8

Genetic Options for Drought Management in Groundnut

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INTRODUCTION

Groundnut is one of the principal oilseeds in the world. It is cultivated on 24.8 million ha with a total production of 32.8 million t and an average productivity of 1.32 t ha^{-1}. Developing countries account for 96.9% of the world groundnut area and 93.8% of total production. Production is concentrated in Asia (56.8% area and 66.5% production of the world) and Africa (38.0% area and 24.7% production). The groundnut productivity in Africa is only 0.86 t ha^{-1} compared with 1.55 t ha^{-1} of Asia. The world groundnut economy—facts, trends and outlook are described in detail by Freeman et al., 1999. Briefly, in medium-term (i.e. up to 2010), 'groundnut production and consumption is likely to shift increasingly to developing countries; production will grow in all regions but most rapidly in Asia, slowly in sub-Saharan Africa and decline in Latin America; and utilization will continue to shift away from groundnut oil toward groundnut meal, specially confectionery products'.

GROUNDNUT IN AFRICA

Groundnut is one of the important legume crops in most of the production systems in Africa. The agro-climatic and production system environments of the region are very diverse and the constraints that limit groundnut production are many. In spite of large research effort in the past in groundnut in Africa, the yields remain low. The low yields are mainly attributed to unreliable rainfall patterns with frequent droughts, lack of high-yielding adapted cultivars, damage by diseases and pests, poor agronomic practices and limited use of inputs. Although nature provides some narrow window of sowing opportunities, logistic problems like shortage of labour and draft power cause delays in sowing and weeding, thus, entailing further reduction in yields.

Although groundnut is grown as a sole crop in commercial cultivation, the widespread traditional practice throughout the region involves intercropping/mixed cropping with cereal crops, particularly sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) under subsistence farming conditions. The production of groundnut as a sole crop was first dictated by the colonial emphasis as a cash crop. Therefore, sole cropping research results were not applicable and remain non-adopted by the farmers for traditional mixed cropping systems. It is only recently that research on mixed/intercropping systems has been initiated.

GROUNDNUT IN SOUTH AND SOUTHEAST ASIA

Groundnut, the major oilseed legume in Asia, is grown under varying agro-ecologies: rainfed, irrigated, and residual moisture, as a sole crop or intercropped with low inputs to well managed production conditions. Generally, under irrigated conditions, the crop is managed well and high yields are obtained. Under rainfed conditions, the crop receives little input and suffers from similar constraints that operate in Africa. Consequently, realized yields are low and quality of the produce is inferior. In the event of end-of-season drought, which is common under rainfed and residual moisture conditions, the produce becomes vulnerable to aflatoxin contamination. In Southeast Asia, groundnut is sown as a sole crop in rice-based cropping system either before or after rice. In many areas in South Asia, groundnut is intercropped with sorghum and pigeonpea (*Cajanus cajan*) under rainfed conditions.

YIELD LOSSES DUE TO DROUGHT

Drought is a major abiotic stress factor affecting yield and quality of rainfed groundnut worldwide. Yield losses due to drought are highly variable in nature depending on timing, intensity, and duration coupled with other location specific environmental stress factors such as high irradiance and temperature. An annual estimated loss in groundnut production equivalent to US $ 520 million (at the market prices of 1994) is caused by drought. Almost half of it (US $ 208 million) can be recovered through genetic enhancement for drought resistance with a benefit: cost ratio of 5.2 (Johansen and Nigam, 1994). Further, in the presence of drought, the beneficial effects of improved crop management practices in terms of increased production are not fully realized. Calcium uptake by pods and N_2 fixation processes are adversely affected by drought. The photosynthesis is reduced due to limited gas exchange. As the crop under end-of-season drought conditions has high probability of aflatoxin contamination, it becomes unfit for human consumption. Aflatoxin is a key problem for African and Asian countries wishing to enter the trade of edible groundnut on a large scale. Since the aflatoxin problem is accentuated under drought conditions, genetic enhancement for drought resistance should also include aflatoxin resistance.

SCOPE FOR GENETIC ENHANCEMENT IN DROUGHT RESISTANCE

At ICRISAT, three genetic enhancement approaches were developed and implemented simultaneously to enhance the adaptation of groundnut to drought-prone environments. These were:

(1) Development of short-duration genotypes that can escape the end-of-season drought

(2) Development of genotypes with superior yield performance in drought- prone regions following conventional breeding approaches

(3) Development of drought-resistant genotypes following physiological breeding approach

The last approach involved two steps:

- (i) An understanding of physiological mechanisms of drought resistance and development of selection tools to identify genotypes with high levels of desirable traits associated with it
- (ii) Initiation of a targeted breeding program to enhance the levels of drought resistance traits using novel selection methodologies

A large *Arachis* germplasm collection available with ICRISAT gene bank provides the base material to follow the above three approaches of genetic enhancement in drought resistance.

DEVELOPMENT OF SHORT-DURATION GENOTYPES

Where the growing season is short and terminal drought predominates, matching of phenological development of a cultivar with the period of soil moisture availability is an important drought-escape strategy to minimize the impact of drought stress on crop production. In most of the semi-arid tropic (SAT) groundnut growing regions, the rainfall distribution is erratic and the season length is less than 100 days (Virmani and Piara Singh 1986). ICRISAT has made considerable progress in shortening crop duration of groundnut without unduly penalizing realized yield (Vasudeva Rao et al., 1992). The short-duration varieties developed at ICRISAT have shown 23% to 411% superior pod yield over local control varieties in the VIIth series of international trials across several countries (ICRISAT, unpublished data).

There is scope for more judicious matching of genotype duration with most probable soil moisture pattern using soil moisture balance models in association with crop-weather modelling and GIS technology. A multi-location field testing programme will be time consuming and costly. A better preselection of test genotypes, based on their adaptability to the weather and soil data of target locations, should improve overall efficiency of the process. In a more predictable environment, a better optimization of crop duration can be achieved. However, various growth penalties are associated with reducing crop duration to better fit likely soil moisture patterns. Primarily, a hurried approach ultimately reduces the yield potential of the crop by reducing the length of the growing season. To some extent, either increasing the plant density, or identifying genotypes that can flower early and have a synchronous pod set, can overcome this. It is sometimes observed that early-maturing genotypes have shallow root systems (Fereres et al. 1986; Arihara et al. 1991). This renders such genotypes more susceptible to intermittent dry spells if grown as a rainy-season crop and to a reduction in yield potential due to reduced water use under moisture stress free conditions (Fereres et al. 1986). However, genotypic differences in rooting depth have been observed in groundnut (Wright et al. 1991; Nageswara Rao et al. 1993), suggesting scope for combining early maturity with efficient root system.

