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WATER DEFICIT STRESS AND ITS MANAGEMENT IN GROUNDNUT

A.L. Singh, R.N. Nakar, Nisha Goswami, K.A. Kalariya, K. Chakraborty and Man Singh*

Directorate of Groundnut Research, P.B. 5, Junagadh 362 001, Gujarat, India
Email: alsingh@nrcg.res.in and alsingh16@gmail.com
**WTC, Indian Agricultural Research Institute, New Delhi 110012, India*

INTRODUCTION

The groundnut (*Arachis hypogaea* L), is an important food legume of tropical and subtropical world presently grown on about 24 million hectare (ha) of land in about 120 countries under different agro-climatic zones between latitudes 40ºS and 40ºN. It is native of South America and was disseminated through colonial sea board by Spanish and Portuguese to other countries and presently cultivated mainly in Asian (11.5 m ha), African (11.5 m ha) and American (1.1 m ha) countries mainly in semi-arid regions and India, China, Nigeria, USA, Myanmar, Senegal, Sudan, Indonesia, Argentina and Vietnam are the major groundnut producing countries. Groundnut is an energy rich crop, but mostly grown under energy starved conditions across wide range of environments where frequent drought is one of the limiting factors adversely affecting its productivity in rainfed area. As a result the groundnut productivity is less than 1000 kg ha^{-1} in more than 50% of the groundnut growing countries in the world, between 1000-2000 kg ha^{-1} in 35-40% of the countries and only 10-15% of the countries had the productivity above 2000 kg ha^{-1} (FAO, 2012). However, the world average yield is around 1600 kg ha^{-1} and about 70% of the world groundnut production occurs in the semi-arid to arid tropics where the average yield is still around 1000 kg ha^{-1}.

Groundnut production fluctuates considerably as a result of rainfall variability. There is wide range of groundnut productivity varying from about 500 kg ha^{-1} (poor) in Angola and Mozambique (extremely low about 300 kg ha^{-1}), Madagasker, Namibia, Niger, Uruguay and Zimbabwe, about 3000 kg ha^{-1} (high) in China, Egypt, Syrian Arab Republic, about 4000 in USA, Malaysia, Saudi Arabia, Palestine and Nicaragua, as much as 6400 kg ha^{-1} (very high) in Israel and extremely high (more than 12000 kg ha^{-1}) in Cyprus (FAO, 2012).

Abiotic stresses are the major challenge in sustainable food production, with a potential yield reduction of 70% in crop plants. Of all the abiotic stresses, drought is regarded as the most damaging. In India the groundnut is grown on an area of about 6 million hectare, producing about 8 million tonne (mt) of pod and is the most important oilseed crop of the country. Presently, India has the largest groundnut area (24% of the world) accounting for only 20% of the world groundnut production, but China with only 18% area contributes 39% of the world production due to high productivity and better management practices. Though the average groundnut yield in India is around 1400 kg ha^{-1}, combination of improved varieties and better agronomic practices recorded more than 6000 kg ha^{-1} pod yield frequently and occasionally 8000 kg ha^{-1} (Singh 2004a, 2011). This clearly indicates that the potential of groundnut has not been exploited even by one-third and there is tremendous scope to increase the yield through understanding of its physiology and water relation.

Characterization of agricultural drought is essential before undertaking a yield improvement programme in semi-arid zones. A simplified model combining evapotranspiration (ET) and water balance concepts with basic data on plant responses to drought for groundnut, the applicability of the same for diagnosing drought types. The physiological studies and drought tolerance of this crop started in 80s and by now ample of studies have been conducted. Due to underground fruiting, indeterminate growth habit and different botanical types still certain aspects of physiology of this crop are not very clear. To develop a water stress response function in groundnut, research works have been done to improve the performance under varying degrees of stress at various physiological stages of crop growth. The water stress affects the vegetative, root and reproductive growth and a proper scheduling of irrigation is required.

The complex nature of drought tolerance limits its management through conventional breeding methods. Innovative biotechnological approaches have enhanced our understanding of the processes underlying plant responses to drought at the molecular and whole plant levels. Hundreds of drought stress-induced genes have been identified and some of these have been cloned. Plant genetic engineering and molecular marker approaches allow the development of drought-tolerant germplasm.

In groundnut drought-stress effects depend primarily on the stress pattern because genotypic variation is usually of secondary significance. The different responses of groundnut cv. to drought when assessed relative to the mean response of all genotypes to drought as two major aspects of drought (duration, intensity, and timing relative to crop pheno-phases) may vary independently. The timing of drought has a large impact on the variation about the mean response. The sensitivity of a genotype to drought increases with yield potential, increasing the closer the drought ends to final harvest. Genotypic variation in response to drought exists in the water-use ratio of genotypes, with some being able to accumulate up to 30% more shoot DM than others with the same total transpiration.

The knowledge of crop physiology and management under water-deficit stress is important for achieving optimal crop yield under limited water availability as introduction of an improved genotypes into new region is largely determined by temperature and phenology, which are essential component of whole crop simulation model and can be used to specify the most appropriate rate and time of specific developmental process to maximize yield. In this chapter an attempt was made to combine all the knowledge of water deficit stress and its impact on groundnut agronomy and physiology and management practices to grow high yielding groundnut varieties with targeted yield and recommend the same to groundnut workers to increase the productivity. Effects of water stress on these components are discussed separately; however all of them are interrelated.

2. EXTENT OF PROBLEM AREAS AND SOILS

The cultivation of groundnut, due to its wide adaptability has been spread on almost all soils in all the tropical and subtropical countries throughout the world. However, on large scale it is mainly grown in India, China, Nigeria, USA, Myanmar, Indonesia, Sudan, Senegal, Argentina and Vietnam producing more than 0.5 million tonne (mt) and in Ghana, Chad, Congo Republic, Mali, Guinea, Niger, Argentina, Brazil, Tanzania, Burkino Faso, and Malawi producing in between 0.25-0.5 mt. Though it is a energy rich crop, more than 85% of the world groundnut production come from low income food deficit countries with an average productivity of about 1500 kg ha^{-1} and having more than 90% of the groundnut growing areas of the world.

Though native of south America, the groundnut cultivation is settled in southern, eastern and south-eastern part of Asia, western Africa and northern and south America due to favourable soils and climates. The commercial groundnut cultivation is mainly in Asian (48% of the world groundnut area contributing 64% of the total world production), African (47% area, 27% production) and American (4.2% area and 8% production) countries due to suitable environment and matching growing season. Though grown in limited area, the groundnut productivity of Cyprus (<100 ha area) is highest (>12000 kg ha^{-1}) followed by Israel (2600 ha and 6440 kg ha^{-1}) in the word mainly due to favourable season and high cultivation practices. On the other hand the productivity of many African countries, with significant areas, are still around 400 kg ha^{-1} because of poor resources and scanty rainfall. However, on large scale cultivation the productivity of USA, China, Egypt, Turkey, Argentina and Nicaragua are very high (>3000 kg ha^{-1}).

In India, the groundnut is grown in about 260 districts mostly as rainfed dry lands, crop on well drained sandy soils in low (<750 mm) and medium (750-1000 mm) annual rainfall areas, often subject to the vagaries of the weather and only 20% of groundnut area is under irrigation. Between the decades of 60s and 70s, there is practically little difference in productivity (700-800 kg ha^{-1}) and the increase in production was largely due to the expansion in areas. But during 1988-89 due to favorable season and transfer of available technologies first time the productivity crossed one tonne (1132 kg ha^{-1}) and it was 1357 kg ha^{-1} during 2005-06 and 1459 kg ha^{-1} during 2007-08. In India generally the groundnut is grown as rainfed crop during rainy season (Kharif) with one or two protective irrigation and also during Rabi, summer and spring season as a irrigated crop with higher yield potential than in kharif. Presently, in India the average productivity of rabi-summer groundnut is about 1850 kg ha^{-1}, much higher than kharif season (1410 kg ha^{-1}) indicating more production potential during this season.

Presently, Gujarat (30% total area and 36-40% of production), Andhra Pradesh (28% area and 20-28% of production), Tamil Nadu (7% area and 11% of production), Karnataka (14.5% area and 10% of production), Rajasthan (6% area and 8.2% of production) and Maharashtra (6.1% area and 5.5% of production) are the main groundnut growing states. The Madhya Pradesh, Orissa, Uttar Pradesh and West Bengal are the other groundnut growing states with 7% of area contributing 7% of the total production of the country. If we critically analyse the situation of groundnut production in India, though the productivity (average of both the season) of groundnut during the year 2001 to 2010 ranged from 700-1460 kg ha^{-1}, the productivity in three major groundnut growing states, accounting for about 75% of the total productivity of the country, was in between 1473-2390 kg ha^{-1} in Gujarat, 1400-2130 kg ha^{-1} in AP and 2100-3730 kg ha^{-1} in Tamil Nadu during rabi-summer season, but fluctuated in between 510-2270, 300-1360, 1150-1880 kg ha^{-1}, respectively in these states during kharif season.

Drought is an insidious hazard of nature and is considered to be the most complex but least understood of all natural hazards. Large historical datasets are required to study drought and these involve complex interrelationships between climatological and meteorological data. Rainfall is an important meteorological parameter, the amount and distribution influence the type of vegetation in a region. Drought being very complex phenomenon, there is no universally accepted definition. It is a meteorological term and is commonly defined as a period without significant rainfall denoting scarcity of water in a region. Prolonged deficiencies of soil moisture adversely affect crop growth indicating incidence of agricultural drought. It is the result of imbalance between soil moisture and evapo-transpiration needs of an area over a fairly long period so as to cause damage to standing crops and to reduce the yields. The irrigation commission of India defines drought as a situation occurring in any area where the annual rainfall is less than 75% of normal rainfall. The book "Drought: Assessment, Monitoring, Management and Resources Conservation" by Nagarajan, listed chronically affected districts by drought conditions, of these groundnut growing one in various states are mentioned in Table 1.

