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Strategies for Improving Rabi Sorghum Productivity*

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In India, sorghum [*Sorghum bicolor* (L.) Moench] grown during the postrainy season (rabi sorghum) accounts for nearly 40% of the total sorghum hectarage in the country. It is an important grain and fodder crop on 6.5m hectares on Vertisols in south-central India. Efforts to improve rabi sorghum yields have not resulted in any significant gain as they have for the rainy season sorghum. Continuously receding soil moisture, poor nutrient availability, and low night temperatures are some of the major reasons for the low yields. Rabi sorghum environments are diverse. They are inadequately characterized especially from the angle of recommending new genotypes. This paper reviews pertinent literature and summarizes results from the authors' studies relating the environmental factors during rabi to crop growth, development, water use, and grain yield. It also examines plant physiological traits of rabi sorghum likely to be useful for effective utilization of resources under stored soil-moisture conditions. Finally, suggestions are made on research directions for stabilization of rabi sorghum yields at higher levels. They include better characterization of environments, search for unique phenological response and root growth pattern.

Key Words: Adaptition, crop physiology, rabi climate, Sorghum *bicolor*, N, stress, Water stress

Introduction

Sorghum is the third most important cereal in India, accounting for 13% of gross cropped area in the semi-arid parts of the country (Tarhalkar 1986). It is grown on approximately 16 million ha including both the rainy (June-September; kharif) and postrainy dry (September-February; rabi) seasons. During rabi, mostly it is sown between September and the end of October in the Deccan Plateau between 10 and 20°N latitude. Rabi sorghum covers up to 40% of the total sorghum-growing area in the country, which is more than the land occupied by maize (*Zea mays L.*). It is also more than half of that planted to pearl millet [*Pennisetum glaucum* (*L.*) R.Br.]. However, it accounts for less than 30% of the annual sorghum production (Tandon Kanwar, 1984). Average farmer's yields are about 0.5 t ha^{-1}. In recent years, sorghum yield per unit area during kharif has been steadily increasing, but during rabi it has remained stagnant (Vidyabhushanam 1986, NRCS 1989). Yet, rabi sroghum is an important and convenient component in the cropping systems practiced on stored moisture, as the quality of the grain harvested during this season is good, and the stover is keenly sought after as fooder.

Rabi sorghum of India, in spite of some major differences in both the environment and the cultural practices, shares many commonalities with sorghum crops grown on residual moisture elsewhere in Africa (Rao et al. 1988) or in the

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Mediterranean (e.g., Israel) and temperate regions (e.g., those on Vertisols in Texas, USA). There are two important differences between African postrainy and Indian rabi sorghums. In case of the former, soil fertility is less limiting as they are cropped on the receding flood-plains after burning the vegetation, and low plant density is employed. The temperate or Mediterranean sorghums are planted in fully water-saturated and highly fertilized soil. However, still research on rabi sorghum of India is expected to have some implications for sorghum production elsewhere throughout the world where sorghum is grown mainly on stored soil moisture, and *vice versa*.

In this paper we examine possible reasons for the low productivity of rabi sorghum. Evidence and data cited are based on the literature and the experience both at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, and at several Indian national programs. Suggestions are made for further improvement of rabi sorghum productivity.

Environmental Factors Limiting rabi sorghum Productivity

Climatic Factors

Rainfall: Most of the rabi sorghum areas are situated in a belt with low and variable annual rainfall of ~600-800mm isohyet. Cropping during kharif is uncertain in this belt because of erratic rainfall and high evaporation. However, only about 8% of the annual rainfall is received during the rabi season. The probability of receiving rainfall of more than 10 mm is about 60% during first week of October; soon after it decreases rapidly by about 2-5% per week (Virmani et al. 1982).

Solar radiation: The mean daily radiation is similar during kharif and rabi seasons. At Patancheru (17°32'N, 78°16'E), it is about 16.5 MJ m^{-2} $days^{-1}$ during rabi; this is only about 6% less than during kharif (Sivakumar Virmani 1982). However. Sivakumar and Huda (1985) have shown that the conversion of incident solar radiation to dry matter by rabi sorghum is only half of that during kharif, especially during panicle development (GS2) and grain-filling stages (GS3). While this seasonal difference is mainly due to lower leaf area indices during rabi than during kharif, radiation-use efficiency is also reduced (Seetharama et al. 1982b).

Temperature: The mean daily temperature during rabi season are a little less than during kharif: 24.9°C during rabi compared to 27.9°C during kharif at Patancheru (Sivakumar & Virmani 1982). However, the diurnal variations are greater during rabi. The lower night temperatures during rabi are believed to cause reduction in growth and grain yield (Rao et al. 1977, Choudhary 1989).