CONVENTIONAL BREEDING APPROACH

Following the empirical approach of selecting for high pod yield and other desirable agronomic characteristics under simulated mid- and end-of-season drought conditions in segregating populations and evaluating advanced breeding lines under such conditions led to identification of several genotypes which could perform well under limited moisture conditions. These genotypes, mostly of medium-duration, showed 12% to 144% pod yield superiority when tested in the IVth series of international trials across several countries (ICRISAT, unpublished data).

However, the empirical approach is time consuming, less efficient, requires more resources, and does not provide information on the mechanisms of better performance of genotypes under drought conditions.

PHYSIOLOGICAL BREEDING APPROACH

As permutations of drought patterns are infinite, it is necessary to have information on the effects of various combinations of timing, intensity and duration of drought on a range of genotypes to assess the scope for genetic enhancement. The effects of varied intensities of single and multiple drought patterns on yield of a range of groundnut genotypes have been described in detail by Nageswara Rao et al. 1989. A poor relationship between the yield potential (achieved under adequate water availability) and the sensitivity of genotypes to mid-season drought suggested a possibility of identifying and/or developing genotypes with high yield potential and relatively low sensitivity to mid-season droughts (Figure 1).

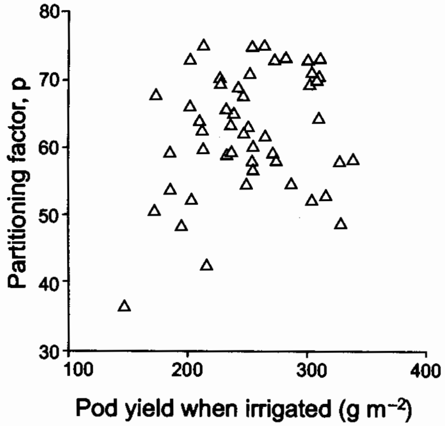

Figure 1. Relationship between yield loss due to mid-season drought and pod-yield potential under irrigated conditions in sixty groundnut genotypes. (Source: Nageswara Rao et al. 1989)

However, when droughts occurred during the seed filling period, genotypic yield accounted for 90% of the variation in pod yield sensitivity to water deficits, suggesting that it may be unlikely to combine the high yield potential and low sensitivity to severe drought spanning seed-filling phase (Figure 2). These results suggested that drought escape mechanism by early-maturing genotypes is the safe option in the short-season environments. However, it is still necessary to screen genotypes in a given maturity group for resistance to end-of-season drought because of two reasons. Firstly, to identify genotypes with reasonable pod yields and better vegetative growth (in view of groundnut haulms being the valuable live-stock feed in most of the SAT environments) under severe end-of-season droughts. There exists a significant variation in the ability of genotypes to tolerate end-of-season drought and produce vegetative dry matter (data not shown). Secondly, end-of-season drought is closely linked with aflatoxin contamination of the produce and that the screening for end-of-season drought also provides scope for

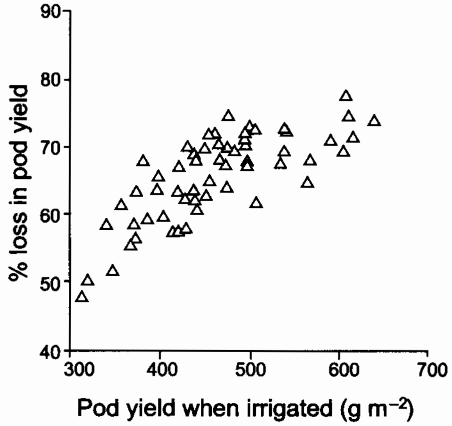

Figure 2. Relationship between yield loss due to end-of-season drought and pod-yield potential under irrigated conditions in sixty-four groundnut genotypes. (Source: Nageswara Rao et al. 1989)

identification of genotypes with resistance to *Aspergillus flavus* infection and aflatoxin production (Mehan et al. 1988, 1991).

In view of these results, a large scale screening of germplasm for drought resistance focussed on assessing the genotypic response to mid- and end-of-season droughts.

(a) Screening for drought resistance

Drought is a complex syndrome with three major and widely varying components, i.e. timing of occurrence during the season, duration and intensity. Occurrence of high radiation and temperatures and soil characteristics of the locations significantly influence the effects of drought and add to the complexity of defining the problem. The extreme variability in the nature of drought has made it difficult to define plant attributes required for improved performance under drought, consequently, limiting the plant breeding efforts to enhance drought tolerance in groundnut. The approach and methodology followed at ICRISAT for enhancing drought resistance in groundnut are described in detail by Nageswara Rao (1994). Briefly, ICRISAT adopted a holistic approach in screening and selecting groundnut genotypes with superior performance to two most critical droughts i.e. mid-season and end-of-season drought conditions. Because, both vegetative and pod yields are traits of economic importance in semi-arid tropics, selection of genotypes for drought resistant has been based on total dry matter and pod-yield production under a range of drought environments. In order to avoid confounding the effects of drought incidence with phenology of the crop, the varietal comparisons for drought sensitivity are made within a given taxonomic

(Spanish, Virginia bunch and Virginia runner) group. Genotypes resistant to drought have been identified by assessing their total and pod dry matter productivity under a range of drought intensities imposed at critical phases, using a line source sprinkler technique. The line-source system offers certain advantages, in that it allows large numbers of genotypes to be evaluated at varying intensities of drought in a given environment. The sprinkler irrigation technique simulates rainfall of varying intensities which subsequently wet the soil to different depths, a factor that is particularly important for groundnut with its subterranean podding habit. However, the technique has some limitations. For instance, screening has to be conducted in dry seasons where interference from rainfall is minimized. Also, strong wind during irrigation can influence the systematic nature of water deficits created, requiring complex statistical techniques for data analysis (Singh et al., 1991). The genotypes identified as being superior yielding with this technique, however, have to be re-evaluated under rainfed conditions in drought-prone environments.