Table 1. Groundnut growing districts chronically affected by drought conditions

Andhra Pradesh	Anantpur, Chittoor, Cuddapah, Karnool, Prakasam, Nalgonda, Mehboobnagar, Hyderabad
Gujarat	Ahmedabad, Amrely, Banaskantha, Bhavnagar, Jamnagar, Kheda, Kutch, Mehsana, Panchmahal, Rajkot, Surendranagar
Haryana	Bhiwani, Mahendranagar, Rohtak
Karnataka	Bangalore, Belgaum, Bellary, Bijapur, Chitradurga, Chickmagalur, Dharwad, Gulbarga, Hassan, Kolar, Mandya, Mysore, Raichur, Tumkur
Madhya Pradesh	Betul, Jhabhua, Khandak, Shahdol, Shahjapur, Sidhi, Ujjain
Maharashtra	Ahmednagar, Aurangabad, Beed, Nanded, Nashik, Osmanabad, Pune, Parbhani, Sangli, Satara, Solapur
Orissa	Phulbani, Kalahandi, Bolangir, Kendrapada
Rajasthan	Ajmer, Banswara, Barmer, Churu, Dungarpur, Jaisalmer, Jalore, Jhunjhunu, Jodhpur, Nagaur, Pali, Udaipur
Tamil Nadu	Coimbatore, Dharmapuri, Madurai, Ramanathapuram, Salem, Tiruchirapali, Tirunelveli, Kanyakumari
Uttar Pradesh	Allahabad, Banda, Hamirpur, Jalan, Mirzapur, Varanasi, Mainpuri
West Bengal	Bankura, Midnapore, Purulia
Jharkhand	Palamau
Chhattisgarh	Khargaon

Important causes for agricultural drought are inadequate precipitation, erratic distribution, long dry spells in the monsoon, late onset of monsoon, early withdrawal of monsoon along with lack of proper soil and crop management. Drought stress tolerance is seen in almost all plants but its extent varies from species to species and even within species.

Water deficit and salt stresses are global issues to ensure survival of agricultural crops and sustainable food production. Stress resistance may involve following mechanisms

- Avoidance mechanisms prevents exposure to stress
- Tolerance mechanisms permits the plant to withstand stress through osmotic adjustment

- Acclimation alter their physiology in response to stress

At whole plant level the effect of stress is usually perceived as a decrease in photosynthesis and growth, and is associated with alteration in carbon and nitrogen metabolism (Mwanamwenge *et al*., 1999). Drought stress affects the growth, dry matter and harvestable yield, but the tolerance of genotypes to this menace varies remarkably.

Drought is the major abiotic constraint affecting groundnut productivity and quality worldwide. Groundnut plants are drought tolerant because of deep rooting and a water supply-related flexibility in time of flowering and fruiting. Various conservative water management treatments over a 3-yr period when used to determine water use and yield response of groundnuts growing on deep well-drained sandy soils yields were not reduced by droughts of short duration unless the seasonal water use was below about 50 cm. The pod yields were 2.26, 3.0 and 3.82 t/ha with approximately 33, 40 and 46 cm water, respectively (Hammond *et al*., 1978).

Groundnut drought adaptation mechanisms when surveyed (with a view to developing selection criteria for breeding) under the headings (1) drought evasion (ability to complete the development cycle before water deficits occur), (2) drought avoidance (mechanisms such as modified root and leaf morphology which allow the plant to keep its tissues at a high water potential during drought) and (3) tolerance to drought (maintenance of potential turgidity by osmotic adjustments, and tolerance of desiccation due to properties of the cell membrane) (Annerose, 1988).

In a study the joint regression approach of stability analysis is briefly discussed and the economic concepts of risk and utility maximization and alternative approaches are considered. For groundnut improvement in India at 3 regions (Hyderabad, Anantapur and Gujarat) the response relationships between groundnut yields and relative available water are estimated and empirical yield distributions were simulated and the results of alternative risk analysis approaches when compared with the traditional stability analysis of the experimental data and recommendations for future plant breeding methodology and risk analysis are presented (Bailey and Boisvert, 1989).

To analyse the changes in vegetation cover due to variation in rainfall and identify the land-use areas facing drought risk, rainfall data from 1981 to 2003 were categorized into excess, normal, deficit and drought years. The Advanced Very High Resolution Radiometer (AVHRR) sensor's composite dataset was used for analysing the temporal and interannual behaviour of surface vegetation. The various land-use classes - crop land (annual, perennial crops), scrub land, barren land, forest land, degraded pasture and grassland were identified using satellite data for excess, normal, deficit and drought years. Normalized Difference Vegetation Indices (NDVIs) were derived from satellite data for each land-use class and the highest NDVI mean values were 0.515, 0.436 and 0.385 for the tapioca crop in excess, normal and deficit years, respectively, whereas in the drought year, the groundnut crop (0.267) showed the maximum. Grassland recorded the lowest value of NDVI in all years except for the excess year. Annual crops, such as groundnut (0.398), pulses (0.313), sorghum (0.120), tapioca (0.436) and horse gram (0.259), registered comparatively higher NDVI values than the perennial crops for the normal year. The Vegetation Condition Index (VCI) was used to estimate vegetation health and monitor drought. Among land-use classes, the maximum groundnut witnessed the maximum values of 78.2, 64.5 and 55.2% for normal, deficit and drought years, respectively. Based on the VCI classification, all land-use classes fall into the optimal or normal vegetation category in excess and normal years, whereas in drought years most of the land-use classes fall into the drought category except for sorghum, groundnut, pulses and grasses. These crops (sorghum 39.7%, groundnut 55.2%, pulses 38.5% and grassland 38.6%) registered maximum VCI values, with sustained under drought conditions. It is suggested that the existing crop pattern be modified in drought periods by selecting the suitable crops of sorghum, groundnut and pulses and avoiding the cultivation of onion, rice and tapioca (Muthumanickam *et al*., 2011).

Most breeding programmes in groundnut follow an empirical approach to drought resistance breeding, largely based on kernel yield and traits of local adaptation, resulting in slow progress. Recent advances in the use of easily measurable surrogates for complex physiological traits associated with drought tolerance encouraged breeders to integrate these in their selection schemes. However, there has been no direct comparison of the relative efficiency of a physiological trait-based selection approach (Tr) vis-a-vis an empirical approach (E) to ascertain the benefits of the former.

In field studies, for 5 years at ICRISAT Patancheru, groundnuts advanced breeding lines produced greater pod yields on Vertisols (2.02-3.81 t/ha) than on Alfisols (0.61-1.56 t) and there was a strong soil type x genotype interaction. In another study, 4 cultivars irrigated or water stressed during flowering, pod-set or pod-filling showed that while CGR were greater on Alfisols, they were linearly related to those measured on Vertisols. However, pod growth rates and partitioning of DM to pods showed a strong soil type x genotype interaction and the genotypes developed on the Alfisol maintain relative ranking for total DM on Vertisol, but not necessarily for pod yields (Rao *et al.,* 1992).

A study was carried out to quantify the impact of drought on production of five major kharif crops (rice, groundnut, cotton, bajra, soyabeans) and a rabi crop (wheat) using the standardized precipitation index (SPI) that captures cumulative rainfall deviations at various time scales, computed for 36 meteorological sub-divisions at monthly (SPI1), bimonthly (SPI2) and tri-monthly (SPI3) scales using monthly rainfall data for the period of 1971-2002. July was identified as the most drought affected, followed by September, while June and August were near normal. In July, out of 36 meteorological sub-divisions, 26 showed rainfall below normal. Amongst these 26 drought affected sub-divisions, six sub-divisions were very severely affected. Correlation coefficients were computed between production of major kharif crops (1980-2001) and SPI values and September was the crucial month for defining the crop yield for most of the kharif crops throughout the country. Production forecast using SPI3 (July to September) showed good agreement with statistics provided by state department of agriculture for kharif crops (Chaudhari and Dadhwal, 2004).

The potential (no-water stress) and the lowest (no irrigation) yields for maize, soyabean and groundnut were calculated using three crop growth and water use models - CERES-Maize, SOYGRO, and PNUTGRO where rainfall, temperature and solar radiation records were used with these models to identify the 15 most severe drought years in the 53 year record in a 36-county region of Georgia, USA, that contains 75% of Georgia's irrigated land. In the 15 driest years, simulated yield losses averaged 75% for maize, 73% for soyabean, and 64% for groundnut. Irrigation amount and timing needed to provide 90% of the no-stress yields when calculated the irrigation needs of maize in these drought years occurred before that of groundnut or soyabean. For the reported irrigated crop acreage of the study area, simulated water withdrawals exceeded 3 million m^3/day, on an average, for most of the 130 days between late May and late September (Hook, 1994).

