le tallage chez certains génotypes de mil. Suit une analyse portant sur la matière sèche totale calculée en fonction de la lumière interceptée par le couvert végétal, ainsi que sa répartition entre les différentes parties de la plante. A la lumière des informations disponibles, les auteurs proposent un cadre pour la mise au point d'un modèle.

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International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Pearl millet (*Pennisetum americanum* [L.] Leeke) is a major cereal grown by subsistence farmers in the dry semi-arid tropics. It is most extensively grown as a rainfed crop in sandy and often shallow soils in areas with 200 to 800 mm annual rainfall. More than 95% of the world's millet crop is grown in Africa and South Asia, principally in the Sahelian-Sudanian zones of West Africa and in the semi-arid regions east and southeast of the Thar desert in India. The areas of adaptation of the species are clearly defined by the mean annual rainfall isohyets of 200 to 600 mm in both continents (Bidinger et al. 1982). These zones are generally characterized by short rainy seasons (2-4 months), high mean temperatures, high potential evapotranspiration rates, and shallow, sandy soils (Cochemé and Franquin 1967, Kowal and Kassam 1978). Inter- and intraseasonal variability in available soil moisture is the major hazard to pearl millet production.

Millet grain yields exceeding 5 tonnes/ha can be obtained in favorable environments (Rachie and Majmudar 1980). Physical environment plays an important role in determining crop establishment, crop duration, water availability, occurrence of pests and diseases, and thereby the ultimate growth and yield. Excellent information on the relationship between environment and sorghum growth and development is available in the literature (Downes 1972; McCree 1974; Arkin et al. 1976; Vanderlip and Arkin 1977; Sivakumar et al. 1978; Huda and Virmani 1980; and Huda et al. 1980b). However, we have very little quantitative information on the response of pearl millet to environment; the available information mostly deals with the effect of temperature.

Effect of Temperature

Fussell et al. (1980) studied the effect of temperature during various growth stages on grain development and yield of *Pennisetum americanum* in glasshouses. They found that high temperature (33/28°C day/night) during all three growth stages (vegetative, stem elongation, and grain development) lowered grain yields by reducing basal tillering, number of grains per inflorescence, and single-grain weight. Low temperatures (21/16°C) when imposed at different growth stages had different effects on grain yield. Low temperatures during the vegetative stage increased grain yield due to increased basal tillering, and during the grain development stage due to a longer grain-filling period. However, low temperatures during the stem-elongation stage reduced spikelet fertility and inflorescence length, and thereby reduced the potential main-shoot grain yield.

Monteith et al. (1983) found that germination rate increased linearly in millet with temperature from a base of 10 to 12°C to a sharply defined optimum at 33 to 34°C and declined to zero at about 45 to 47°C. Other developmental processes such as leaf and spikelet initiation and the period from panicle initiation to anthesis responded similarly to temperature (Ong and Monteith, these Proceedings).

Little is known about the effects of high temperature (>32°C) on leaf area development in millet. Evidence from maize (Watts 1972) and sorghum (Peacock 1982) suggests that the rate of leaf extension declines rapidly between 35 and 40°C. Ong and Monteith (these Proceedings) suggested an optimum temperature of 32 to 34°C for leaf extension in millet.

Ong (1983) reported that soil temperature ([illegible] 25, and 31°C) appeared to affect many aspects of vegetative development such as seedling emergence, the initiation and appearance of leaves and early tillering. The rates of these processes increased linearly with temperature. He suggested that the rate of these processes can be described by a specific thermal time (summation of degree days above an extrapolated base temperature). However, the duration of the vegetative phase (GS1) appeared to be independent of meristem temperature within a range of 19 to 30°C at 12 h daylength (Ong 1983).

Simulation Modeling

Simulation modeling is an effective approach to interpreting the interrelationships between weather and physiological processes leading to final yield. Currently no simulation model for pearl millet is available in the literature. However, because of the similarity in some of the growth and development processes of pearl millet and sorghum, the possibility of adapting certain subroutines of an existing sorghum model, SORGF (Arkin et al. 1976) will be examined (Fig. 1). In brief, the SORGF model simulates timing of development of the plant, dry-matter production by a single plant, and partitioning of that dry matter into different plant parts based upon the stage of development of the plant as it is influenced by the environmental conditions.