The ability of a genotype to recover from mid-season drought when water again becomes available plays a dominant role in genotype adaptation to a drought pattern where deficits are relieved by intermittent rains (Harris et al., 1988; Nageswara Rao et al.,1988). In this type of drought, as mentioned earlier, selection in well-watered environments is unlikely to identify genotypes with greater recovery responses. Although early water stress reduces the initial shoot growth and development, synchronous renewal of vegetative and reproductive development is often observed when the drought is relieved (Stirling et al., 1989). An increase in ^{14}C translocation into stem apices and pegs has been observed when a crop was re-watered following a drought during the early reproductive phase. Significant variation among groundnut genotypes in ability to recover from mid-season drought has been observed (Figure 3) (Harris et al. 1988). The physiological factors responsible for genotypic variation in recovery patterns are unclear at this stage.

The extensive screening done at ICRISAT has resulted in identification of genotypes with stability, and higher mean yield (compared to the experimental mean) under a range of drought environments. The selections from drought screening are evaluated for their performance in drought-prone locations and are also used as parents in conventional breeding programme. The flow of germplasm through the screening and breeding cycle is shown in Figure 4.

(b) Understanding resistance mechanisms and developing selection tools

Current breeding methods utilize the empirical approach based on selection for high yield under a given drought environment. While such an approach has been partly successful, it requires huge investments in land, labour and capital to screen large numbers of progenies. In a general crop improvement

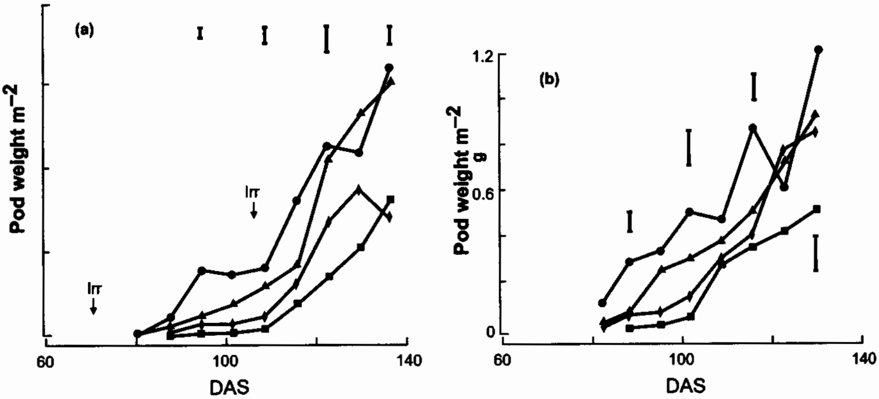

Figure 3. Time course of (a) pod weight; and (b) partitioning factor, p. Symbols represent ●, TMV 2; □, Kadiri 3; ⅃, NC Ac 17090; and Υ, EC 76446 (292). 'Irr' indicates time of irrigation. Vertical bars are standard errors of the mean. (Source: Harris et al., 1988)

point of view, there is evidence of increasingly marginal returns from conventional breeding (Fehr 1984), suggesting that there is a need to seek more efficient methods for genetic enhancement of drought tolerance. Bidinger et al., 1982 and Garrity et al., 1982 argued that genetic improvement in yields of crops can be brought about if attributes that confer yield advantage under drought conditions can be identified and used as selection tools in breeding programmes to enable identification of drought tolerant genotypes.

In recent years, there has been significant improvement in physiological understanding of genotypic response to drought in groundnut, suggesting scope for selecting genotypes with traits contributing to superior performance under water limited conditions. For instance, substantial genetic variation has been observed in partitioning of dry matter to pods (Mathews et al. 1988; Nageswara Rao et al. 1993). Conventional methods of determining partitioning ability of genotypes are laborious and cumbersome, and are unsuitable when large number of entries need to be valued for this trait. However, simple, non-destructive methods can be effectively used as preliminary screening tools to identify genotypes with efficient partitioning attributes (Williams and Saxena 1991).

A significant genotypic variation in root system with the capacity to penetrate deeper soil layers has been reported (Ketring 1984; Wright et al. 1991; Wright and Nageswara Rao 1994). This trait allows increased mining of water present in deeper layers. However, it does not imply that all genotypes with this trait are efficient water utilizers.

Significant genotypic variation in total amount of water transpired, *T*, and transpiration efficiency, *TE* (defined as amount of dry matter produced per unit amount of water transpired), has been shown under field