3. QUANTIFICATION OF DROUGHT AND YIELD LOSSES

Groundnut is an important crop of the semi-arid tropics where potential yields are frequently reduced by heat and water stress. Studies on occurrence and intensity of the drought during crop growing season revealed the effect of moisture stress on the groundnut yields in the dry lands. The groundnut is relatively drought resistant and important crop of semi-arid regions where evaporation exceeds precipitation for 5-10 months of the year. The plant water-status is the result of a balance between water uptake and loss which has been less understood in groundnut. Groundnut plant contains about 80% of water on fresh weight basis and reduction of the plant water status much below this level causes wilting and affects the rate of several plant functions. Though different stages have different sensitivity to water deficit, none of these can proceed normally below some minimum water. Increasing moisture stress from 0 to 2, 4 and 6 atm decrease the leaf RWC, increased water saturation deficit and relative saturation deficit, decreased DM accumulation in the shoot and increased it in the root, decreased RGR, increased specific leaf weight, decreased non-reducing sugar and increased reducing sugar in groundnut seedlings (Sharma *et al.*, 1985).

A study was conducted to characterize the plant extractable water pattern at four locations in India (Tirupati, ICRISAT, Jalgaon and Junagadh) and one location in Queensland, Australia (Kingaroy) and explore the possibility of clustering the multi-location trial environments based on similar water stress patterns. The APSIM groundnut model was used to compute daily changes in plant extractable soil water (P_{esw}) at each site, by using climate parameters (ambient temperature, radiation, rainfall or irrigation amounts), soil hydraulic parameters and crop parameters (planting and harvest dates). Results from the P_{esw} characterization of experimental sites clearly demonstrated that the crops grown at the multi-location have experienced a wide variation in timing, intensity and duration of crop water deficits during the growing season and that quantification of the P_{esw} during the growing season and clustering of environments based on P_{esw} patterns can assist in understanding the basis of G x E interactions for yield between clusters, and to examine the effect of breeding methods on yield variation within each of the clusters (Rachaputi, 2003).

Most part of India, shortage of water is caused by uneven distribution of rains, gaps between rain events and field water losses rather than from low seasonal or annual rainfall totals. The groundnut grown in the micro catchment during the rainy season, utilized 364-733 mm water in evapotranspiration (ET) and deep percolation (P) (Rathore *et al.*, 1996). In a water balance studies in M.P. in a 1.05 ha field, with a 0.09 ha farm pond (which stored excess water from the wet season) 28-37% of seasonal rainfall was available as surface runoff from a microcatchment (0.66 ha growing groundnut) for collection in the pond and is sufficient to prevent drought stress (Rathore *et al.*, 1996). Analysis of 20 years of rainfall data of Tirupati for drought classification using aridity index on annual and monthly basis the correlated groundnut yields were low due to uneven distribution of rainfall during crop growing season and moisture stress during July and September coincided with moisture critical periods (Sumathi and Subramanyam, 2007).

The crop coefficient curve facilitates the prediction of groundnut ET in preparation of planting at a new site from estimates of reference crop ET. On a sandy loam soil of Hyderabad, A.P. the crop coefficient (Kc) values of groundnut at different crop-growth subperiods were influenced by evapotranspiration deficits and leaf area development of the crop (Devi and Rao, 2003). The fully irrigated control (W-W-W) showed higher Kc values at all the crop-growth subperiods than other treatments. The crop coefficient curve for W-W-W showed that the Kc value was low (0.564) during the establishment of plant (0-10 DAS), increased linearly through vegetative period and remained constant at 1.024 from flowering to start of the pod filling period (35-80 DAS), then decreased through pod filling period and reached a lowest value of 0.547 during the final 10 days of the crop period. The crop coefficient curve facilitates the prediction of groundnut ET and for field application the net (39.9 cm) and gross irrigation requirements, both at field inlet (5563 m^3/ha) and headwork (9850 m^3/ha) were determined (Devi and Rao, 2003). The reported yield losses in groundnut due to soil water deficit stress under different conditions are summarised in Table 2.

Table 2. Yield losses due to water stresses in groundnut at various locations

SN	Groundnut varieties	Soil type and places	% Yield losses	Conditions	References
1	ICGV 86031, TMV 2 NLM	Andhra Pradesh	17-18% losses in total dry matter production	Under various soil water stress	Reddy, 1999
2	-	36-county region of Georgia, USA	64% pod yield	15 most severe drought years in 53 year simulated yield losses, PNUTGRO model	Hook, 1994
3	-	-	22, 18, 47 and 47%, Yield reductions with drought at 10-30, 30-50, 50-80 and 80-120 DAS, respectively.	Imposing drought at various stages	Billaz and Ochos, 1961
4	Six cultivars	Akola, Maharashtra	47% yield reduction in six cultivars under stressed conditions	Kharif on shallow soil (<20 cm) with 30% water holding capacity	Dhopte *et al.*, 1992
5	JL-24		32% in JL-24 a water stress tolerant	Kharif	Dhopte *et al.*, 1992
6	TAG-24		67% in TAG-24 the most susceptible cultivar.	Kharif	Dhopte *et al.*, 1992
7	GAUG-10 and J-11	Junagadh, Gujarat	Pod yield by 27, 45, 56 and 6%, respectively in J-11, and 13, 15, 38 and 6% , in GAUG-10 with water stress at FL, Pg I, pod development and pod maturation stages.	Summer, water stress at FL (28-48 DAE), Pg I (40-60 DAE), PD (55-75 DAE) and maturation (75-95 DAE)	Golakiya, 1993
8	SB-XI	-	24% yield reduction at IW:CPE ratio of 0.5 than with 0.75 IW:CPE throughout.	Irrigated at (IW): (CPE) ratios of 0.75 or 0.5 (40 mm/ irrigation)	Patil and Gangavane, 1990
9	Robut 33-1	-	28-96% reduction in seed yield at stress during the start of seed growth to maturity.	water stress during post-rainy	Rao *et al.*, 1985
10	GG 6	Clay soil at Junagadh	18% and 31% reduction due to water stress at FL (25-47 DAS) and P D (50-72 DAS) stages, respectively.	Soil moisture stress at various growth stages, summer season	Vaghasia *et al.*, 2010a

11	-	-	5% decrease in pod yields at soil moisture stress 30-45 DAS	Soil moisture stress at 30-45 DAS, caused drying of first flush of flowers up to 45 DAS	Gowda and Hegde, 1986
12	Robut-33 and McCubbin	Redland Bay, Queensland	Reduced pod yield by **30%** in the Virginia Bunch Robut-33 and by **45%** in a Spanish McCubbin	water was withheld from 84 d after sowing to maturity	Chapman *et al.*, 1993
13	-	-	20 and 59%, reduction in seed yields with drought for 3 weeks starting week 5 and 6 respectively.	Drought for 3 weeks at 7 growth stages starting 4-10 weeks after sowing in field	Zaharah, 1986
14	-	-	83 - 97% , yield reduc-tions due to water stress	Rainfed conditions	Huang and Ketring,1985
15	-	18 different locations in India	49% reduction in yield, water limiting yield 2750 kg ha^{-1} as against simulated water non-limiting yield of 5440 kg ha^{-1}	CROPGRO-Peanut model	Bhatia *et al.*, 2009
16	TG-17	-	Water stress during early and late VG, FL, Pg I and PD stages reduced pod yields by 20, 26, 33, 45 and 56%.	Water stress of -14 bar soil water potential during the various growth stages	Parmar *et al.*, 1989
17	GG-2	Junagadh, medium clay soil	36, 48, 52 and 56% pod yields losses due to water stress at FL, PgI, pod formation and pod development , respectively	Water stress at various growth stages	Sakarvadia and Yadav, 1994

Where, FL= Flowering, FR= Fruiting, PI= Pod initiation, PD= Pod development, VG= Vegetative, RP= Reproductive, M= maturity, MI= Maturity initiation stages, FI= Flower initiation, Pg I=Peg initiation

In central India Azam Ali, (1984) studied the interaction between population and water stress in 4 populations of groundnut by estimating, transpiration, stomatal resistance (rs), boundary layer resistance (ra), vapour concentration difference between leaf and air (deltachi) and LAI and the frequency distributions of rs, ra, deltachi and seasonal changes in LAI when plotted to analyse the dependence of transpiration rate on each variable both per unit area of leaf surface (E1) and per unit land surface (Ee), for estimates of E1, both rs and deltachi were of similar importance, exerting a far greater influence than changes in ra. However, in terms of Ee, changes in LAI were far more important than in any other variable, particularly late in the season when water was scarce. The ability of this technique to describe temporal and spatial variations as well as the dominant environmental and physiological influences on transpiration may outweigh any small loss in accuracy of estimates.

In Eastern India at Bhubaneswar, the crop coefficient of groundnut cv. AK12-24, for use in estimation of crop Et during the dry season (November-March) using different irrigation cycles, the daily moisture use rate increased gradually and reached the peak value (4.10-4.94 mm) during 55 to 60 days. The crop coefficient values followed the same trend as that of crop Et, which were lower at the initial stage of growth (0.61-0.80), increased gradually and attained the maximum value of 0.94-1.33 towards the peak period of crop growth and declined thereafter. The crop coefficient value approached unity or slightly exceeded it during the maximum growth stage of the crop. Plants stressed at the early vegetative stage showed lowest crop coefficient value (0.61) at initial stage and the highest value (1.33) at peak crop growth stage, and witholding irrigation at an early stage (14 DAS) resulted in lesser evaporation of water from the soil surface (Kar *et al*., 2001).