Yields of sorghum and millet grown over a wide

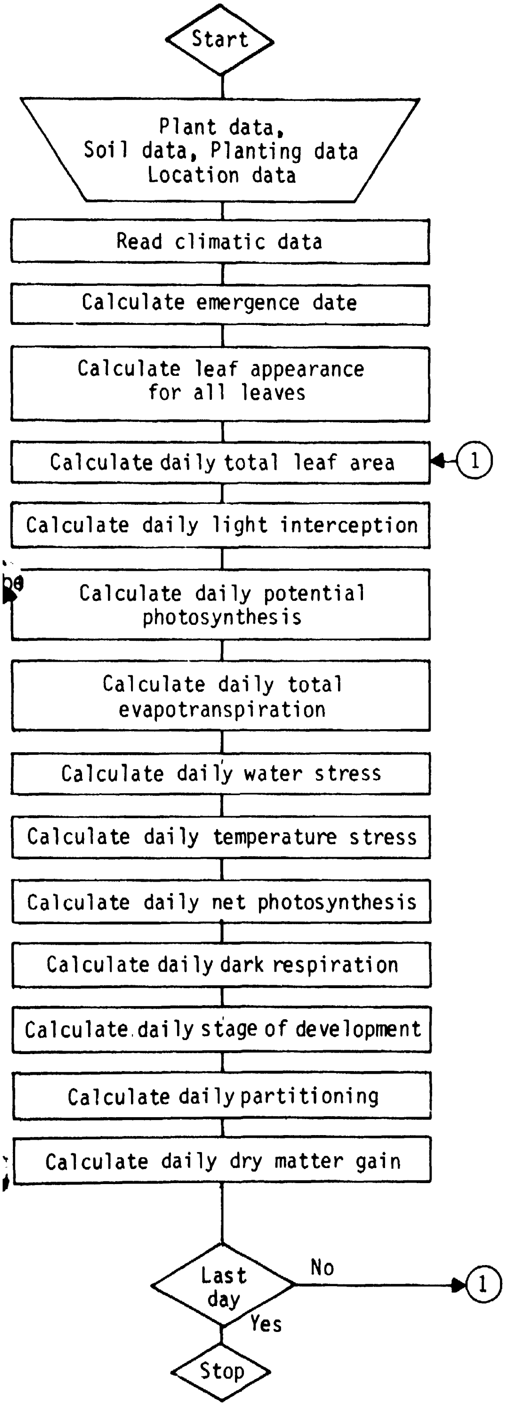

Figure 1. A generalized flow diagram of the growth model SORGF. (Source: Arkin et al. 1976.)

range of environments in the USA showed that the response of these two crops to the same environmental conditions is different (Fig. 2). Thus suitable modifications in SORGF are required for modeling pearl millet growth and development to mimic such differential responses to a given environment.

Problems and Prospects in Pearl Millet Modeling

It is recognized that much more physical and physiological information is required for building a sound simulation model for pearl millet. Therefore, interdisciplinary experiments similar to the sorghum modeling experiments coordinated by ICRISAT (Huda et al. these Proceedings) were initiated in the 1981 rainy season. Standard data sets on soil, crop, weather, microclimate, and management factors as suggested by Huda et al. (1980a) are collected to help develop a pearl millet simulation model. In this paper, the problems and potential of building relevant subroutines of a millet model that would describe features such as phenology, tillering, leaf area, evapotranspiration, dry-matter accumulation and its partitioning, etc., are described.