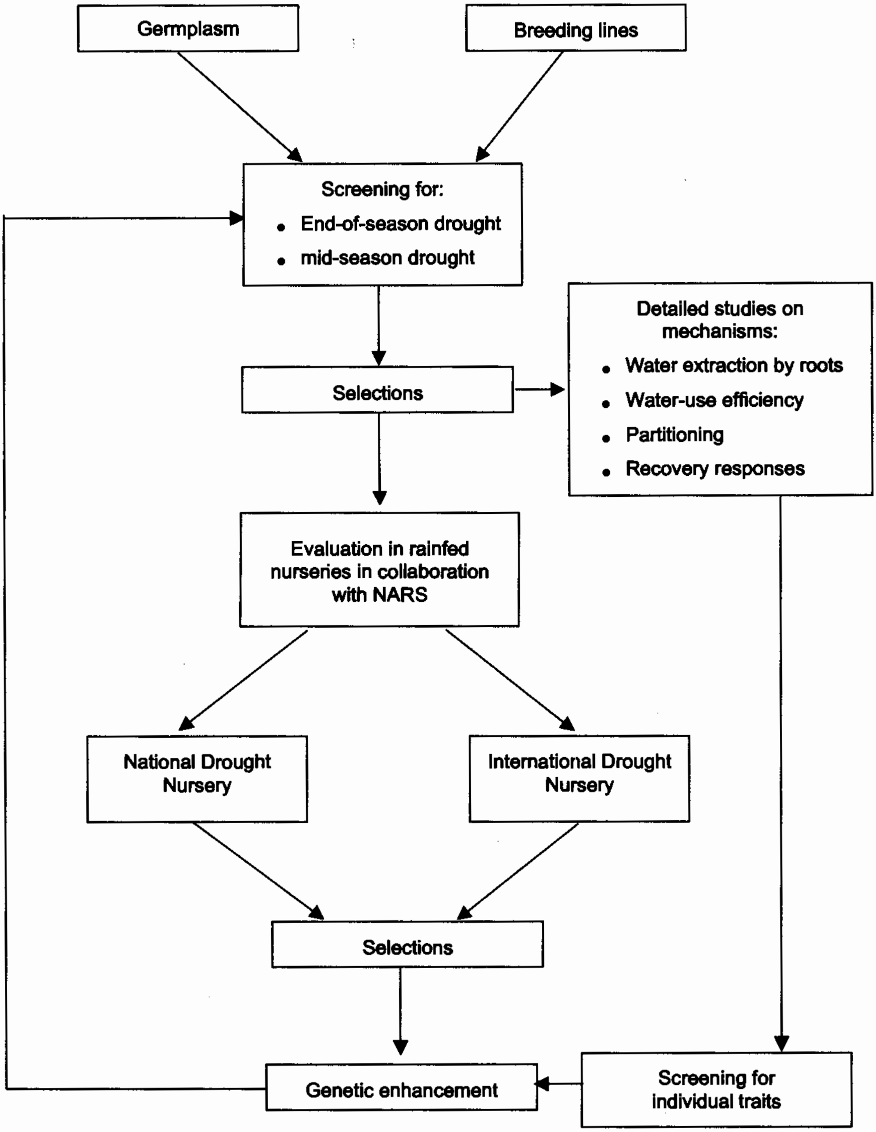

Figure 4. Flow of groundnut genotypes in drought screening programme at ICRISAT.

conditions (Mathews et al. 1988). Further studies have confirmed large cultivar differences in *TE* in groundnuts grown in glasshouses and field conditions (Hubick et al. 1986, 1988; Wright et al. 1988, 1994a). These studies have made it possible to analyse the yield variation under drought conditions using a physiological frame work proposed by Passioura (1977), where

$$\text{pod yield} = T \times TE \times \text{Harvest Index (HI)}$$

Although a large variation has been found for each of these physiological traits in groundnut, there are substantial difficulties in accurately measuring them in large number of plants/populations needed for selection programmes. However, there has been a significant progress in understanding these mechanisms and developing novel and indirect selection tools for the model parameters (Wright and Nageswara Rao 1994b, Wright et al. 1996). For example, research has shown that TE and carbon isotope discrimination in leaf (Δ) are indeed well correlated in groundnut (Hubick et al., 1986, 1988; Wright et al. 1988, 1993, 1994b), suggesting a possibility of using Δ as a rapid, non-destructive tool for selection of *TE* in groundnut (Figure 5A). However, further research has shown that specific leaf area (SLA, cm^2/g) is well correlated with Δ and *TE* in groundnut (Figure 5B) (Wright et al. 1994).

The stability of relationship between Δ and SLA over a wide range of cultivars and environments (Nageswara Rao and Wright 1994b) has raised the possibility of using SLA as an even more rapid and inexpensive technique for selection of *TE* (Figure 6).

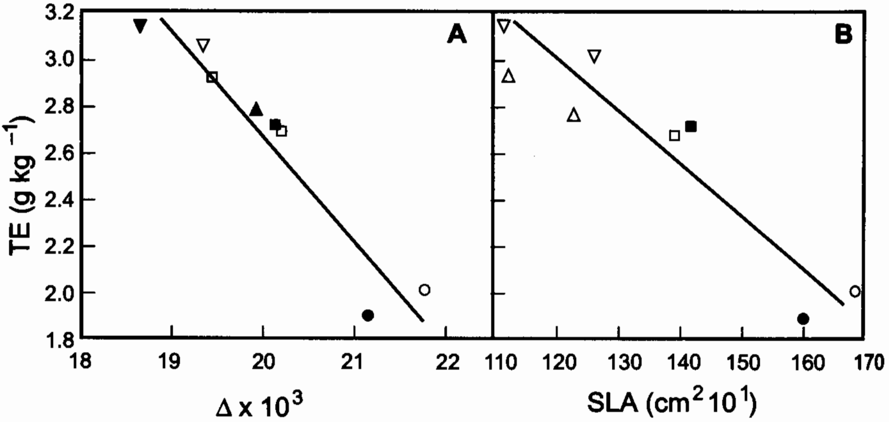

Figure 5. Relationship between TE and ρ (A) and *TE* and SLA (B) in leaves of Chico (O), McCubbin (□), Shulamit (ρ) and Tifton-8 (σ) under intermittent (closed symbols) and continuous (open symbols) drought treatments. $TE = 11.31 - 0.43\ \rho$, ($r^2 = 0.89$, $P < 0.01$); $TE = 5.4 - 0.2$ SLA, ($r^2 = 0.84$, $P < 0.01$). (Source: Wright et al. 1994)

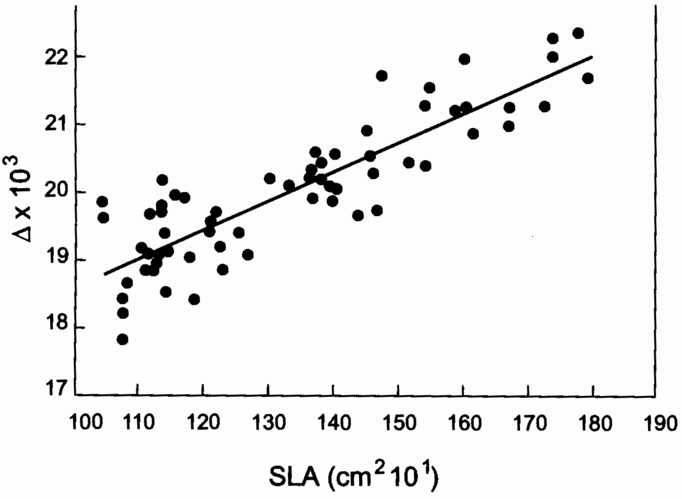

Figure 6. Relationship between the mean SLA and ρ in leaves of four groundnut cultivars under the two drought treatments. $\rho = 14.2 + 0.04$ SLA, ($r^2 = 0.81$, $P < 0.01$). (Source: Wright et al., 1994)