Estimation of surface sensible and latent heat flux is the most important to appraise energy and mass exchanges among atmosphere, hydrosphere and biosphere and the surface energy fluxes were measured over irrigated groundnut during winter (dry) season using Bowen ratio (beta) micrometeorological method in a representative groundnut growing areas of eastern India, at Dhenkanal, Orissa by growing the crop with four irrigations based on phenological stages viz., (i) branching, (ii) pegging, (iii) pod development and (iv) seed filling and assessed what the crop stress was at those times to see if irrigation scheduling could be optimized further. The net radiation R_n varied from 393-437 to 555-612 W m^{-2} during two crop seasons. The soil heat flux (G) was higher (37-68 W m^{-2}) during initial and senescence growth stages as compared to peak crop growth stages (1.3-17.9 W m^{-2}). The latent heat flux (LE) showed apparent correspondence with the growth which varied between 250 and 434 W m^{-2} in different growth stages. The diurnal variation of Bowen ratio (beta) revealed that there was a peak in the morning (9.00-10.00 a.m.) followed by a sharp fall with the mean values varied between 0.24 and 0.28. The intercepted photosynthetic photon flux density or photosynthetically active radiation (IPAR) by the crop was measured and relationship between IPAR and leaf area index (LAI) was established with DAS, which will be useful in developing algorithm of crop simulation model for predicting LAI or IPAR. The stressed and non-stressed base lines were also developed by establishing relationship between canopy temperature and vapour pressure deficit (VPD). With the help of base line equation, $[(T_c\text{-}T_a) = -1.32VPD+2.513]$, crop water stress index (CWSI) was derived on canopy-air temperature data collected frequently throughout the growing season. The soil moisture depletion during the crop period when plotted with CWSI at different stages the values of CWSI varied between 0.45 and 0.64 just before the irrigations were applied and at two stages (branching and pegging), CWSI were much lower (0.46-0.49) than that of recommended CWSI (0.60) for irrigation scheduling. Therefore, more research is required to optimize the phenology based irrigation scheduling further in the region (Kar and Kumar, 2007).

Field data on pod yield and seasonal ET as influenced by irrigation schedules during the summer predicted that the pod initiation and development stage (70 d to harvest) was the most sensitive stage for moisture stress with a yield response factor of 2.10. Water stress during 10 to 40 d was beneficial in enhancing pod yield with a yield response factor of 2.10 (Ramachandrappa and Nanjappa, 1994).During winter at Rajendranagar, Hyderabad, groundnut cv. ICGS 44 irrigated to give moderate to severe ET deficits at various stages showed that reproductive stage (35-115 DAS) was the most sensitive to a reduction in water supply, whereas water stress in the vegetative stage (10-35 days) had the least effect (Reddy *et al.,* 1996). At Coimbatore, TN, during summer 1994, water stress in groundnuts cv. Co 2 and VRI 2 at flowering, pegging, pod development or pod maturation when compared water stress at pod development was most detrimental on yield (Velu, 1998).

In Western India, a lysimeter experiment on black calcareous vertic Inceptisol at Junagadh, two groundnut cultivars subjected to water stress from the seedling to flowering (24-48 DAE), flowering to pegging (40-60 DAE), pegging to pod development (55-75 DAE) or pod development to maturation (75-95 DAE) decreased pod yields compared with plants given normal irrigations however yield reductions were greatest with stress imposed during the period between pegging and pod development and lowest with stress imposed from pod development to maturation (Patel and Golakiya, 1988). Further lysimeter trials on Spanish bunch groundnuts cv. J11 and GG 2 revealed that water stress from pegging to pod development gave the lowest pod yields with increased leaf temperature (35°C) markedly lowering photosynthesis. In all stress treatments, GG 2 out yielded J 11 mainly due to lower fluctuations in leaf temperature, stomatal resistance and lower vegetative growth (Patel and Golakiya, 1993). Also in another lysimeter studies, groundnut subjected to soil moisture tensions (SMT) of 330, 530 or 730 mbar, maximum daily water consumption occurred at 50-80 and 50-65 days in groundnuts grown at the 2 lower and the highest SMT, respectively and increase in SMT decreased total DM yield, but increased unshelled nut yields (Vivekanandan and Gunasena, 1976).

The total dry matter at harvest had positive correlation with TE, leaflet size was negatively correlated with TE under drought stress, the N content in leaves at 80 DAP and the chlorophyll content in leaves during moisture stress (28 days after imposing stress) showed positive relationship with TE. The leaf temperature 28 days after imposition of moisture stress had significant negative relationship with TE under adequately irrigated and simulated drought treatments. The mineral ash content of leaves 80 DAS in Spanish cultivars (ICG 476, ICG 221, ICG 1697, ICGV 86031 and TAG 24) had significant positive correlation with

TE in simulated drought treatment (Babitha and Reddy, 2001). Sharma *et al*. (1987) studied the performance of two groundnut cv. under soil moisture stress during rainy season where number of gynophores and pods/plant, 100-seed wt, pod yield and shelling percentage were highest with two irrigations at 50 and 80 DAS and were lowest under rainfed conditions. Irrigation at 80 DAS was more effective than irrigation at 50 DAS. The moisture stress suppressed pod setting more in cv. M13 than in cv. M37. Oil content in seeds was not affected by moisture stress in both cultivars.

Studies on radiation and energy budgets over a cropped surface in the Sabarmati river basin, Gujarat, India by recording continuous data on temperature, humidity, wind speed and direction at 1 and 4 m on a 9-m tower, soil heat flux sensible and latent heat fluxes from March to August1997, a polynomial relationship between residual flux and biomass under different phenological phases of the crop was observed, a linear relationship was found between residual flux and plant height under different phenophases and the biomass of crops increased exponentially with increasing AE: PE ratio and a polynomial trend was observed in water deficit, biomass and height (Padmanabhamurty *et al*., 2001). A linear relationship for each month was observed in the AE: PE ratio parameterized for three months.

The water requirement of groundnut varies with the stages and is lowest from germination to flower formation and reaches maximum during pod formation. However, the utilization of available moisture is greatest during flowering and pod formation and the crop receiving adequate water during these stages only can give equal yield to the well watered crop. During these stages if stress is given and later on water supply is resumed only the vegetative growth is benefited not the reproductive growth of crop. Thus the period of maximum sensitivity to drought occurs between 50-80 DAS, the period of maximum flowering and vegetative growth. The groundnut production was directly proportional to light interception and to the ratio between water lost and the vapour pressure deficit from leaf to air. Root growth and development was favoured under limited water supply and high water demand. Leaf conductances to gas exchange were similar at different combinations of soil water content and atmospheric saturation deficit (Goncalves de Abreu, 1988).The groundnut cv. SB 11 grown at 3 levels of water stress applied at 4 growth stages, water stress of 0.8 (ratio of IW: CPE) applied at any growth stage reduced pod yield, Maximum pod yield obtainable (3.06 t/ha) was predicted to be obtained with 1131 mm irrigation water (Shinde and Pawar, 1982).

The water–yield relationship in groundnut when studied in Bhavanisagar under deficit irrigation, the yield response factor (k_y) ranges from 0.45 and 0.42 (normal irrigation) to 1.72 and 1.70 (full deficit irrigation) for summer and Rabi seasons, respectively and the pod formation and flowering stages were more sensitive to moisture stress and irrigation during these stages is more important to overcome the yield reduction in groundnut (Thiyagarajan *et al*., 2010). Response of groundnut cv. Robut 33-1 to drought stress imposed at (a) emergence to maturity, (b) emergence to peg initiation, (c) from the start of flowering to the start of seed growth, and (d) from the start of seed growth to maturity when studied during the post-rainy seasons, the amount of water applied during these phases varied and the greatest reduction in seed yield (28-96%) occurred when stress was imposed during (d)(Rao *et al*., 1985). Decreased irrigation during (b) increased pod yield relative to the fully irrigated control treatment by 13-19%. The evapotranspiration-yield relationships showed a strong interaction with timing of drought (Rao *et al*., 1985).

4. FACTORS INFLUENCING WATER DEFICIT STRESS

4.1. Heat Stress

Groundnut is an important crop of the semi-arid tropics where potential yields are frequently reduced by heat and water stress. Craufurd (2000) studied 8 groundnut genotypes varying in heat tolerance in controlled environments at high (40/28°C) and near-optimum (30/24° C) temperatures from 32 DAS to maturity where significant variation among genotypes in main stem leaf number and total flower number at 30/24° and 40/28° and rates of appearance were faster at 40/28° than at 30/24°. Days from sowing to first flowering varied among genotypes from 28 to 41 days and therefore the time of plants were exposed to high temperature relative to first flowering ranged from -4 to 9 days. Fruit number at 40/28° was linearly and negatively related to the time of first flowering relative to the onset of high temperature (r^2=0.93; n=7; $P < 0.001$), indicating that 'escape' was an important component of heat tolerance. Further the fruit number in all genotypes at 40/28°C was closely associated with the cumulative number of flowers that had opened between first flowering and 3 days after the onset of the high temperature regime (r^2=0.95; n=8; $P < 0.001$). Variation in fruit number was due both to the timing of flowering and the initial rate of flower production. The most sensitive stage of development to high temperature occurred around 3 days before flowers opened and hence, it was the timing of flowering, rather than heat tolerance or susceptibility that was the dominant attribute determining fruit number (Craufurd, 2000). The DM partitioning to stems, leaves and pods in groundnut cv. Robut 33-1 investigated at mean air temperature ranging 19-31°C and water stress growing plants at variable levels of saturation vapour pressure deficit, pod: shoot wt. ratio (PWR) was max. at 22°C and decreased from 0.28 to 0.04 as temperature increased to 31°C, mild water stress promoted peg and pod production and increased PWR (Ong, 1984).