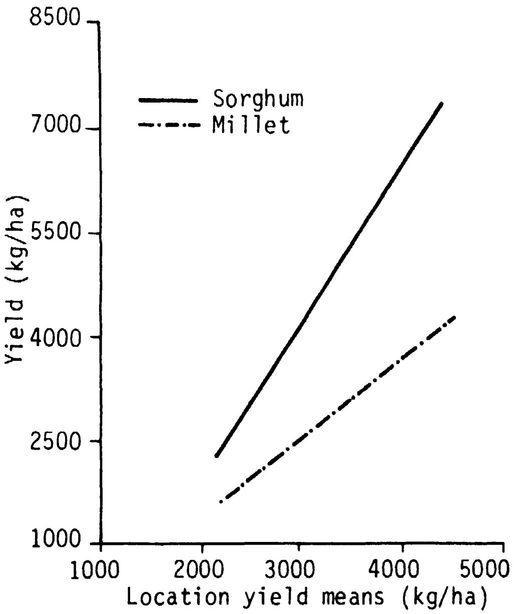

Figure 2. Average yields of sorghum and millet grown over a wide range of environments in the USA.

Phenology

Accurate simulation of phenological development is also important to determine partitioning of dry matter to different plant parts. The duration of three growth stages—emergence to panicle initiation (GS1), panicle initiation to anthesis (GS2), and anthesis to physiological maturity (GS3)—were studied. Duration of three growth stages for genotypes BJ-104, Ex-Bornu, and ICH-412 grown at ICRISAT Center during the 1982 rainy season is given in Table 1 to show the genotypic variability for phenological development. The maximum and minimum number of days, mean number of days, and the coefficient of variation for three growth stages for millet (BJ-104) pooled from different experiments conducted in different seasons at ICRISAT Center are given in Table 2. Greater variability in GS1 than in GS2 or GS3 suggests that variation in environmental factors (temperature, daylength) should be examined to explain the variability in GS1.

Table 1. Duration (days) of growth stages of three genotypes of pearl millet grown in the 1982 rainy season at Patancheru, India.

	Genotype		
Growth stage	BJ-104	ICH-412	Ex-Bornu
GS1	15	18	18
GS2	25	36	34
GS3	27	28	27
GS1 + GS2	40	54	52
GS1 + GS2 + GS3	67	82	79

By using the concept of growing degree days (GDD) (Stapper and Arkin 1980), we studied the variability in the growth stages of pearl millet genotype BJ-104 (Table 3). However, no progress was made in reducing the variability in growth stages by accounting for the effect of temperature alone. Previous work showed the effect of daylength on the duration of GS1 in sorghum (Huda 1982) and maize (Stapper and Arkin 1980). Pooled data from our field studies in different seasons and from an experiment on the influence of daylength on millet phenology (personal communication, Peter Carberry, Research Scholar, ICRISAT) were used to plot the relationships (Fig. 3). Since pearl millet has a quantitative short-day response, the duration of GS1 increased with increased daylength. When daylength correction was introduced, variability [illegible] GS1 was reduced to 10%. Further work in this direction is under way.

Tillering

In the SORGF model sorghum was described as a single-culm plant. However, pearl millet generally produces tillers, the total number and appearance dates of which vary. Moreover, the number of effective (grain-producing) tillers varies depending upon genotype and environment. Tiller initials or buds

Table 2. Variation in phenology of pearl millet genotype BJ-104 grown over different seasons at Patancheru, India.

Growth stage	Maximum	Minimum	Mean	SD	CV (%)
	Days				
GS1	34	13	18	5	28
GS2	36	21	25	3	13
GS3	35	25	30	3	10

Table 3. Growing degree days (GDD) required for different growth stages of pearl millet genotype BJ-10 grown over different seasons (base temperature = 7°C) at Patancheru, India.

	Growing degree days (GDD)				
Growth stage	Maximum	Minimum	Mean	SD	CV (%)
GS1	687	257	351	103	29
GS2	664	375	472	66	14
GS3	657	486	567	51	9

develop in the axils of the lower leaves and are initially enclosed by the leaf sheath. Tillers develop on alternate sides of the main shoot, following the alternate arrangement of leaves. The development and growth of the tillers follow a pattern identical with that of the main shoot, with a difference in time scale. Tiller development may be nearly synchronous with the development of the main shoot or may be considerably delayed, or even suppressed by the main shoot.