These studies implied that SLA, which is a crude but easily measurable parameter, can be used as a rapid and inexpensive selection criterion for high *TE*. The ability to measure *TE* (using indirect tools such as Δ and SLA) made it possible to detect an apparent negative association between *TE* and *HI*. Although the selection for high *TE* resulted in high total dry matter production, there was a consistent trend for negative relationship between *TE* and *HI* in a number of glass house and field studies (Hubick et al. 1988, Wright et al. 1993). A preliminary crossing programme showed that the negative association of moderate strength ($r = -0.55$) was consistent through F_4 suggesting that concurrent improvement for the two traits may be difficult but should be possible. However, a more comprehensive survey of groundnut germplasm for *T*, *TE* and *HI* traits resulted in identification of genotypes with high levels of both *TE* and *HI*, suggesting that the negative linkage between *TE* and *HI* could have been broken (Nageswara Rao and Wright, unpublished data).

Screening of groundnut germplasm for SLA indicated significant variability within and between taxonomic groups (Figure 7a). It was interesting to note that the genotypes belonging to variety *hypogaea* (Virginia bunch and runner types), had a lower mean SLA than those of variety *fastigiata* (valencia and spanish types) suggesting a likelihood of higher *TE* (Nageswara Rao et al. 1994). However, the former had lower partitioning ability than the latter (Figure 7b).

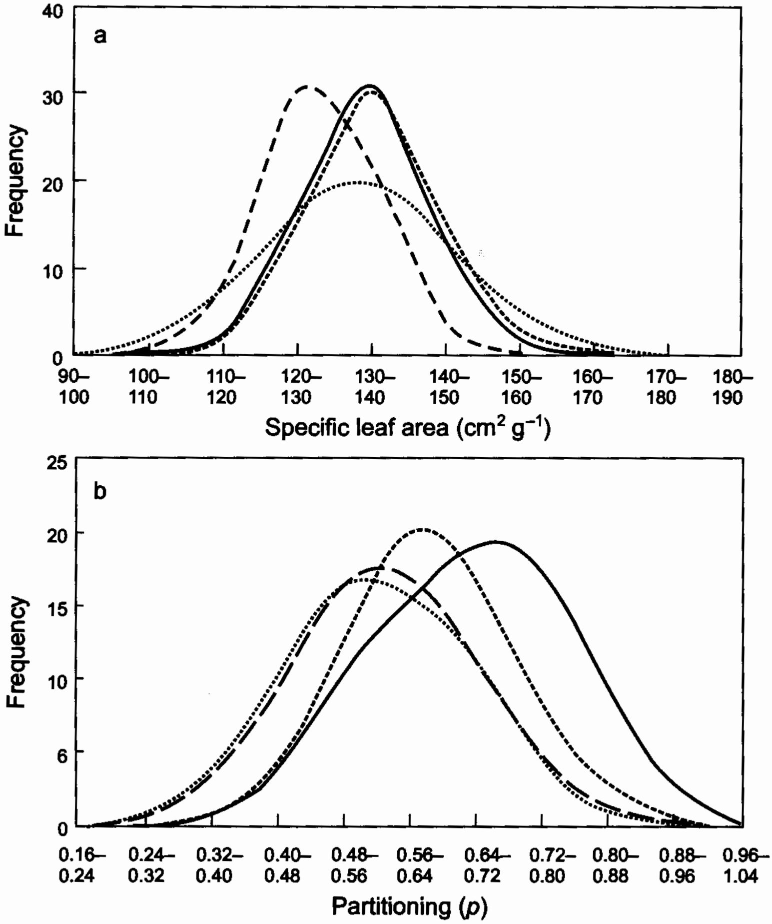

Figure 7. Specific leaf area (SLA) (a) and partitioning, *P* (b) in 64 groundnut germplasm accessions of different botanical types. Postrainy season 1992, ICRISAT Center (Spanish—, valencia______, Virginia bunch...., Virginia runner— —). (Source: Nageswara Rao et al., 1994).

Recent progress in developing new and novel indirect methodologies to assess the model parameters with minimum and cost-effective measurements on the crop created new avenues for selecting groundnut genotypes with high levels of *T*, *TE*, and *HI* (Wright et al., 1996). There is some evidence that the groundnut genotypes having lower SLA (high *TE*) showed more stability in dry matter production under drought (Nautiyal et al., 2000, in press). It will be interesting to see if the concurrent selection for the drought-resistance traits (*T*, *TE*, and *HI*) in a selection programme will lead to development of genotypes with stable yields across erratic rainfall seasons/environments.

An ongoing ACIAR-funded collaborative project is currently assessing the value of the indirect selection tools in improving the efficiency of selection in a large-scale groundnut breeding programs in India and Australia.

PROSPECTS OF MARKER-ASSISTED SELECTION (MAS)

Most of the physiological traits are quantitative in nature. However, only a few loci with major effects and their allelic forms (polymorphisms) account for significant genetic variation in traits (i.e., the traits QTL). Using molecular markers, QTL can be detected in an appropriate population of plants. A locus for any quantitative trait can be mapped as long as polymorphism is observed in segregating populations under analysis and phenotypic information is available for lines in the population. However, compared to other crops, cultivated groundnut with currently available DNA markers shows limited polymorphic variation. Because of this reason, it has not been possible to construct a genetic map for cultivated groundnut. It is expected that newer markers/techniques will be able to discern polymorphic variation in cultivated groundnut clearly. Use of molecular markers for simultaneous improvement of traits associated with drought resistance will be more efficient than direct selection based on the phenotype because of the potential application of markers in breaking the negative association between traits.