Groundnut cv. Florunner subjected to drought and high temperature stress (28-30ºC) for periods of 20, 30, 40 or 50 d, and the seeds from these plants when separated into Jumbo, Medium and No. 1 market size categories, the soluble and total carbohydrate content in seed of Jumbo and Medium categories increased due to drought and temperature stress. The alpha -amino N content of the Jumbo category decreased while that of the No. 1 category increased following a 30-d stress exposure. Protein and oil content of all the categories were not affected after exposure to drought and temp stress. However, the protein and polypeptide profiles showed that a polypeptide with a MW of 70 000 and a pI between 6.2 and 7.0 increased with increasing periods of drought and temperature stress. Thus, Drought and temperature stresses increase accumulation and/or synthesis of carbohydrates and certain polypeptides may enhance *Aspergillus* invasion and aflatoxin production (Musingo *et al*., 1989).

Groundnut germplasm evaluated for heat- and drought-tolerance traits, genotypic differences in tolerance to temperature above 35°C and heat tolerance, indicated by membrane thermostability (in vitro leaf-disc method with leaf tissue) were observed (Ketring, 1986). The means to improvement of hydration maintenance of this crop under soil-moisture deficits have been sought through genotypic diversity in rooting traits and water-potential components. Genotypes differed in rooting habit and ability to maintain plant-water and water-potential, differences in rate of decrease in water-potential components, osmotic adjustment, and apoplastic water fraction indicating potential for improved heat and drought tolerance (Ketring, 1986). The heat tolerance of ten groundnut genotypes studied under irrigated and rain-fed conditions in the field evaluated on four dates between 23 June and 14 August using an electrolyte leakage technique which measures the thermostability of cellular membranes observed genotype x date interactions, and in general Pearl Early Runner, X 537B, Florunner and X 487A were the most heat tolerant and water stress resulted in increased heat tolerance among four of the five genotypes (Bennett and Hammond, 1982).

Differential canopy/ambient temperature was used by Schubert and Sanders, (1985) to calculate a stress degree day index (the sum of the numbers of °C by which canopy temperature exceeded ambient temperature) for scheduling irrigation in groundnut cv. Florunner at Yoakum, Texas and observed that the plots irrigated after 5-25 stress degree days (SDD) showed declined yield and linearly as SDD level increased. The most irrigated plot, 5 SDD, yielded 2.98 t/ha while 10, 15, 20, 25 SDD and the unirrigated control yielded 2.67, 2.57, 2.45, 1.70 and 1.51 t/ha, respectively. Increased water stress increased the proportion of small seeds (Schubert and Sanders, 1985). Babu *et al*. (1983) studied the mechanism of alleviating water stress by leaflet angle variation in groundnut cv. Tindivanam 2 and a simple method of measuring leaflet angle was devised. Radiation avoidance by leaf closure was exhibited to different degrees by water stressed and non-stressed plants and leaflets under continuous water stress had reduced areas and showed greater leaflet movement (leaf closure) compared to the amount of movement of leaflets on plants without water stress (Babu *et al*., 1983).

At Tirupati, India, Babitha *et al*. , (2006) screened several genotypes and found that Spanish genotype TIR 21 showed less reduction in Fv/ Fm ratio when exposed to 45°C (1.13% reduction) and 55°C (22% reduction), while the Virginia genotype TIR 34 maintained high Fv/ Fm ratio at temperature >50°C. Genotypes TIR 20 and JAL 31 showed a higher reduction of 84 and 82% respectively in Fv/ Fm ratio when exposed to 55°C. However, these genotypes showed more reduction (62%) in Fv/ Fm ratio at 55°C. Virginia groundnut CSMG 84-1 showed low membrane injury (34%). The genotypes TIR 21, TIR 34, JAL 07 and CSMG 84-1 are better under higher temperatures and hence can be recommended for the specified situation in order to increase the yield potential under high temperature conditions (Babitha, 2006).

4.2. Root Growth and Water Extraction

The groundnut is deep-rooted plant and its root can penetrate a depth ranging from 1.5-2.0 m, but rarely goes beyond 1 m. The groundnut roots extract most of the moisture from upper layer (36% in 0-30 cm depth and only 7% in the region of 120-150 cm depth). However, under moisture stress the crop extract water from greater depth. The root system is normally concentrated at a depth of 5 to 35 cm, and spread is confined to a radius of 12-14 cm. The spreading types are generally more vigorous than bunch types. Most of the roots are in shallower region having root densities of 1.5 cm cm^{-3} in 0-30 cm zone and only 0.1-0.4 cm cm^{-3} at higher depth. The epidermis sloughs off as the root extends destroying the basis for root-hair production resulting in no root hairs. However, Meisner and Karnok (1991) observed the existence of both lateral (0.3 mm) and rosette type (4 mm) root hairs on groundnut root under varying soil and soil-water conditions. In some wild species the hypocotyl and root may be modified to form tubers. Tap roots may vary from a few millimeters in diameter in annual species to 10 cm in perennial species.

Meisner (1991) studied groundnut root growth under 30 d water stress period beginning from 20, 50, 80 and 110 DAS using two non-destructive methods, a rhizotron and minirhizotron where root growth was reduced significantly by stress during 20-50 DAS in the rhizotron but was not affected by stress in the minirhizotron. Groundnut roots grew rapidly, representing a considerable portion of the C partitioned early in the growing season and by 80 DAS, >80% of the total root system was established, while flowering, peg and foliage production had peaked. Yield was significantly reduced by stress treatments 50-80 and 80-110 DAS in both studies. Most of the C partitioned after 80 DAS went into pod formation and pod filling, thus explaining yield reductions during the 50-80 and 80-110 DAS, stress treatments. Two types of root hairs were observed and quantified: rosette-type hairs surrounding lateral initiates emerging from primary roots and shorter, more profuse hairs on root lengths. While root hairs were not significantly affected by water stress, soil type and rooting depth significantly affected hair occurrance. Drought tolerance contributing factors in groundnuts was: an extensive root system established before maximum leaf area and consequent peak transpirational demand was reached; flowering, delayed when under water stress, recurred once stress was relieved; water storage cells in the abaxial side of the leaves provided a source of water when transpiration was greater than the roots to extract soil moisture; leaf folding during stress reduced solar incidence; and transpiration was regulated by high stomatal resistance during stress (Meisner, 1991).

The maintenance of higher leaf-water status, by few genotypes of groundnut during soil water deficits is due to greater density of roots in the lower depth of the soil profile, however, this does not account for the major variation in the HI associated with drought (Matthews *et al*., 1988a; De Vries *et al*., 1989). Meisner and Karnok (1992) in a Rhizotron study observed reduction in root growth in upper 40 cm depth during moisture stress from 20 to 50 DAS compared to well watered control, but the root growth was not affected in the lower depth due to adequate moisture. In groundnut more than 60% of the root growth is established by 50 DAS and 80% by 80 DAS, water stress imposed after 50 DAP reduces only root growth in upper depths where root density is highest and soil moisture readily extracted. NCAc 17090 is an efficient in extracting water from the top 40 cm of soil and also got greater WUE (ICRISAT, 1986).

A rainfed and two irrigated treatments of groundnut in Malaysia when compared in terms of yield and water use by taking rainfed treatment (A) as the control, (B) irrigation at 7-d intervals, (C) irrigations made whenever readings of tensiometers at the 20-cm soil depth were equal to or less than -30 kPa, where there was no significant difference in yield between the two irrigation treatments. The average groundnut yields obtained from treatments A, B and C were 1.9, 3.1 and 3.2 t ha^{-1}, respectively. The crop in the rainfed plot was exposed to water stress during its flowering stage owing to limited rainfall. The total water use of groundnut for a 30-d period beginning 30 d after planting (DAP) was 64.5, 124.5 and 152 mm for rainfed, irrigated B and irrigated C, respectively, and the low water use in the rainfed plot resulted in a low yield. As indicated by a continuously decreasing value of the soil water hydraulic head (< -70 kPa) in the rainfed plot from 35-54 DAP, the soil at 20 cm depth was continuously dry. With the yield response factor (ky) during flowering stage being 0.74, therefore the decrease in groundnut yield due to water deficit was relatively large (Ahmad *et al*., 1999).

The effect of water deficit on phenology (vegetative and reproductive growth) of two groundnut cultivars (Tatu and PI 165317) reveals that, water stress reduced both root and shoot dry matter production, and root/shoot ratio and flower production, but number of secondary and tertiary ramifications was not affected, the peg and fruits were reduced by water stress affecting both yield and HI (Oliveira *et al.,* 2004). The soil moisture extraction patterns and root growth parameters when examined in five groundnut cultivars under various levels of soil water stress variation in soil moisture extraction, root length density and total dry matter production were observed among the cultivars and the differences in water extraction in deeper soil profiles were related to the variation in root length density and the cv. ICGV 86031 and TMV 2 NLM were efficient in soil water extraction and suffered least losses (17-18%) in total dry matter production under moisture stress (Reddy *et al.*, 1999).