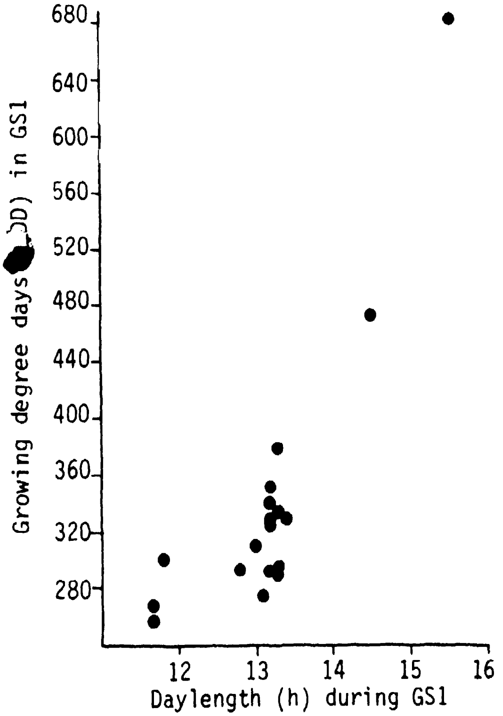

Figure 3. Relationship between growing degree days for GS1 and daylength during GS1 for pearl millet genotype BJ-104 at Patancheru, India.

Some varieties produce nodal tillers from the upper nodes of the main stem after grain set in the main panicle. These have a short developmental cycle, producing only a few leaves and usually a small panicle. Nodal tillers are common when grain set on the main panicle is poor or the main panicle is damaged in some way (Bidinger et al. 1982).

Base temperature for rate of tillering is lower than for the production and expansion of leaves (Pearson 1975; Ivory and Whiteman 1978). Ong and Monteith (these Proceedings) reported that longer days increased the duration of GS1 and produced more tillers. Tiller production at 21 °C was seven or eight times more than at 31 °C (Fussell et al. 1980).

Genotypic variability in the production of tillers was observed in an initial experiment conducted at ICRISAT Center during the 1981 rainy season (Table 4), using three genotypes—BJ-104, WC-C75, and ICMS-7703. The number of effective tillers per main shoot was much lower than the total number of tillers produced. The number of effective tillers was highest in BJ-104.

In the same experiment, we also observed that the number of effective tillers also depends on the time of planting. In the first planting, emergence occurred on 22 June; in the second, on 7 July. Table 5 compares the effects of early and late planting, showing the relative contributions of main plant and tillers to grain yield in each genotype. Early planting produced more effective tillers than late planting. The contribution of tillers to total grain yield also varied among genotypes. In late planting, contribution of tillers to total grain yield for genotypes BJ-104, WC-C75 and ICMS-7703 were 52, 20, and 16% respectively.

The interaction of time of planting (temperature, daylength, etc.), genotype, environment (moisture availability), and management conditions (planting

Table 4. Number of tillers and the time of their appearance in pearl millet genotypes grown in the 1981 rainy season at Patancheru, India.

Genotype	No. of tillers 1	2	3	4	5	No. of effective tillers/main plant
	—Days after emergence—					
BJ-104	23	23	25	30	45	1.2
WC-C75	23	23	30			0.4
ICMS-7703	23	25	30	45		0.5

Table 5. Effect of early and late planting on contribution of tillers to grain yield of pearl millet grown in the 1981 rainy season at Patancheru, India.

	Grain yield (kg/ha)				Effective tillers/ main plant	
	Early		Late			
Genotype	Main culm	Tiller	Main culm	Tiller	Early	Late
BJ-104	1563	2308	1600	1759	2.3	1.2
WC-C75	1889	984	2306	572	1.0	0.4
ICMS-7703	1609	1281	2462	469	0.3	0.5

density) makes it difficult to quantify tillering. Much work is needed to understand the tillering habit so as to incorporate this information into a subroutine of the pearl millet model.

Leaf Area

The rate of development of the total leaf area per plant in pearl millet is a product of the rate of leaf expansion and the size and longevity of the individual leaves for both the main shoot and the tillers. Rate of leaf area development is slow early in the season, because of the small size of the embryonic leaves, but increases rapidly approximately 15 to 20 days after emergence, as the size of the individual leaves increases and as tillers begin to expand their leaves (Maiti and Bidinger 1981).