Contrary to the cultivated groundnut, its diploid wild species in section *Arachis* have shown abundant polymorphism and a linkage map, based on RFLPs, has been developed (Halward et al. 1994). DNA markers linked to a root-knot nematode resistance gene derived from wild *Arachis* have been identified. Following interspecific hybridization and using DNA markers for selection, advanced breeding lines with nematode resistance have been developed (Burow et al. 1996). Recently polymorphic variation in DNA has been detected in selected germplasm of cultivated groundnut, using RFLP and AFLP methods (He and Prakash 1995, Subramaniyan et al., 2000). However, there is limited information on biochemical and molecular basis for variation among genotypes for drought resistance (Nageswara Rao et al. 1995). Further research is necessary to develop linkages between the drought resistance traits and the molecular markers so that the MAS tools can be applied in the drought resistance breeding. With the rapid progress in analytical technology, it will not be too long before the markers associated with various phenological and physiological attributes will be detected and used in the breeding programmes. It would also be worthwhile to evaluate wild *Arachis* species for physiological traits associated with drought and aflatoxin resistance and identify suitable DNA markers for drought resistance gene(s) for use in interspecific breeding to develop drought-resistant lines.

INTEGRATED MANAGEMENT SOLUTIONS FOR ENHANCING DROUGHT ADAPTATION IN GROUNDNUT

The following three approaches can lead to increased soil moisture availability to the plants:

(a) Matching crop phenology to environment

(b) Optimal use of supplementary irrigation, if available

(c) Increasing soil-available water to crop

(a) Matching genotype to environment

Significant diversity exists in the groundnut germplasm for various phenological traits (Wyne and Coffelt 1982) and offers the possibility of selecting genotypes with desired phenology for use in breeding programmes. In regions where the growing season is longer, cultivars belonging to the Virginia group (subspecies *hypogaea*) are generally selected. In regions where the season is shorter, Spanish and valencia types (subspecies *fastigiata*) are selected. With perceivable changes in global climate (principally temperature and rainfall patterns), it has become necessary to match genotype more carefully to the length of the growing season. For example, groundnut production in West Africa has declined remarkably over the past several years due to severe droughts. The isohyets have moved towards south, resulting in shortening of the period of useful rains in the northern part of the region. The cultivars, which were productive earlier in the northern part, are no more suitable. Newer cultivars with short growing period (seventy-five to ninety days) are now required to sustain groundnut production in northern parts where the growing season is short and rainfall low. Agro-climatological analysis of major rainfed groundnut-growing environments in the SAT clearly indicates that growing areas are characterized by short growing seasons, i.e. 75-110 days (Virmani and Piara Singh 1986). This explains why short duration genotypes are generally successful in West African region (Gautreau, 1967; Bocklee-Morvan, 1983) as well as in some parts of India (S.N. Nigam, ICRISAT, personal communication).

(b) Supplementary irrigation

Irrigation is a popular production practice wherever groundnut is cultivated under high input conditions. It is well recognized that water will be a costly commodity in future agriculture and there is an increasing need to optimize the use of this resource. Variable results on the response of groundnuts to irrigation have been obtained, depending upon several factors including the timing and amount of irrigation, method of irrigation, the intensity of water deficit experienced by the crop and climatic conditions. Nageswara Rao et al. (1985) observed that drought during the pre-flowering phase, followed by adequate water availability, resulted in pod yields of between 13% and 19% greater than fully irrigated crops in a two-year study. This study showed a significant interaction between evapotranspiration and pod yield with different timings of drought, which in turn, resulted in significant effect on the number of mature pods at harvest (Nageswara Rao et al., 1988). As mentioned earlier, the sensitivity of the crop to drought was less in early and mid-season drought compared with late-season droughts. Several reports have indicated that the pod-filling phase is most sensitive to drought (Pallas et al. 1979; Nageswara Rao et al. 1985), suggesting that the supplementary irrigation, if available can efficiently be used to alleviate drought during pod-flling phase. However, it is interesting to note that Nageswara Rao and Williams (1984) found that exposing the crop to a short drought during the early vegetative phase reduced the impact of a second drought at the seedling phase, indicating an adaptive response of groundnuts to drought. It is possible that early drought may enhance root development and reduce transpiration losses by limiting leaf area development, which subsequently allows the use of soil moisture from deeper layers in the soil profile. The beneficial effect of subjecting the crop to an early drought has considerable practical implications for irrigation management. Since the crop can endure long droughts during the early growth phase without major yield losses, supplementary irrigation, when available, should be used largely to support crop growth during the reproductive stage. For instance, in a five-year study in India, sowing of groundnut with one irrigation prior to the arrival of the monsoon (in July) resulted in moderate crop water deficits during the early growth stage and an increase in yield of up to 22% (Pasricha et al. 1987). However, there is further need for research in this area to fine tune agronomic recommendations considering wide variation in the crop maturity of varieties grown by the SAT farmers and agro-climatic environments.

(c) Management practices to increase water availability to the crop

Under irrigated or rainfed systems, another agronomic practice having a positive influence on yield of groundnut was the broad-bed and furrow (BBF) method of land preparation. Although BBF system of land preparation has been developed as a soil conservation practice for vertisols, this system has been shown to be advantageous for rainfed groundnut production on alfisols. Large-scale experiments conducted at ICRISAT and other locations in India have shown that BBF method of land preparation resulted in about 18-20% increased pod yields in groundnut under rainfed conditions (Table 1). In addition to the pod yield, an important consideration in these results is the significant increase in total dry matter under BBF system. Forming broad-bed and furrows across slopes of the land can result in enhanced storage of rainwater, thus increasing water availability to the crop. Furrows also act as drainage channels under excess rainfall conditions, thus increasing aeration to pods and nodules by avoiding water logging in and around the pod zone. Under irrigated conditions, the furrows are usually used as irrigation channels. However, the width of the bed is subjected to the soil physical properties governing the lateral movement of water.

Table 1: Effect of raised and furrow (BBF) and flat sowing system on yields of groundnut genotypes at the Dry Farming Research Station, Anantapur (1988 rainy season)

	Pod wt.		**Veg. wt.**		**Total dry matter**		**HI (%)**	
	kg ha^{-1}		**kg ha^{-1}**		**kg ha^{-1}**			
Genotype	**BBF**	**Flat**	**BBF**	**Flat**	**BBF**	**Flat**	**BBF**	**Flat**
NC Ac 17090	1290	990	1575	1440	3710	3070	45	40
ICGV 86055	1330	1140	950	920	3150	2800	58	56
TMV 2	1275	1110	930	906	3030	2735	58	55
J 11	1420	1250	1040	1115	3380	3185	58	53
SE	±74.7		±96.0		±199.6		±1.6	
CV (%)	13.7		19.4		14.7		6.1	

Generally, yield advantages from BBF were realized only when the structure of BBF was maintained through the growing season. An additional advantage of having BBF is that the furrows also act as pathways for people and animals to carry out crop management practices without physically disturbing the pod zone during the pod filling phase.