The consideration of effects of temperature on rabi sorghum is further complicated as sowing dates vary considerably, while temperatures decrease till December and again increase during rabi season. Temperature profile during the season has implications for the extent of decrease in grain yield with delayed planting, and for yield components (ICRISAT, 1983). Thus, for example, at Patancheru, an early-sown crop (say, on 15 September) is likely to be exposed to low temperature (< 10°C) only during grain-filling [the probability of a low temperature spell of ≥ between 60-90 days after sowing (DAS) = 17%]. On the other hand, a late-sown crop (15 November) is likely to suffer from low temperature stress only during the vegetative phase. High temperature affects only a late sown crop. The effects of high temperature are aggravated by low soil moisture and high evaporative demand during the late grain-filling stage.

Open-pan evaporation and saturation vapor-pressure deficit (SD): Open pan evaporation rates vary between 3 and 5 mm day^{-1} during rabi (during kharif: 4-7mm day^{-1}). The SD continuously increases during rabi; the possible implication of this (such as on radiation-use efficiency of rabi sorghums) is not yet sufficiently studied (Monteith 1986).

Photoperiod: The change in photoperiod between early September and November is less than 2 hr in rabi sorghum areas (< 80 min at

Patancheru). While the actual difference between photoperiods around panicle initiation across different planting dates may be much smaller, depending upon interaction with temperature, it may be still significant.

Edaphic factors

Most of the rabi sorghum is grown on deep (≥ 1.0m) Vertisols; in about 20-25% of the rabi sorghum areas the soil is deeper than 1.5m. Yield differences between 'shallow' and 'deep' Vertisols can be up to 1 t ha^{-1} (Tandon & Kanwar 1984).

Soil-water storage: It was estimated that about 175 mm of water is required for successful rabi sorghum cropping (Tarhalkar 1986). The highest water-use efficiency (WUE) reported for rabi sorghum is 50 kg $ha^{-1}mm^{-1}$ (Seetharama et al. 1984). Thus, 175mm of water use can result in about 9 t ha^{-1} of above-ground biomass. The southwest monsoon rains are usually sufficient to fully recharge the profile, particularly if the field is left fallow during kharif. However, abrupt termination of the monsoon early in September and poor management practices until the time of sowing (such as not keeping land weed-free) may result in unsaturated soil profiles at sowing. This will reduce crop growth especially after flowering (Table 1).

The pattern of soil-water changes in the 1.9 m deep soil profile during kharif and rabi seasons at Patancheru are illustrated by the data obtained at the ICRISAT Center in 1977 (Figure 1). This soil is classified as a very fine clayey, montmorillonitic, calcareous member of the hyperthermic family of Typic Pellustert with a plant available water-holding capacity of 100 mm m^{-1} depth. The moisture content increased during kharif. It receded continuously (unless irrigated) during rabi. The seasonal cumulative evapotranspiration (ET) increased almost linearly in both, being some 400mm by the end of each season. The irrigated rabi sorghum used water at the rate of approximately 4.0mm day^{-1}, while the dryland rabi crop had a much lower rate of 2.5mm day^{-1}, especially during the terminal growth stage. Even in areas where rainfall is more than 600mm,

Table 1 *Comparison of performance of a dryland (Dry) and irrigated (Wet) sorghum crops (hybrid CSH 8R) grown during 1977 and 1980 (Based on Seetharama et al. 1978, and unpublished data of N Seetharama and Sardar Singh).**

Irrigation treatment	1977		1980	
	Dry	Wet	Dry	Wet
Plant biomass (g m^{-2})—at flowering	423±26.1	503±19.1	562±82.9	483±95.5
—at maturity	658±27.8	1061±93.5	908±221	960±13.0
—increase during GS_3†	235±34.7	558±93.2	346±138	477±82.5
Grain weight (g m^{-2})	236±27.0	490±19.6	405±0.71	532±29.5
Harvest index (%)	35.8±2.62	46.2±6.42	44.7±11.67	55.4±3.82
Distribution index (%)	100·±13.7	88±20.7	117±56.0	112±13.5
Seeds m^{-2} × 10-3	9.8±0.90	16.4±0.75	14.1±0.1	16.8±0.5
Seed size (g 100 $seeds^{-1}$)	2.29±0.07	2.98±0.06	2.88±0.02	3.17±0.07
Time to flower (days)	63±0	63±0	64±0	65±1.0
Time to physiological maturity (days)	101±0	103±0	99±0.7	104±0.5
Plant height (m)	0.98±7.3	1.63±2.1	1.34±1.5	1.54±1.8

* During 1977 the soil profile was only 77% charged with water at sowing, and during 1980 the profile was fully charged. Wet treatment received two irrigations to recharge the profile each time, before flowering

† GS3 = Grain filling period

‡ Proportion of grain yield as that of dry matter produced during GS3

terminal drought stress is still common. This is so in spite of sowing in a nearly fully water-charged soil, and leaving fields fallow during kharif.