In millet the maximum number of leaves to be produced is determined during the GS1 growth stage (Ong and Everard 1979). The contribution of the tillers to the total leaf area in pearl millet varies with genotype and with other conditions such as fertility, water availability, etc. Gregory and Squire (1979) reported that leaves from tillers can account for 60 to 70% of the total leaf area in a healthy millet crop. Maximum leaf area is attained at approximately 50% flowering of the crop, by which time the majority of the tillers have expanded all their leaves.

As the plant reaches physiological maturity, the decrease in leaf area index (LAI) is faster in pearl millet than in sorghum (Fig. 4). Because of this difference in leaf senescence between sorghum and pearl millet, and the complex nature of the tillering habit, simulation of daily progression of leaf area throughout the season in pearl millet needs an approach different from that adopted in SORGF.

Daily LAI may be estimated in millet by modeling its components (tillers/plant, leaves/tiller, and leaf area/leaf). The other approach could be to calculate the leaf area based on the weight of available leaf dry matter (Penning de Vries 1980).

Evapotranspiration

Evapotranspiration (ET) is an important component for computing soil water. Daily available soil water can be simulated by Ritchie's (1972) procedure as used in SORGF. Potential evapotranspiration (PET) can be calculated after computing potential evaporation from bare soil (E_0) and using LAI values. E_0 is calculated using the Priestley-Taylor (1972) equation that requires net radiation as input data. Net radiation is computed from albedo, maximum solar radiation reaching the soil surface, and sky emis-

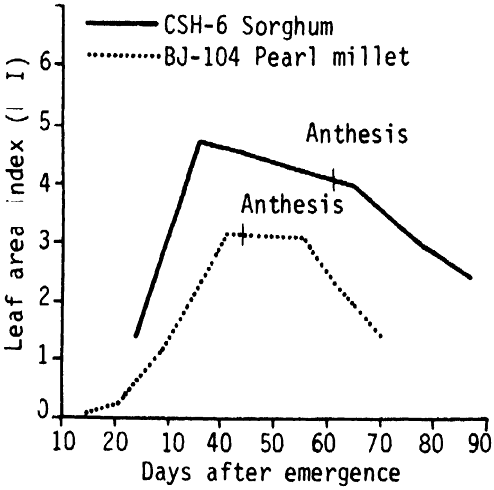

Figure 4. Comparison of leaf area index for sorghum (CSH-6) and pearl millet (BJ-104) grown during the rainy season at Patancheru, India.

sivity. The actual ET data for pearl millet obtained from Kansas (personal communication, E.T. Kanemasu, Kansas State University, Manhattan, Kansas, USA) were compared with simulated ET data (Fig. 5). The agreement between simulated and actual data is quite good, and the difference between them is consistent. However, further testing of this subroutine with additional data sets for millet is required.

Dry-matter Accumulation

Dry-matter production is related to intercepted radiation (Biscoe and Gallagher 1977; Sivakumar 1981; Ong and Monteith, these Proceedings). A simpler relationship for calculating daily dry-matter production in sorghum from intercepted radiation is discussed by Huda et al. (1982). Ong and Monteith (these Proceedings)—who studied the relationship between photosynthetically active radiation (PAR) and dry-matter production of pearl millet in the glasshouse at mean temperatures between 19 and 31°C—showed that 3.1 g of dry matter was produced for each MJ of PAR intercepted until anthesis. They expected larger values for field crops growing in the tropics.

The relationship between intercepted PAR and dry matter during the growing season was studied for three pearl millet genotypes (BJ-104, WC-C75, and ICMS-7703) grown at ICRISAT Center during the 1981 rainy season. It was observed that the rate of production of dry matter per MJ of PAR intercepted was considerably high until the completion of anthesis; thereafter, the conversion of intercepted radiation into dry matter was less efficient due to aging of the leaves. Hence it appears that simulation of dry matter from intercepted radiation should carefully consider the need to use different dry-matter conversion factors before and after anthesis.