REFERENCES

Arihara, J., N. Ae, and K. Okada. 1991. Improving responses of chickpea and pigeonpea to phosphorus application in Vertisols and Alfisols. Pages 157-165 in *Phosphorus Nutrition of Grain Legumes in the Semi-Arid Tropics* (Johansen, C., Lee, K.K., and Sahrawat, K.L., eds.). Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

Bidinger, F.R., V. Mahalaksmi, B.S. Talukdar, and G. Alagarswamy. 1982. Improvement of drought resistance in pearl millet. Pages 357-375 in *Drought Resistance in Crops with Special Emphasis on Rice.* Los Baños, Laguna, Philippines: International Rice Research Institute.

Bocklee-Morvan, A. 1983. The different varieties of groundnut. Geographical and climatic distribution, availability. *Oleagineux,* 38:73-116.

Burow, M.D., C.E. Simpson, A.H. Paterson, and J.L. Starr. 1996. Identification of peanut (*Arachis hypogaea* L.) RAPD markers diagnostic of root-knot nematode (*Meloidogyne arenaria* (Neal) Chitwood) resistance. *Molecular Breeding* 2:369-379.

Fehr, W.R. 1984. (ed.). Genetic Contributions to Yield Gains of Five Major Crop Plants. CSSA Special Publication No 7. Madison, Wisconsin, USA.

Fereres, E., C. Gimenez, and J.M. Fernandez. 1986. Genetic variability in sunflower cultivars under drought. I. Yield Relationships. *Australian Journal of Agricultural Research* 37:573-582.

Freeman, H.A., S.N. Nigam, T.G. Kelley, B.R. N'tare, P. Subrahmanyam, and D. Boughton. 1999. *The World Groundnut Economy: Facts, Trends, and Outlook.* Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 52 pp.

Garrity, D.P., C.Y. Sullivan, and W.M. Ross. 1982. Alternative approaches to improving grain productivity under drought stress. Pages 339-356 in *Drought Resistance in Crops with Special Emphasis on Rice.* Los Baños, Laguna, Philippines: International Rice Research Institute.

Gautreau, J. 1967. Varietal research on drought resistance in groundnut. *Oleagineux,* 22:25-29.

Halward, T., H.T. Stalker, and T. Kochert. 1994. RFLP map of peanut. Pages 246-259 in *DNA-Based Markers in Plants* (Phillips, R.L. and Vasil I.K., eds.). Kluwer Academic Publishers, The Netherlands.

Harris, D., R.B. Mathews, R.C. Nageswara Rao, and J.H. Williams. 1988. The physiological basis for yield differences between four groundnut genotypes in response to drought. III. Developmental processes. *Experimental Agriculture* 24:215-226.

He, G. and C.S. Prakash. 1997. Identification of polymorphic DNA markers in cultivated peanut (*Arachis hypogaea* L.). *Euphytica* 97:143-149.

Hubick, K.T, G.D. Farquhar, and R. Shorter. 1986. Correlation between water use efficiency and carbon isotope discrimination in diverse peanut (*Arachis*) germplasm. *Australian Journal of Plant Physiology* 13:806-816.

Hubick, K.T, G.D. Farquhar, and R. Shorter. 1988. Heritability of genotypic × environmental interactions of carbon isotope discrimination and transpiration efficiency in peanut (*Arachis hypogaea* L.). *Australian Journal of Plant Physiology* 15:779-813.

Johansen, C. and S.N. Nigam. 1994. Importance of drought stress and its alleviation in legumes. Pages 17-19 in *Selection for Water-Use Efficiency in Grain Legumes* (Wright, G.C. and Nageswara Rao, R.C., eds.). Report of a workshop held at ICRISAT Center, Andhra Pradesh, India. 5-7 May 1993. ACIAR Technical Report No. 27: The Australian Centre for International Agricultural Research. 70 pp.

Ketring, D.L. 1984. Root diversity among peanut genotypes. *Crop Science* 24: 229-232.

Mehan, V.K., Ba Amadou, D. McDonald, J.L. Renard, R.C. Nageswara Rao, and S. Jayanthi. 1991. Field screening of groundnut for resistance to seed infection by *Aspergillus flavus. Oleagineux.* 46:109-118.

Mehan, V.K., R.C. Nageswara Rao, D. McDonald, and J.H. Williams. 1988. Management of drought stress to improve field screening of peanuts for resistance to *Aspergillus flavus. Phytopathology* 78:659-663.

Mathews, R.B., D. Harris, R.C. Nageswara Rao, J.H. Williams, and K.D.R. Wadia. 1988. The physiological basis for yield differences between four groundnut genotypes in response to drought. I. Dry matter production and water use. *Experimental Agriculture* 24:191-202.

Nageswara Rao, R.C., and J.H. Williams. 1984. Effects of duration, timing, and intensity of single and multiple droughts on peanuts. *American Peanut Research and Education Society* 16:31 (Abstract).

Nageswara Rao, R.C., Sardar Singh, M.V.K. Sivakumar, K.L. Srivastava, and J.H. Williams. 1985. Effect of water deficit at different growth phases of peanut. 1. Yield responses. *Agronomy Journal* 77:782-786.

Nageswara Rao, R.C., J.H. Williams, M.V.K. Sivakumar, and K.D.R. Wadia. 1988. Effect of water deficit at different growth phases of peanut. II. Response to drought during pre-flowering phase. *Agronomy Journal* 80:431-438.

Nageswara Rao, R.C., J.H. Williams, and Murari Singh. 1989. Relationship between sensitivity to drought and yield potential in peanut genotypes under different drought patterns. *Agronomy Journal* 81:887-893.