Among many factors that are associated with drought tolerance in legume crops, root traits have been considered to be the most important attributes enabling the plant to mine water efficiently from deeper soil layer under dry environments. Most of the methods used to evaluate roots are time consuming that provide valuable information about the root morphology but they do not reflect the dynamic characteristics of roots and root systems. Also the morphological variation in roots which has specific significance of adaptation, their functional aspects involving direct water uptake and their related kinetics are equally important. Vadez *et al*. (2007) reviewed root structure, root hydraulics, and modes of water and nutrient absorption, mainly focusing on how inter- and intra-specific variations in these aspects can modify the way roots respond to a range of abiotic stresses and summarized the contribution of roots to stress tolerance including research on the role of roots in near isogenic lines containing terminal drought tolerance quantitative trait loci, and on the role of DREB1A gene in root growth in transgenic groundnut under drought conditions. Chemical and hydraulic signalling between roots and shoots, and its role in drought and salt tolerance also mentioned (Vadez *et al*., 2007). Rooting depths were of the order of 200 cm with a density of 1.5 cm/cm^3 in the 0-30 cm zone and 0.1 to 0.40 cm/cm^3 at greater depths. Tensiometers and neutron meters showed that water extraction continued during prolonged drought at depths below the shallow irrigated surface soil layer (Hammond *et al*., 1978).Considerable amount of genetic variability with respect to root traits involving length, dry weight and root length density (RLD) were observed and a large lysimetric system has been developed at ICRISAT to make progress in this direction. In groundnut, DREB1A triggers native genes that might be involved in root development. In this review, the progress made so far on roots in legume crops has been elucidated which might explore possibilities of breeding genotypes to inherit efficient root system in legumes (Vadez *et al*, 2008).

In a root block study in groundnut at DGR (DGR, 2010), the primary root length (cm) was directly associated with secondary root length (r=0.85**), root weight density between 61-75 cm (r= 0.41**), total biomass (r=0.21*) and inversely with degree of leaf folding (r =-0.19), and primary root length seems to be a desirable trait to increase biomass productivity under rain-dependent condition. The secondary root length was directly associated with secondary dense root length (r= 0.51**), root volume (r=0.35**), root weight density (r= 0.53**) in deeper soil layers, total biomass (r = 0.37**) and inversely with degree of leaf folding (r =-0.24*) and higher secondary root length seems to be a desirable trait in groundnut. Secondary dense root length (cm) was positively associated with root volume (r=0.52**), root weight density (r= 0.51**), total biomass (r=0.44**) and inversely with degree of leaf folding. Root volume was directly associated with number of branches (r=0.28*), root weight density in upper soil layers (r= 0.83**), shoot weight (r= 0.46**), total biomass (r=0.52**) and root shoot ratio (r=0.41**) but non-significant with degree of leaf folding. These desirable root traits associated with drought tolerance need to be utilised for developing water use efficient groundnut.

Soil compaction makes the soil denser, decreases permeability of gas and water exchange as well as alterations in thermal relations, and increases mechanical strength of the soil. Compacted soil can restrict normal root development. Simulations of the root restricting layers in a greenhouse are necessary to develop a mechanism to alleviate soil compaction problems in these soils. Duruoha *et al*. (2008) in an experiment, in Alabama, USA, assessed groundnut root volume and root dry matter in three distinct bulk densities (1.2, 1.4, and 1.6 g cm^{-3}) and two levels of soil water content (70 and 90% of FC) in a sandy loam soil (Plinthic Kandiudults) where groundnut yield responded favourably to subsurface compaction in the presence of high mechanical impedance clearly indicating the ability of its root to penetrate the hardpan with less stress. The root volume was not affected by the increase in soil bulk density and this mechanical impedance increased root volume when roots penetrated the barrier with less energy. Root growth below the compacted layer (hardpan), was impaired by the imposed barrier. This stress made it impossible for roots to grow well even in the presence of optimum soil water content. Generally, soil water content of 70% FC ($P<0.0001$) enhanced greater root proliferation. Nonetheless, soil water content of 90% FC in some occasions proved better for root growth. The mechanical impedance is not a good indicator for measuring root growth restriction in greenhouse and future research required using more levels of water to determine the lowest soil water level, which can inhibit plant growth (Duruoha *et al*., 2008).

4.3. Water Use Efficiency

The water use efficiency (WUE) is g of total dry matter produced kg^{-1} water used. The transpiration efficiency of the leaf is the ratio of CO_2 assimilation rate to transpiration rate. The quantity of water transpired is proportional to the percentage of soil covered by the crop (KCOV), evaporative demand (EVPAN) and potential transpiration (CROPET) is estimated as CROPET = KCOV*KM*KCROP*EVPAN, where KCROP is equivalent of a crop coefficient. For well irrigated groundnut crop it is estimated as: KCROP=Crop's water requirement/ standardized class A EVPAN (Dan cette, 1981). The actual water used (E_t) from emergence onwards increased to potential use evapotranspiration (E_0) until both become equal about midway when canopy has closed cover and remains equal until harvest. The ICRISAT developed a technique for measuring WUE, partitioning of dry matter to pod and efficient root systems which was successfully used in groundnut by Nageswara Rao *et al*. (1985) who also computed the seasonal evapotranspiration using the water balance equation:

$$ET = (M_i - M_f) + (I + P) - (R + D)$$

where ET is evapotranspiration, M_i is initial moisture in 0 to 127 cm profile, M_f is final moisture in 0 to 127 cm profile, I is irrigation, P is precipitation, R is run-off, D is deep drainage (deeper than 127 cm) considered negligible.

The WUE was 19-68 kg pods/cm of water depending on the stage at which the crop was exposed to moisture stress (Raju *et al*., 1981). In Junagadh, highest water use (84 cm) and benefit: cost ratio (2.42) were obtained under no moisture stress, but maximum water-use efficiency (WUE) was achieved under water stress imposed at flowering stage. Among the genotypes GG 6 recorded higher water-use efficiency (WUE) and benefit: cost ratio (Vaghasia *et al*., 2010a and 2010b). In a multilocation trial, the WUE was high 3.71 g kg^{-1} in Virginia type and low 2.46 g kg^{-1} in Spanish type groundnut (Wright *et al*., 1988). In Maharashtra the WUE was highest in (5.23 kg ha-1 mm) groundnuts with irrigation at 0.5 IW: CPE 0-40 d after sowing and 0.75 IW: CPE thereafter (Patil and Gangavane, 1990). Irrigation based on stress day index at Bhubaneswar, had the highest water consumptive use (WCU) and water requirement. WCU and water requirement were lowest when moisture stress was imposed at pod development stage. The WUE was highest in plants stressed at pod development stage and lowest in plants stressed at peg penetration stage. Irrespective of treatment, the extraction of soil moisture decreased with the increase in soil profile depth (Kar *et al*., 2002).

A field method for evaluating the sensitivity of groundnut genotypes under various patterns of drought using line source sprinkler technique was developed by ICRISAT (Singh *et al*., 1991) where water deficit (W_D) is estimated using the amount of water applied during the period of drought and the cumulative class `A' pan evaporation for the same period as: W_D=100 x (E -I/E), Where W_D is water deficient %, E is CPE for the period of drought and I is cumulative irrigation applied for the period of drought.

Collino (2000) compared the water extraction capability and WUE of two Argentinian groundnut varieties Florman INTA (a drought-sensitive) and Manfredi 393 INTA (a drought-tolerant) at two different water supply regimes (irrigated between 47-113 DAS, and no water) by measured soil water contents, canopy temperature, dry matter and root length density (RLD) periodically during the drought period, and calculating the water use (WU), stress degree days (SDD), extraction front velocity (EFV), uptake coefficient, shoot and pod WUE corrected (WUEc) by vapour pressure deficit, and the soil resistance, where Manfredi 393 INTA had a higher WU than Florman INTA in both irrigated (IRR) and water-stressed (WS) environment mainly due to higher transpiration rate as demonstrated by SDD time course values and higher uptake coefficient values. However, the EFV from lineal and logistic fitted models showed a similar pattern for both varieties. Uptake coefficient differences between varieties were not associated with RLD indicating that it was not useful as an indicator of the genotypic ability to extract soil water. Florman INTA possessed higher WUEc than Manfredi 393 INTA in both IRR and WS treatments. Both varieties showed similar values under the irrigated regime because the higher WU on Manfredi 393 INTA was compensated for a higher pod production due to an enhanced partitioning of assimilates to pods, but under WS regime, pod WUEc was significantly reduced in both varieties. The mechanical impedance in the soil upper layer contributed to this reduction, and although critical soil resistance was similar for the two varieties, its effect was remarkable on Florman INTA due to a delay in the onset of the beginning pod stage and non-synchronous reproductive development.

4.4. Carbon Isotope Discrimination and its Relationship with WUE and SLA

The groundnut plant, during carbon accumulation, discriminates against ^{13}C which changes the composition of isotopes of CO_2 the $^{13}C/^{12}C$ ratio in dry matter (Hubick *et al*., 1986). Carbon isotope discrimination (CID) of plant dry matter is linearly related in a negative manner to leaf transpiration efficiency via Pi/Pa, the ratio of intercellular CO_2 pressure Pi, to ambient CO_2 pressure Pa (Hubick *et al*., 1988). There is a strong negative correlation between transpiration efficiency (the ratio of dry matter produced to water used, W) and carbon isotope discrimination, Δ (Hubick, 1990) and also between Δ and total dry matter (Wright *et al*., 1988). The discrimination against ^{13}C (Δ) in leaf dry matter is calculated as:

$$\Delta = (\delta a - \delta p) / (1 + \delta p)$$

Where, δa and δp being the isotope composition of the air and plant materials, respectively relative to PDB (Pee Dee Bele minite).

A high heritability of Δ and its strong relationship with W indicate that breeding programme which includes selection for W based on differences in Δ could lead to increase dry matter production and yield of groundnut in water limiting environments. Thus measurement of Δ may prove a useful trait for selecting cultivars with improved W and total dry matter yield. In a mini-lysimeters study the WUE, ranged 1.81 in Chico to 3.15 g kg^{-1} in Tifton -8, was negatively correlated with Δ (19.1 to 21.8%) and thus Δ is a useful trait for selecting groundnut genotypes with improved WUE under drought conditions in the field (Wright *et al*, 1994). A strong negative relationship also existed between WUE and SLA (cm^3

g^{-1}) and between Δ and SLA, indicating that genotypes with thicker leaves had greater WUE. Significant correlations amongst WUE, CID in leaf and SLA suggested that CID and SLA could be used to identify genotypes with high WUE (Rao *et al*, 1994). SLA could therefore be used as a rapid and inexpensive selection index for high W where mass spectrometry facilities are not available.