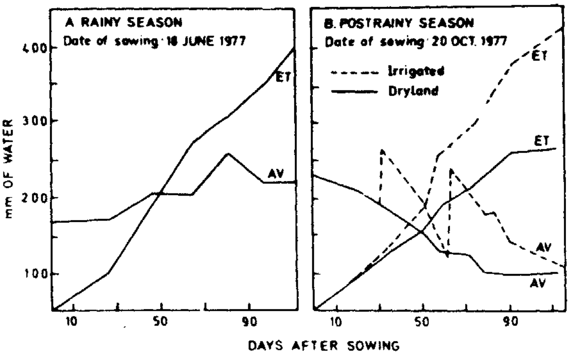

Figure 1 Seasonal trends in evapotranspiration (ET), and available-profile water (AV) for kharif (A), and rabi season (B) sorghum grown on a deep Vertisol, ICRISAT Center, 1977 (unpublished data of Sardar Singh)

The proportion of available soil-water used for transpiration through the crop is obviously higher in rabi than during kharif. The reason is less soil evaporates during rabi which is limited to the early part of the season. Hence high WUE is observed during rabi (Seetharama et al. 1984). Nitrogen (N) fertilization (Kanwar et al. 1984) and mulching on shallow soil (Mane & Shingte 1982) increase WUE of rabi sorghum substantially. However, it is difficult to find sufficient plant residues for mulching in most farm situations.

Soil nutrient content: The traditional practice of kharif fallowing, when kept weed-free, increases water and N reserves (Rago et al. 1982); otherwise N deficiency is common, especially following an unfertilized kharif crop. Effects of other nutrients were poorly documented.

Soil cracking: Although cracking can potentially result in severe soil water loss, there is no documented evidence to indicate the resulting extent of yield loss. Most farmers regularly intercultivate to conserve moisture.

Insect and Disease Problems

The number and severity of insect and disease problems during rabi are much less than during kharif. Shootfly, and root and stalk rot incidence are the problems over large areas, the rest (like rust) being only of local importance in some years. Weeds are not a serious problem during rabi.

Management Factors

Date of sowing: It is difficult to work with wet Vertisols because of their high clay content. Hence the farmers normally sow a week after the cessation of rain during September-October. Farmers also avoid sowing early immediately after the end of monsoon to reduce shootfly incidence (Nwanze et al. 1990). This traditional practice of sowing late (as late as six weeks), especially during years receiving October rains, results in considerable reduction in grain and fodder yields. A 10-week delay in planting of a set of cultivars resulted in 68% decrease in grain yield (Figure 2), and 37% decrease in stover yield (Reddy et al. 1987). Advancing the sowing date of improved cultivars by one month has brought about yield increases of 0.5 to 3.0 t ha^{-1} (Randhawa & Venkateshwarlu 1980, Spratt & Chowdhary 1978). Umbrani and Patil (1985), Umbrani (1989) and Kale (1989) have demonstrated that early sowing without adequate fertility had no significant effect on yield.

Depth of sowing: If sowing is delayed and the top soil is drying rapidly, farmers are inclined to sow deep. Deep sowing (> 30mm) results in a different type of root system from shallow sowing. A deep-sown seed will produce a smaller seedling (fewer expanded leaves), longer mesocotyl, shorter primary (seminal) root, and fewer secondary roots during the early season than a shallow-sown seed. This practice may severely affect water and nutrient uptake from the top soil layer and early growth (Kanitkar et al. 1968). In spite of sowing at 20 to 50mm depth, initial establishment of seedlings may not be optimum if no rains are received after field preparation but prior to sowing.

Irrigation: Less than 12% of the rabi sorghum is irrigated, usually once or twice during the season (Tarhalkar 1986). The beneficial effects of irrigation can be large, especially on shallow soils, and when evapotranspiration is expected to be high. Following are the percentages of yield gains over dryland crops due to irrigation: 414% (Hari Krishna 1981); 133-225% with one, and 284-411% with two irrigations (Verma 1978); 220% with two irrigations (Sivakumar et al. 1979). Two supplementary irrigations increased the mean grain yield in a set of five cultivars across four sowing dates by about 25% on a deep soil (Figure 2); the response to irrigation increased from 20% in an early sown crop to 40% in a crop sown 10 weeks later (Reddy et al. 1987). At Patancheru, irrigated rabi sorghum fetches more monetary benefit than irrigated chickpea (K L Srivastava, ICRISAT, personal communication).