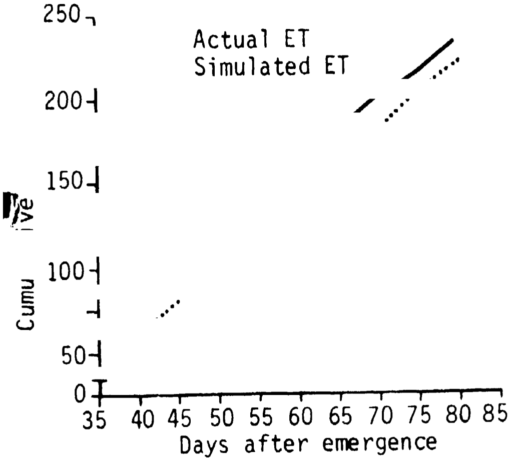

Figure 5. Comparison of actual and simulated evapotranspiration (ET) at Manhattan, Kansas, USA.

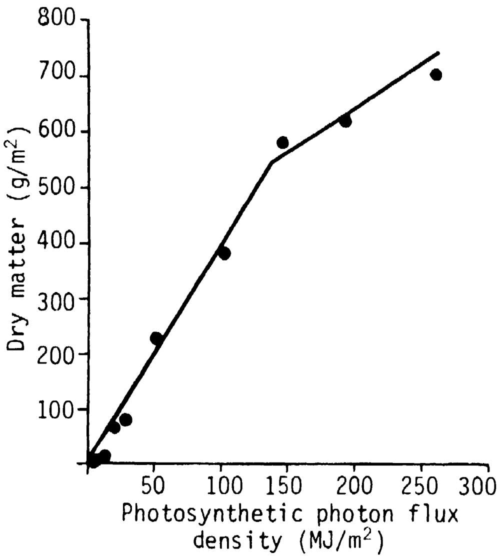

Figure 6. Relationship between dry-matter and intercepted photosynthetic photon flux density (PPFD) for pearl millet genotype WC-C75 grown during the 1981 rainy season at Patancheru, India.

For example, equations fitted to the relationship between intercepted PAR and dry matter for WC-C75 (Fig. 6) show that 3.96 g of dry matter was produced per MJ of radiation intercepted up to anthesis (GS2); after anthesis, dry matter produced dropped to 1.6 g per MJ of radiation intercepted. Williams et al. (1965) also showed for maize that dry-matter conversion from intercepted radiation could be treated in a two-stage process before and after anthesis. Gallagher and Biscoe (1978) found that aging or lack of adequate nutrition could reduce the efficiency of conversion of absorbed radiation in wheat; they obtained values of 3.1 and 2.8 g dry matter/MJ with and without applied nitrogen.

Dry-matter Partitioning

Accurate simulation of both dry-matter accumulation and plant development is essential to model partitioning of dry matter to various plant parts. Total dry matter and its partitioning to leaf, culm, head, and grain were periodically estimated throughout the growing season both for main culm and tillers in three genotypes (BJ-104, WC-C75, and ICMS-7703) grown at ICRISAT Center during the 1981 rainy season. Combined total dry matter of main culm and tillers and its partitioning to different plant parts in genotype BJ-104 are shown in Figure 7. Table 6 shows the proportion of total dry matter partitioned to various plant parts at three growth stages in genotype BJ-104 grown in different seasons at ICRISAT Center.

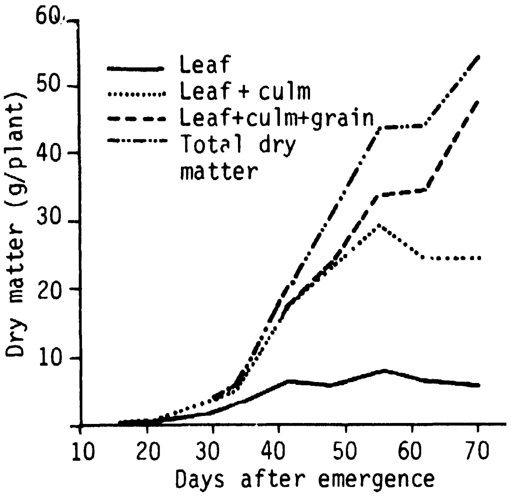

Figure 7. Total dry matter of pearl millet genotype BJ-104 and its partitioning to different plant parts during the 1981 rainy season at Patancheru, India.