Nageswar Rao *et al*. (1993) reported that in groundnut the WUE was 1.38-2.5 g/kg and were inversely related to discrimination against $^{13}CO_2$ fixed in leaves (DELTA) in 8 of the 10 genotypes, but WUE and transpiration were not significantly correlated. The CGR were negatively related to DELTA under irrigated conditions, but not under drought with CGR value 12-17 g/m^2 per d with irrigation and 2-8 g/m^2 in stressed crops. Partitioning of DM to pods in drought conditions ranged from 0.56 in cv. ICGV 86707 to >0.95 in 3 early maturing genotypes.

Jayalakshmi, *et al*. (2002) studied CID in 21 F_1 hybrids of groundnut in Andhra Pradesh during the post rainy season observed lower values of CID in TMV2-NLM, ICG 2716, Tirupati 1 and ICGV 86031, highest significant heterosis in ICG 2716 x TAG 24 and positive heterosis over better parent in TAG 24 x TMV2-NLM. The ribulose-1, 5-bisphosphate carboxylase-oxygenase (Rubisco) content increase under water deficit and top leaves had a higher Rubisco content and lower DELTA, than bottom leaves (Rao *et al*, 1995). Cultivar x leaf position interaction observed for DELTA and Rubisco, indicate the importance of leaf position in selecting for WUE, using leaf traits in groundnut. Rubisco content and DELTA were negatively related ($r^2 = 0.65$, $P<0.01$). There is a positive correlation between Rubisco content and leaf weight per unit leaf area (rhoL) in the upper leaves ($r^2 = 0.60$, $P<0.01$). And the basis of genotypic variation in DELTA was mostly (>60%) attributable to Rubisco content. In view of the leaf positional effects on DELTA and Rubisco, the upper leaves in the canopy should be used for selecting genotypes for W based on leaf traits like rhoL or DELTA.

Under adequately irrigated and simulated drought treatments at Tirupati, Andhra Pradesh with 20 groundnut genotypes differing in their transpiration efficiency and repeated with 7 genotypes in the second season wher SLA and CID exhibited significant positive relationships indicating that SLA can be utilised as a surrogate to CID (Asalatha, *et al*., 1999). Further SLA was negatively related to transpiration efficiency, while it was positively related to partitioning, suggesting that selection for low SLA might result in production of more dry matter with minimal influence on pod weight (Asalatha *et al* 1999). The mineral ash and total chlorophyll contents of leaves were strongly correlated with SLA and due to the simplicity in measurement these have merit considering screening tools in selection and breeding programmes for higher WUE under limited water environments Reddy, *et al*. (2000).

Krishnamurthy *et al*. (2007) evaluated the variation for Transpiration efficiency (TE) in a set of 318 recombinant inbred lines (RILs) of groundnut at F_8 generation, derived from a cross between a high TE (ICGV 86031) and a low TE (TAG 24) parent, and the value of SLA, SPAD chlorophyll meter readings (SCMR) and carbon isotope discrimination (Delta ^{13}C) as surrogates of TE were measured (on the dried tissue after harvest) and the study reveals that overall distribution of TE among the RILs indicated that TE, governed by dominant and additive genes, was negatively associated with SLA after the completion of stress treatment (r^2=0.15) and Delta ^{13}C in leaves (r^2=0.13) positively associated with SCMR during stress (r^2=0.17). Although the heritability of SCMR was relatively higher than that of TE, the stress-dependence of the relationship with TE, and the poor regression coefficients (r^2) with that RIL population, do not confer that these surrogates are adequately robust enough in that population (Krishnamurthy, *et al*., 2007). Chuni Lal *et al.* (2009) evaluated 9 groundnut genotypes to investigate the influence of water stress on some phenological, morpho-physiological, and yield traits and found that water saturation deficit (WSD) and epicuticular wax load (EWL) increased in response to water stress and age of the crop, while SLA decreased with water stress and age of the crop. Though, the correlations of WSD, EWL, and SLA with yield traits were fairly weak, WSD in the early stage was positively associated with pod yield and EWL in the early stage was negatively associated with HI under stress. Genotypes that accumulated flowers sooner after initiation showed less yield reduction and the negative association between HI under stress and its reduction deems HI under moisture stress an important criterion of selection for drought tolerance in groundnut (Chuni Lal *et al*., 2009).

The desirable traits such as WUE, partitioning of dry matter to pods and efficient root systems vary with genotypes and are heritable. A time-integrated approach based on stable isotope ratios of carbon and oxygen (Delta ^{13}C/Delta ^{18}O) were described by Bindumadhava *et al*. (2005) using groundnut (NCAC 17090, VRI 4, ICGS 11 and Sen Nghean) genotypes to identify crop genotypes with high mesophyll capacity for carbon assimilation as it has specific advantage in crop improvement, since such genotypes besides sustaining productivity under water-limited conditions can also save substantial amounts of irrigation water, this approach would provide a strong impetus to plant breeding efforts with assured success to improve productivity. Experimental evidence is presented to show that the ^{18}O enrichment in the leaf biomass and the mean (time-averaged) transpiration rate are positively correlated in groundnut genotypes (Sheshshayee, 2005). The relationship between oxygen isotope enrichment and stomatal conductance (g_s) was determined by altering g_s through ABA (abscisic acid), and subsequently using contrasting genotypes of groundnut. The Peclet model for the ^{18}O enrichment of leaf water relative to the source water is able to predict the mean observed values well, while it cannot reproduce the full range of measured isotopic values. As all the genotypes of both species experienced similar environmental conditions, the differences in transpiration rate could mostly be dependent on intrinsic g_s and hence, Delta ^{18}O of leaf biomass can be used as an effective surrogate for mean transpiration rate, further, at a given vapour pressure difference, Delta ^{18}O can serve as a measure of stomatal conductance as well (Sheshshayee, 2005).

4.5. Gene Action, Genotype and Environment Interactions

In an investigation to determine the gene action controlling the inheritance of SCMR and SLA in two crosses, ICG 7243 x ICG 9418 and ICG 6766 x Chico, and their reciprocals, 6 generations of each cross (P1, P2, F1, F2, BC1P1, and BC1P2) were evaluated for SCMR and SLA at two stages of the crop growth viz., 60 and 80 days after sowing (DAS) by Upadhyaya, (2011) where for SCMR at 80 DAS, additive effects were important in both the crosses whereas predominance of dominance effects with duplicate epistasis was observed for SCMR at 60 DAS and SLA at both stages in both the crosses. Predominance of additive effect for SCMR at 80 DAS suggested effective selection could be practiced even in early generations whereas for SCMR at 60 DAS and SLA at both stages in both crosses, it would be better to defer selection to later generations. Further, recording of SCMR and SLA should be done between 60 and 80 DAS for screening the germplasm lines for drought tolerance (Upadhyaya, 2011).

The genotype x environment (G x E) interaction for the relationship between SLA and DELTA were examined by Rao and Wright, (1994) in four groundnut genotypes (Chico, McCubbin, Shulamit and Tifton 8) with contrasting carbon isotope discriminating characteristics where the values of DELTA and SLA were significantly influenced by the location, genotype and irrigation treatments, but genotype x location interaction effects on the relationship between DELTA and SLA were not observed, however positive relationship between SLA and DELTA was maintained when data were combined over sites and treatments ($r^2 = 0.87$, $P < 0.01$). Further the SLA was negatively correlated with nitrogen content per unit leaf area (SLN) which in turn was negatively correlated with DELTA. The genotypic and environmental variation in transpiration efficiency (W) and its correlation with CID (DELTA) further investigated by Wright *et al.* (1993) in 7 groundnut cultivars and *Arachis villosa* and *A. glabrata* where the W was highly correlated with DELTA in leaves, SLA and leaf thickness and G x E interaction for W, DELTA and SLA was very low, while heritability of DELTA was high, indicating that these traits could be used for selecting high W in groundnut breeding programmes.

In Botswana, the breeding lines selected for adaptation to drought stress under rainfed tested in multilocation trials to compare their performance with that of locally grown cultivars showed largest variation across locations and years due to the environment, with minimal variation due to genotype and G x E interaction. All genotypes responded to changes in environmental conditions, with an indication that seasonal rainfall patterns were important in determining genotypic performance. Selection for drought adaptation under rainfed conditions, though commonly practiced, could be misleading, since it may not reflect the ability of the genotype if the stress occurs during the critical stages of plant development. More efficient selection would require simulated drought conditions, and the use of other indirect selection methods that give a good indication of drought adaptation (Maphanyane *et al*., 1994).