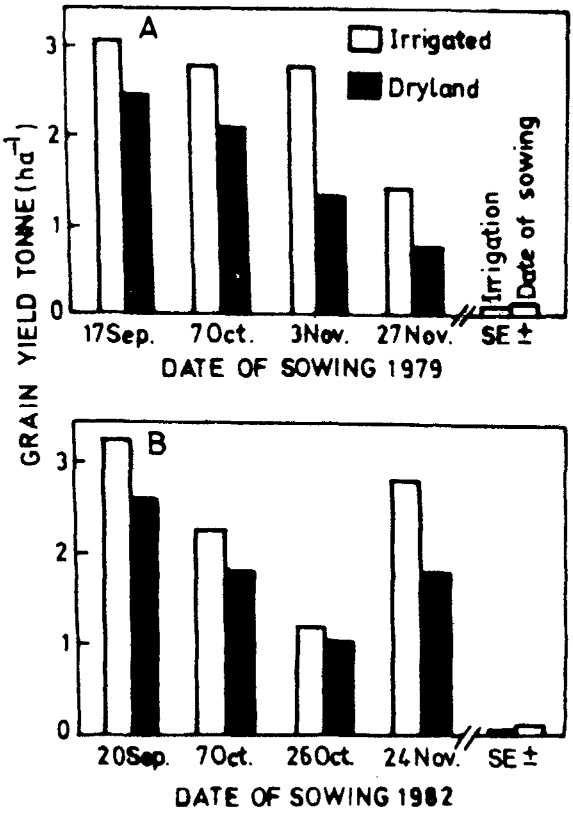

Figure 2 Grain-yield response of sorghum (mean of 5 cultivars) to irrigation and date of sowing during rabi in 1979 (**A**) and 1982 (**B**). Sorghum hybrid CSH 8R was sown on four dates on a deep Vertisol from September to November in 1979, and 1982. Irrigated treatments received two irrigations during each year before flowering, each time to fully recharge the soil profile. Vertisol, ICRISAT Center (Based on Reddy et al. 1987)

Fertilization: The problem of inadequate nutrient availability, mainly N, is further aggravated by the rapidly drying top soil layers which contain most of the applied nutrients. Farmers apply only modest doses of farmyard manures, during some years.

The response of rabi sorghum to fertilizer has been reviewed by Tandon and Kanwar (1984) and Tarhalkar (1986). Fertilizer response is increased by the use of high-yielding cultivars, and by the available soil water (soil depth) or irrigation. Kanwar et al. (1984) showed that with N fertilization both water use and WUE can be increased significantly, when the profile nitrate content is low. They also noted the (applied) N use-efficiency to be in a range of 7 to 40 kg grain ha^{-1} kg N^{-1}, depending upon the intensity of crop management. The optimum dose of N varies from 25-85 kg ha^{-1}, while the dose of phosphorus (P) is about 11 kg ha^{-1}. Deep placement of fertilizer has an advantage in receding moisture situations during rabi (Rego et al. 1982).

Fertility management for rabi sorghum, especially when kharif fallow is substituted by sequential cropping, is poorly understood. The use of a short season legume during the preceding kharif can adversely affect the performance of the following rabi sorghum. Nitrogen application to rabi sorghum may even decrease yield under some circumstances. For example, if it is applied late (just before or at sowing) and if the soil water content at lower layers are inadequate, the crop will develop large leaf area (T J Rego and M Natarajan, ICRISAT—personal communication). Most often the problem is the lack of equipment for placing N deep enough in the soil profile by the farmer. Both early fertilization and deep tillage are not possible if sequential cropping system in followed. Otherwise added N has only little effect on total water use and root growth; however, WUE increases with N application (ICRISAT 1987, 1988).

Little work has been done on P and K fertilizer requirement. Both P and K nutrition of rabi sorghum under intensive cropping appears to play an important role in drought resistance. P promotes root growth at depth (Venkateswaralu & Venkatasubbaiah 1984). Potassium (K) promotes better grain growth and leaf-water relations (Beaton & Sekhon 1985). The differential performance of sorghum genotypes under both terminal water, and nutrient stresses were noted (Kharkar & Deshmukh 1976).

Plant density and row spacing: Wider row spacing and low plant density are expected to promote higher grain yield. A plant density of 90,000-135,000 plants ha^{-1}, (lower in shallower soils) and row spacing 75 or 90cm are recommended (CRIDA 1989; Rao & Ramanath 1989). However the farmer employ narrower 30 cm) rows and high densities to maximize fodder yields and to harvest thin stalks. This practice also predispose the crop to terminal water stress and severe root and stalk-rots (ICRISAT, 1983). The recommendations of lower seeding rate and stripping of every fourth row during years of scare rainfall (Kulkarni & Gaikwad 1989) are not followed by farmers.

Hill planting may increase grain yields under terminal drought stress. But this is not practical as farmers drill seeds. Hill planting under rabi conditions may also promote greater evaporation from soil surface during seedling stage.

Plant protection: Farmers rarely use any plant protection measures although carbofuran is recommended for the control of shootfly.

Crop Physiology of Rabi Sorghum

The biggest challenge to physiologists and breeders working on rabi sorghum improvement is to increase both biomass (stover) and grain in an increasingly hostile environment during crop development. Some of the physiolgical aspects, i.e., leaf-area development, dry-matter distribution, and roots will be discussed below.

Leaf-area Development

Nitrogen and water stresses individually or jointly reduce number, appearance rates, and longevity of leaves (Seetharama et al. 1982). Temperature also plays a major role in leaf-area development (Figure 3). At 25°C, in cultivar CSH 8R the leaf extension rate is 3.65 mm h^{-1}; this is reduced to 2.61 mm h^{-1} under water stress, and to 1.86 mm h^{-1} under N stress. N and water stress together reduce the rate to only 1.84 mm ha^{-1} (Seetharama et al. 1988). Obviously N stress effects were more severe than water stress.