Model Framework

Based on the outline of the sorghum model SORGF and the USDA-SEA winter wheat ecological model, we suggest a framework for a pearl millet model (Fig. 8), with input data similar to the SORGF model. The proposed model operates on a daily basis, calculates phenological development, LAI, tiller appearance, daily ET, soil water, dry-matter accumulation, and its partitioning to different plant parts. The model simulates final grain yield and total dry matter after physiological maturity is simulated.

Table 6. Partitioning of total dry matter (%) at three growth stages of pearl millet genotype BJ-104 grown over different seasons at Patancheru, India.

Plant part	Growth stage Panicle initiation	Anthesis	Maturity
Leaf	66	30	10
Culm	34	54	30
Head		16	16
Grain			44

Simulation Comparison

We used the preliminary suggested model (Fig. 8) to simulate grain yield of three pearl millet genotypes and compared the simulation results with the field data (Table 7). The agreement between observed and simulated values is satisfactory, but readers are cautioned that this data set was not independent of some of the information that was used for building the preliminary model. It includes many intermediate steps of the suggested model and takes the actual LAI and then simulates grain yield and total dry matter.

Table 7. Comparison of observed and simulated grain yield and total dry matter in three pearl millet cultivars.

Genotype	Grain yield (kg/ha) Observed	Simulated	Total dry matter (kg/ha) Observed	Simulated
BJ-104	3363	3200	7884	8000
WC-C75	2878	3313	8282	8582
ICMS-7703	2932	3428	8572	7919

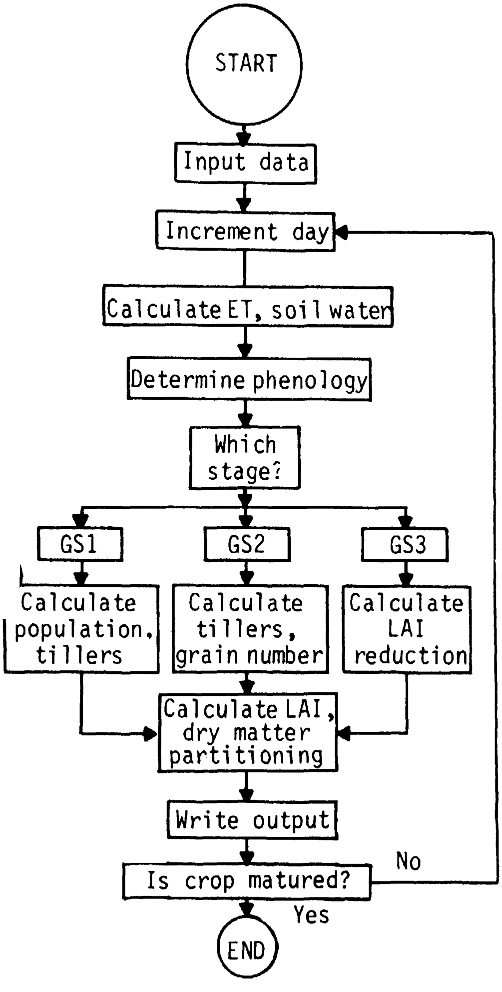

Figure 8. A suggested flowchart for a pearl millet simulation model.

Conclusions

1. A modeling approach similar to that of SORGF could be developed for pearl millet. A minimum data set required for developing and testing the model should be identified.
2. There are major differences in the growth of sorghum and pearl millet that should be carefully considered. The two most critical aspects—leaf area development and dry-matter partitioning—are both related to the tillering response of millet. Associated with that is the problem of trying to simulate the increase in leaf area on a daily basis. The approach in which LAI is computed directly from dry matter produced, instead of considering area of individual leaves, merits consideration.
3. Information on pearl millet growth and development is very scanty compared with that available on sorghum. Our progress in developing the model will therefore depend upon cooperative efforts to collect information. Effective integration of knowledge on pearl millet as it becomes available would go a long way to developing a working simulation model for this crop.

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