Nageswara Rao, R.C., J.H. Williams, K.D.R. Wadia, K.T. Hubick, and G.D. Farquhar. 1993. Crop growth, water-use efficiency and carbon isotope discrimination in groundnut (*Arachis hypogaea* L.) genotypes under end-of-season drought conditions. *Annals of Applied Biology* 122:357-367.

Nageswara Rao, R.C. 1994. Drought Research on Groundnut at ICRISAT Centre (Wright, G.C. and Nageswara Rao, R.C., eds.). Report of a workshop held at ICRISAT Center, Andhra Pradesh, India. 5-7 May 1993. ACIAR Technical Report No. 27: The Australian Centre for International Agricultural Research. 70pp.

Nageswara Rao, R.C., A.K. Singh, L.J. Reddy, and S.N. Nigam. 1994. Prospects for utilization of genotypic variability for yield improvement in groundnut. *Journal of Oilseeds Research* 11:259-268.

Nageswara Rao, R.C., and G.C. Wright. 1994. Stability of the relationship between specific leaf area and carbon isotope discrimination across environments in peanut. *Crop Science* 34:98-103.

Nageswara Rao, R.C., M. Udaykumar, G.D. Farquhar, H.S. Talwar, and T.G. Prasad. 1995. Variation in carbon isotope discrimination and its relationship to specific leaf area and ribulose- 1,5 bisphosphate carboxylase content in groundnut genotypes. *Australian Journal of Plant Physiology* 22:545-551.

Nautiyal, P.C., Y.C. Joshi, and R.C. Nageswara Rao. 2000. Relationship between relative water content and specific leaf area under progressive soil moisture deficit stress in groundnut. *Annals of Applied Biology* (in Press)

Pallas, J.E., J.R. Stansell Jr, and T.J. Koske. 1979. Effect of drought on Florunner peanuts. *Agronomy Journal* 24:355-359.

Pasricha, N.S., M.S. Aulakh, H.S. Baddesha, and G.S Bahl. 1987. Early sowing of groundnut gives higher yield. *Indian Farming* 37:23-24.

Passioura, J.B. 1977. Grain yield, harvest index and water use of wheat. *Journal of Australian Institute of Agricultural Science* 43:117-120.

Singh, M., R.C.N. Rao, and J.H. Williams. 1991. A statistical assessment of genotypic sensitivity of groundnut (*Arachis hypogaea* L.) to drought in line source sprinkler experiments. *Euphytica* 57:19-25.

Stirling, C.M., C.R. Black, and C.K. Ong. 1989. The response of groundnut to timing of irrigation II. ^{14}C partitioning and plant water status. *Journal of Experimental Botany* 20:1363-1373.

Subramanian, V., S. Gurutu, R.C. Nageswara Rao, and S.N. Nigam. 2000. Identification of DNA polymorphism in cultivated groundnut using random amplified polymorphic DNA (RAPD) assay. *Genome* 43:1-5.

Vasudeva Rao, M.J., S.N. Nigam, and A.K.S. Huda. 1992. The thermal time concept as a selection criterion for earliness in peanut. *Peanut Science* 19:7-10.

Virmani S.M. and Piara Singh. 1986. Agroclimatological characteristics of the groundnut-growing regions in the semi-arid tropics. Pages 35-46 in *Agrometeorology of Groundnut,* Proceedings of International Symposium, 21-26 Aug 1985, ICRISAT Sahelian Center, Niamey, Niger. Patancheru, A.P. 502 324, India: ICRISAT.

Williams J.H and N.P. Saxena. 1991. The use of non-destructive measurement and physiological models of yield determination to investigate factors determining differences in seed yield between genotypes of "desi" chickpeas (*Cicer arietum*). *Annals of Applied Biology* 119:105-112.

Wright, G.C., K.T. Hubick, and G.D. Farquhar. 1988. Discrimination in carbon isotopes of leaves, correlates with water use efficiency of field grown peanut cultivars. *Australian Journal of Plant Physiology* 15:815-825.

Wright G.C., K.T. Hubick, and G.D. Farquhar. 1991. Physiological analysis of peanut cultivar response to timing and duration of drought stress. *Australian Journal of Agricultural Research* 42: 453-470.

Wright, G.C., K.T. Hubick, G.D. Farquhar, and R.C. Nageswara Rao. 1993. Genetic and environmental variation in transpiration efficiency and its correlation with carbon isotopediscrimination and specific leaf area in peanut. Pages 247-267 in *Stable Isotopes and Plant Carbon-Water Relations* (Ehleringer, J., Hall, A.E., and Farquhar, G.D., eds.) Academic Press, USA.

Wright, G.C., R.C. Nageswara Rao, and G.D. Farquhar. 1994. Water-use efficiency and carbon isotope discrimination in peanut under water deficit conditions. *Crop Science* 34:92-97.

Wright, G.C., and R.C. Nageswara Rao. 1994a. Groundnut water relations. Pages 281-336 in *The Groundnut Crop: A Scientific Basis for Improvement* (Smartt, J.E., ed.) Chapman & Hall, London.

Wright, G.C. and R.C. Nageswara Rao. 1994b. Carbon isotope discrimination, water-use efficiency, specific leaf area relationships in groundnut. Pages 52-58 in *Selection for Water-Use Efficiency in Grain Legumes* (Wright, G.C. and Nageswara Rao, R.C., eds.). Report of a workshop held at ICRISAT Center, Andhra Pradesh, India. 5-7 May 1993. ACIAR Technical Report No. 27: The Australian Centre for International Agricultural Research. 70 pp.

Wright, G.C., R.C. Nageswara Rao, and M.S. Basu, 1996. A physiological approach to the understanding of genotype by environment interactions—A case study on improvement of drought adaptation in groundnut. Pages 365-381 in *Plant Adaptation and Crop Improvement*: proceedings of an international workshop, 28 Nov-3 Dec 1994, ICRISAT Asia Center, India (Cooper, M. and Hammer, G.L., eds.): CAB International.

Wyne, J.C. and T.A. Coffelt. 1982. Genetics of *Arachis hypogaea* L. Pages 50-94 in *Peanut Science and Technology* (Pattee, H.E. and Young, C.T. eds.). American Peanut Research and Education Association. Yoakum, Texas.