Both N and water stressed reduced leaf-area index (LAI) and leaf-area duration (LAD). The reduced grain and dry matter yields were related primarily to the reduced LAD (Figure 4). Besides effects on leaf-area, the N and water stresses also reduced the efficiency of utilization of intercepted radiation. The crop supplied with adequate N and water produced 1.96 g dry matter MJ^{-1} (of photosynthetically active radiation), whereas the dryland crop without added N produced only 1.14 g MJ^{-1} (Seetharama et al. 1990b). Screening for useful genetic variation in traits of better adaptation to lower soil N and water supply, and of less sensitivity to temperature could be useful. Rabi cultivars CSH 8R and M 35-1 showed higher leaf extension rates in the temperature range typical of this season than did kharif cultivars like CSH 1 and CS 3541 (Figure 5).

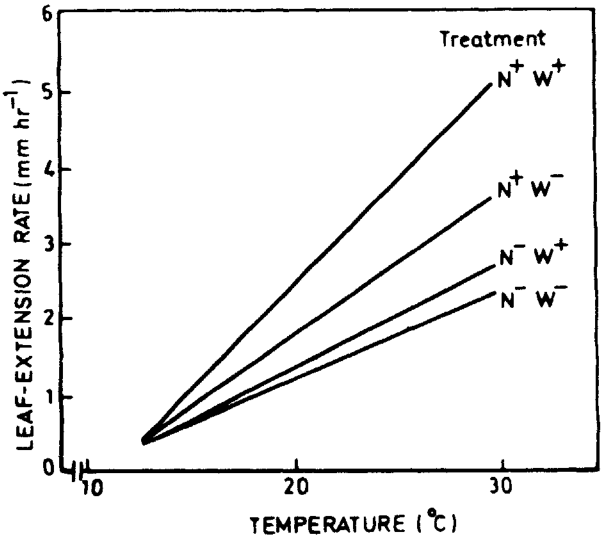

Figure 3 Relationships between air temperature and leaf-extension rates (LER). All linear regressions are highly significant (P < 0.01). ICRISAT Center, rabi 1981 (Based on Seetharama et al. 1982b)

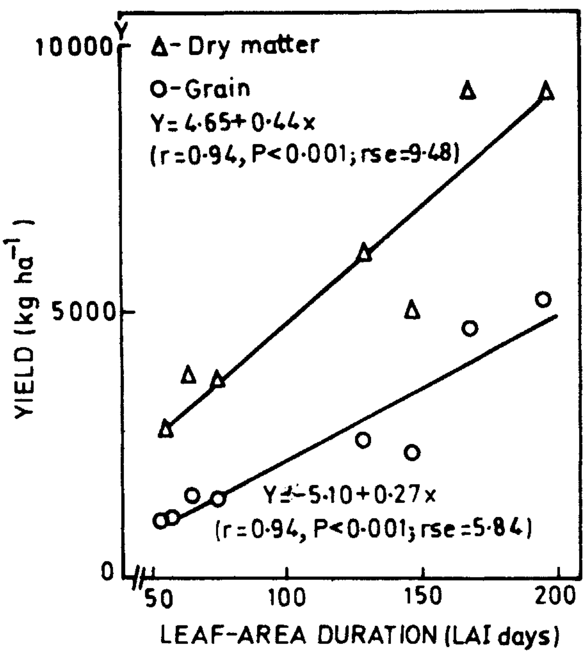

Figure 4 Relationships between leaf-area duration (LAI days) and grain, and total dry matter yields. ICRISAT Center, rabi 1981

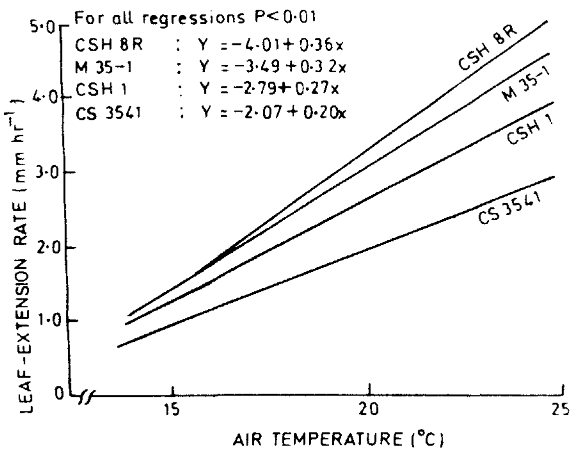

Figure 5 Effect of air temperature on leaf-extension rates of four sorghums genotypes. All regressions are significant at P<0.01 (Unpublished data of N Seetharama)

High grain yield with least incidence of root and stalk rot are observed when the pattern of leaf-area development during the season most closely matches the climatic regime and rate of water use. The LAI range in rabi crops is narrow (2-4) compared to the same during kharif (4-9). The correlation coefficient between LAI at flowering with both grain and biomass yield was significant during kharif ($P < 0.01$) but not during rabi (Parvatikar & Hiremath 1986). However, leaf longevity (persistence) during GS3 was correlated with yield, as evidenced by the strong correlation between LAI at physiological maturity and yield (Kulkarni et al. 1983). Hence breeders normally select for 'stay-green' types in their programs.

Dry-matter Production, Distribution, and Growth Efficiency

Irrespective of the initial soil water at sowing, vegetative (mainly culm) dry matter increases for about 14 days after flowering. Later it decreases to a much lower level than at flowering (Figure 6). This observation suggests that at least a part of this material is remobilized to the developing grain, because the grain weight is more than the total dry matter produced during GS3 (Seetharama et al. 1978). The simple estimates of remobilization of dry matter based on changes in dry weight between flowering and maturity suggests that remobilization is greater under water stress (Table 1). However, studies with C^{14}-labeled photosynthates are required to estimate the exact quantity and the pattern of remobilization from vegetative parts. Genotypic differences for this trait have been reported earlier (Seetharama et al. 1982a, 1988).

Rabi cultivars show greater osmotic adjustment than kharif types (Seetharama 1990). However use of this trait in crop improvement should await quantification of the role of osmotic adjustment in crop productivity. The net carbon gain and loss by respiration in relation to temperature changes during rabi deserves more attention as sorghum genotypes differ in both shoot (Gerik & Eastin 1985) and root respiration (Rice & Eastin 1986). Carbon balance study is especially pertinent to increase root-growth efficiency, and resistance to root and stalk rots (Eastin et al. 1984).

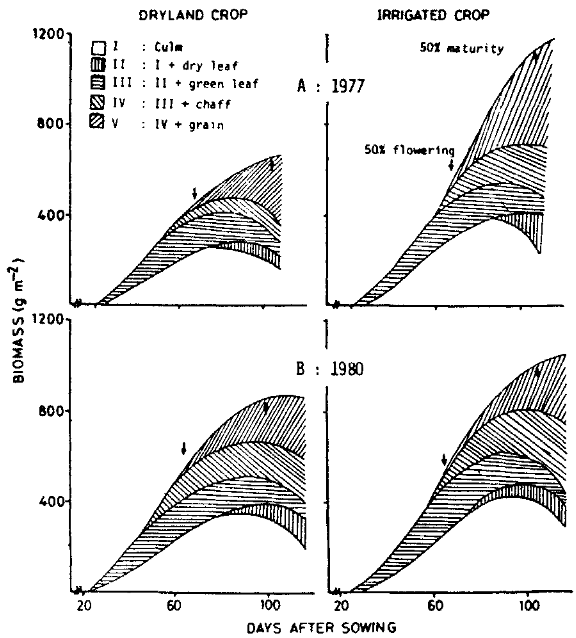

Figure 6 Seasonal changes in dry matter in various plant parts of rabi sorghum grown under dryland and irrigated conditions. The soil water profile was fully charged in 1980, but only 77% charged at sowing in 1977. CSH 8R, Vertisol, ICRISAT Center (Unpublished data of Sardar Singh and N. Seetharama)

Pattern of Water Extraction by Roots and the Root System

Since crop water use holds the key for rabi productivity, it needs detailed examination. The seasonal pattern of water use by a crop is described elsewhere (Russell 1980, Seetharama et al. 1984). The relationships between extraction rates and the available-water fraction (AWF) for four soil layers are shown in Figure 7. The roots were able to extract water fully from the top layers, but no definite relationships between AWF and extraction rates could be seen (Figure 7A&B). One month after sowing, the water potential was below -1.5 MPa in the top 22 cm soil layer in the dryland treatment. At lower depths, rate of extraction increased almost linearly with AWF between AWF values of 0.3 to 0.7 (Figure 7C&D). The roots were not able to extract water below 0.3 AWF in the lower layers, possibly due to low root density (< 0.1 cm cm^{-3}), and a very low soil hydraulic conductivity (1.5×10^{-1} to 1.5×10^{-5} m s^{-1}) because of very high clay content ($> 70\%$) in these layers. When the soil was fully charged, most of the moisture depletion occurred in the top 50 cm layer; depletion below 50 cm was lower, reflecting the root distribution profile.

As the water availability to a rabi crop is finite, saving enough water for use during grain filling is critical (Passioura 1983). About 17 kg ha^{-1} of extra grain is obtained with every additional mm of water available during GS3 (Seetharama et al. 1984). However, unlike wheat, the sorghum plant with its single seminal root (lasting only for a few weeks) and large leaf area per culm needs sufficient water for vegetative growth. Hence the quantity of water that can be saved for later use is limited. Moreover, even the stover is economically important, and hence undue restriction on water use during vegetative phase is undesirable. At ICRISAT Center, grain yields over 4 t ha^{-1}, and biomass over 11 t ha^{-1} were obtained even under dryland conditions with extraction of about 60-70% of stored water before flowering. In deep soils, it is desirable for the plants to extract water fully from the upper layers early in the season and from deeper layers later, to ensure maximum productivity.

A crop growing on the receding soil water should have a deep root system. Seetharama et al. (1984) observed that a dryland rabi sorghum crop had one-third of its root length in the soil layers below 1m depth at 70 days after sowing. The irrigated crop had only one-sixth of the total root system in this layer. During GS3 the root senescence sets in earlier in the dryland crop (as soil dries quicker) than in the irrigated crop; the differences in root density may be insignificant, or a reverse situation (higher density in irrigated crop even at lower depths) may arise (ICRISAT 1988). Venkateswarlu and Venkatasubbaiah (1984) have demonstrated the effect of sub-soil fertilization on increase in deep rooting and greater moisture extraction from deeper layer. Investigations on genotype and crop management stimulation of

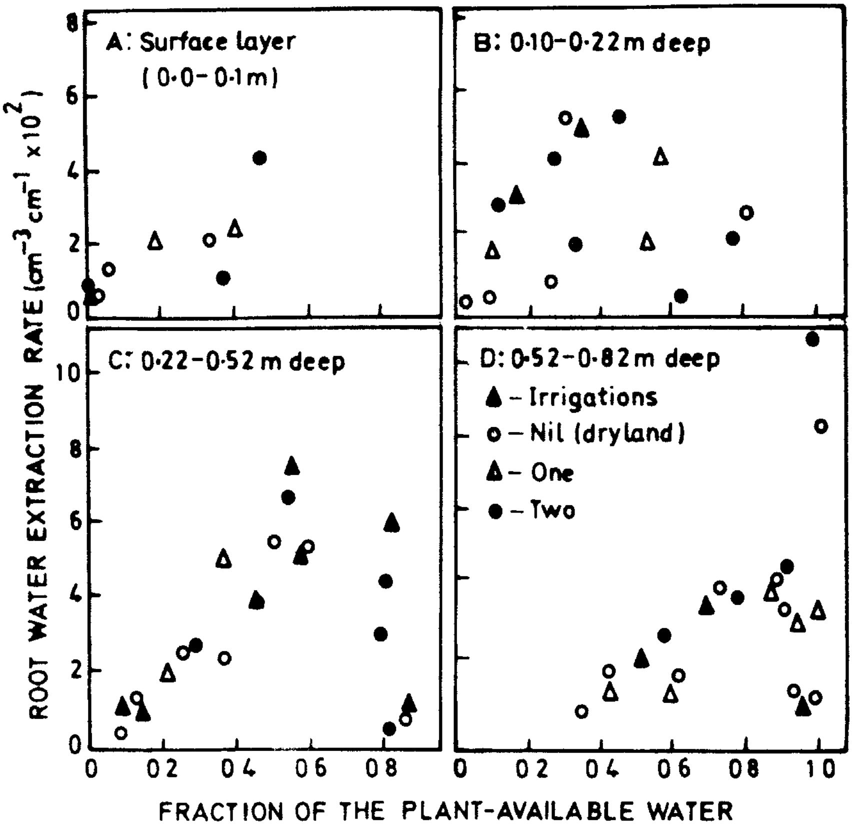

Figure 7 Effect of the fraction of plant-available water on water-extraction rates in four soil layers of a Vertisol by roots of twice irrigated and dryland sorghum crops. (Lines are fitted by hand). CSH 8R, Vertisol, ICRISAT Center (Unpublished data of Sardar Singh

root development to produce adequate root-length density in space and time during rabi sorghum growth are too few and inadequate because of the difficulty in studying roots.

Jordan and Miller (1979) have shown that the rabi cultivar M 35-1 has fewer long root axes (in solution cultures) than the common hybrids grown in the USA. Seetharama et al. (1990) have reported significant genotypic differences in root-density at lower depths under rabi dryland conditions. Root morphology and longevity also need further attention. The amount of dry matter invested in prop roots in a rabi crop, especially after light showers during later stages of growth, is substantial (N Seetharama, unpublished field observations) and deserves further study.

Future Research Needs

Characterization of Rabi Sorghum Environments

Future research on rabi sorghums should aim at increasing grain and biomass productivity during good years, with grain yield stability during marginal years. Although the effects of individual environmental factors on crop growth are reasonably well understood, effects of combination of these factors (e.g., N × Water), and their interaction with the genotypes need to be investigated under representative field conditions. In future greater emphasis should be placed on characterization of rabi sorghum growing environments to match crop growth pattern with the available resources in space and time throughout the growing season.

Yield limiting factors should be quantified in each region. The kind of analysis of sorghum productivity published for Karnataka by Krishnan (1980) may be extended to the whole of rabi sorghum areas. The relative probability of each specific limiting factor (e.g., ranges of soil water at planting, temperature, and evaporative demand) at representative sites should also be studied in relation to both soil-depth variability and cultural practices, such as the date of sowing.

Diagnostic Research, and Crop/Cropping System Management

Studies on relative contribution of specific production parameters for rabi sorghum under dryland conditions as conducted at Sholapur (Umrani & Patil 1985) should be carried out in each representative agroecological zone. The recommendations to the farmer should be made only after the examination of the local conditions, as yield could vary considerably even within a farm due to soil variations.

More research is needed to identify cultivars and agronomic practices when supplemental irrigations are possible, and the growing season can be longer than 110-120 days. Studies comparing the suitability of components for newer cropping systems (such as early pigeonpea before sowing rabi sorghum) are to needed. Both beneficial and deleterious effects of short duration kharif crops (e.g., the effect of sunflower crop preceding rabi sorghum; Radder 1989) need to be quantified.

Also, future work on rabi sorghums should concentrate on production on shallow soils. More attention should be paid to development and spread of equipments to place the fertilizer deep in the soil.

The sorghum grown in southern Andhra Pradesh (e.g., around Nandyal and Madhira) are commonly sown before the end of South-west monsoon [in August; called 'Maghi' (late kharif) sorghum]. Similarly sorghum grown in Tamil Nadu during North-east monsoon, especially in the Kovilpatti region is also subjected to terminal-water stress at later stages only (Rajamannar 1989). In both these cases some rains are received at seedling stage, and hence the crops some rains are received at seedling stage, and hence the crops suffer terminal drought only during grain filling stage. The night temperatures during growth are higher than that experienced by rabi sorghums. The research done elsewhere in the rabi regions should be extended to these areas with due caution.

Phenotypic Plasticity in Phenology and Crop Growth

Early sowing recommended by the All India Coordinated Sorghum Improvement Program (AICSIP) is helpful. But the currently available cultivars are not plastic enough to take full advantage of the extended season resulting from early sowing (Figure 8A). Temperature, rather than photoperiod appear to be the major factor controlling phenological development in the currently used cultivars. The early-sown crop

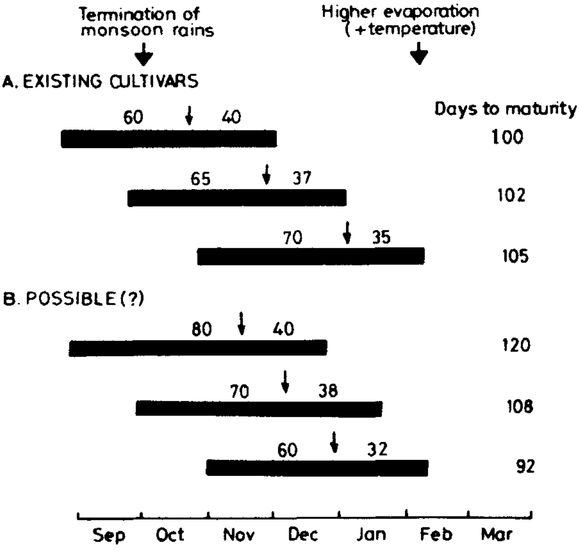

Figure 8 Schematic representation of the time of flowering and maturity of an existing (A), and a hypothetical sorghum genotyped (B) on three different times of sowing during rabi season. The unlabeled arrow indicates time of flowering. The beginning and the end of the bars represent the time of sowing and physiological maturity, respectively

matures too early in the season, and the late-sown crop matures too late during the harsher environmental conditions at the beginning of summer.

We suggest the development of genotypes with high sensitivity to photoperiod and relatively low sensitivity to temperature. This will extend the life cycle of a cultivar sown early, but it will telescope its phenophases under the conditions of later sowing, thereby escaping severe terminal drought caused by delayed sowing (Figure 8B). The plasticity conferred by the above mechanism(s) can help the farmer to grow late and tall phenotype (responding to inputs and natural resources) during those years when early sowing is possible. Same genotypes when sown late will at least produce satisfactory grain yield, although stover yields may be reduced. Flowering is hastened when sown late because of photoperiod sensitivity, which results in a better opportunity for grain production. This approach will avoid the need for deploying separate genotypes which farmers cannot afford for early and late sowing conditions. Such a flowering response was observed in some genotypes in a serial sowing experiment at Puerto Rico (F.R. Miller, Texas A&M University, College Station, TX, USA, personal communication). IS 3758 and other landraces from Ethiopia (e.g., IS 3541; R.V. Vidyabushanam, AICSIP, Hyderabad, India, personal communication) are also likely to show the above kind of response. Preliminary observations on lines at ICRISAT Center (during different dates of sowing) under normal and extended photoperiod have revealed that some of the lines from Ethiopia (E 36-1, IS 12611), Sudan (IS 6928), and Nigeria (POD 35, 166, and 87) show such desirable flowering behaviour (N. Seetharama, unpublished data). Further research is needed to demonstrate conclusively the relevance of such flowering behaviour for rabi adaptation.

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