Molecular markers and genetic linkage maps are pre-requisites for molecular breeding in any crop species. In groundnut, an amphidiploid (4X) species, not a single genetic map is available based on a mapping population derived from cultivated genotypes. In order to develop a genetic linkage map for tetraploid cultivated groundnut, a total of 1,145 microsatellite or simple sequence repeat (SSR) markers available in public domain as well as unpublished markers from several sources were screened by Varshney *et al,* (2009) on two genotypes, TAG 24 and ICGV 86031 that are parents of a recombinant inbred line mapping population and reported the construction of the first genetic map for cultivated groundnut and demonstrated its utility for molecular mapping of QTLs controlling drought tolerance related traits as well as establishing relationships with diploid AA genome of groundnut and model legume genome species. As a result, 144 (12.6%) polymorphic markers were identified and these amplified a total of 150 loci. A total of 135 SSR loci could be mapped into 22 linkage groups (LGs). While six LGs had only two SSR loci, the other LGs contained 3 (LG_AhXV) to 15 (LG_AhVIII) loci. As the mapping population used for developing the genetic map segregates for drought tolerance traits, phenotyping data obtained for transpiration, TE, SLA and SCMR for 2 years when analyzed together with genotyping data, the phenotypic variation explained by these QTLs was in the range of 3.5-14.1% and 2-5 QTLs for each trait were identified (Varshney *et al*, 2009). In addition, alignment of two linkage groups (LG_AhIII and LG_AhVI) of the developed genetic map was shown with available genetic maps of AA diploid genome of groundnut and Lotus and Medicago (Varshney *et al*, 2009). A biochemical test measuring pH of 0.1M EDTA leaf extract was developed by Dwivedi *et al.* (1986c) taking 22 cultivars and 3 wild species of *Arachis* grown under moisture stress and cultivars showing less than 2.77 p. 100 decline in the pH of leaves extract in EDTA, at -10 bar water stress were considered as drought resistant. A significant correlation co-efficient of r = 0.706 between percent decline in the pH of leaves extract and pod yield and r = 0.893 between percent decline in the pH of leaves extract and pH water deficit index (PWDI) were noted. The correlations of this test with drought resistance capacity of cultivars were found to be superior to that of proline accumulation, stomatal resistance, transpiration rate and saturated water deficit.

4.6 Minerals and Salinity

In field trials during summer season two groundnut cultivars subjected to a water stress of -14 bar soil water potential during the early vegetative, late vegetative, flowering, pegging or pod development stages gave average pod yields of 2.0, 1.8, 1.6, 1.3 and 1.0 t/ha, respectively, compared with 2.39 t in crops without water stress. Water stress increased P, K, Ca and Mg contents in both haulms and pods, the N contents increased in pods but decreased in haulms with water stress. Cv. TG 17 gave higher yields than cv. GAUG 1 both with and without water stress (Parmar *et al.*, 1989).

The influence of several pod characteristics on Ca accumulation and Ca concentration in groundnut fruit was studied in 8 genotypes with diverse fruit characteristics for 2 seasons under 5 water stress treatments (drought at 20-50, 50-80, 80-110, 110-140 DAS and an irrigated control) by Kvien *et al.* (1988) where 80-110 DAS drought period had the greatest negative impact on seed Ca concentration. Total Ca accumulation in the pod (hull + seed) was positively correlated (0.97) with pod surface area and five characteristics days required to mature a pod, specific hull wt, pod surface area, hull thickness and pod volume significantly influenced seed and hull Ca concentration. These characteristics were under genetic control, but their absolute value was modified by water stress. Thin light hulls and long pod maturity periods promoted high Ca concentration in the seed and thick dense hulls, short maturity periods and small pod vol. promoted high Ca concentration in the hull (Kvien *et al.*, 1988).

Potassium regulates water in plants, and is important under rainfed or moisture stress conditions have much greater importance than irrigated agriculture. Its application reduced the incidence of tikka disease of groundnut and improves resistance to environmental stresses by osmoregulation, proline accumulation, induction of phenolics, betaines, and phytoalaxins and by morpho-phenological changes in plants. Potassium besides increasing crop yields, seems to have the greatest effect on oil biosynthesis which often results in higher oil yields, its effect is more pronounced at higher rate of application. The current interest in the role of polyunsaturated fatty acids in the heart disease and cancer justifies studies of the effect of fertilizers on the fatty acid composition of vegetable oils. The relative concentrations of the various fatty acids are also important from an economic standpoint because they affect the susceptibility of the oil to flavour reversion and to oxidative rancidity. It is possible to increase production if we go by the attainable yields demonstrated by adoption of the full package of improved practices and if these best management practices can be adopted by the farmers on millions of hectares. Vertical growth in productivity demand higher inputs. Besides increasing fertilizer use, particularly potash, it would also be necessary to improve input use efficiency through proper harvesting of the interaction effects of plant nutrients by balanced fertilizer application (Tiwari, 2005).

Patel and Padalia (1980) studied the soil-water potential on nutrient uptake by groundnut with progressive increase in sequences of soil moisture stress from 1/3 to 5, 10 and 14 bar the root dry wt., haulm and pod yields and N, P, K, Ca, Mg, Fe, Mn and Zn uptake by different parts of plants decreased. Nutrient use efficiency was maximum with 1/3 bar and decreased with increase in soil moisture stress. A single stress of about 10 bar during flowering, pegging and pod development stages significantly decreased the nutrient uptake and shoot and pod yields compared to 1/3 bar. When continuous water was supplied by upward flow from the bottom of the pot keeping the surface soil dry (D), there was excessive vegetative growth yielding less pods; however, nutrient uptake was comparable with 1/3 bar. Pots irrigated according to plant requirement (3 bar) gave intermediate yields of pods and shoots and nutrient uptake ranged between those of 1/3 bar and D condition. Nutrient uptake with saturation (0 bar) treatment was significantly lower than that at 1/3 bar (Patel and Padalia, 1980).

In Oxisol during rabi (winter) at Wakawali, Maharashtra, groundnuts irrigated to 40 or 60 mm depth or at IW:CPE ratios of 0.50, 0.75 or 1.00 and given no fertilizers, 25 kg N + 50 kg P_2O_5 or 50 kg N + 50 kg P_2O_5/ha, where, N uptake in seeds, shell and haulm decreased by 31, 28 and 29% with irrigation at IW:CPE ratio of 0.5, while P uptake was decreased by 35, 45 and 36%, respectively and N and P uptakes were highest with 50 kg N + 50 kg P_2O_5 compared with irrigating at IW:CPE ratio 1.00 (Patil and Kadam , 1993).

In a study, AtNHX1, a vacuolar type Na^+/H^+ antiporter gene driven by 35S promoter was introduced into groundnut using Agrobacterium tumefaciens transformation system. The stable integration of the AtNHX1 gene was confirmed by polymerase chain reaction (PCR) and southern blot analysis. It was found that transgenic plants having AtNHX1 gene are more resistant to high concentration of salt and water deprivation than the wild type plants. Salt and proline level in the leaves of the transgenic plants were also much higher than that of wild type plants. The results showed that overexpression of AtNHX1 gene not only improved salt tolerance but also drought tolerance in transgenic groundnut. Our results suggest that these plants could be cultivated in salt and drought-affected soils (Asif *et al*., 2011).

5. MANAGEMENT OPTIONS AND STRATEGIES

In most groundnut growing areas of the world, shortage of water is caused by uneven distribution of rains, gaps between rain events and field water losses rather than from low seasonal or annual rainfall totals. The groundnut requires 400-450 mm of water, however in sandy soil the water requirement goes to 600-700 mm, but the distinction between *Kharif* and Rabi are not very clear. The water requirement of groundnut varies with the stages and is lowest from germination to flower formation and reaches maximum during pod formation. However, the utilization of available moisture is greatest during flowering and pod formation and the crop receiving adequate water during these stages only can give equal yield to the well watered crop. During these stages if stress is given and later on water supply is resumed only the vegetative growth is benefited not the reproductive growth of crop. However, the period of maximum sensitivity to drought occurs between 50-80 DAS, the period of maximum flowering and vegetative growth. Under water scarcity condition, plant extractable soil water depletion of more than 45% of available soil water (ASW) must be avoided even during non-critical growth stages to obtain high WUE and net return (Panda and Behera, 2005).

The levels of irrigation have a major effect on the amount of water consumed, and it is 300-350 mm in non irrigated field and 500-600 mm in field irrigated at 40-60% moisture availability at 30 cm depth. The irrigation given to a depth of 100 mm showed highest yield. More than 70% of the kharif groundnut in India is rainfed where one or two life saving irrigations are required. The rabi groundnut is grown either in residual moisture or with 3-9 irrigations depending upon the soil and climate. But the summer groundnut is mainly irrigated and 6-15 irrigations are required depending upon the soil types, locations and varieties. The use of drip saves 30-50% water and produces up to 20-30% more yield than flood irrigation (Singh *et al*, 2000; 2001). Most of the scheduling of irrigation is based on the depletion of available soil moisture, IW/CPE ratio and maximum yield is obtained at IW/CPE ratio 0.6-0.9, but in practice mostly the frequency of interval is opted.

In last four decades enough progress has been made on drought research in groundnut and application of knowledge into practice in a systematic manner can lead to significant gains in yield and yield stability of the world's groundnut production, with transferable technology to help farmers of arid and semi-arid regions. Increasing soil moisture storage by soil profile management and nutrient management for quick recovery from drought are some of the areas that need to be explored further (Reddy *et al.,* 2003). The various water management practices and their principles are discussed here separately.

5.1. Evapotranspiration and Irrigation Scheduling

Water use by groundnut in different cropping seasons in different parts of the world varies between 250 mm under rain-fed conditions to 831 mm under irrigated conditions. The total water use of a groundnut crop may be affected by scheduling irrigations based on requirements at the various growth stages. The evapotranspiration (ET) in groundnut varies with crop duration and is nearly 400 mm for 100-110 days crop, 500-600 mm in 120-140 days crop and about 700 mm in 150 days crops. However, the evaporation from the bare soil is 350 mm for the same period. Further, the yield varied with soil types, it is maximum with 75% available soil moisture (ASM) in red loamy soils and only at 50% ASM in black loams, however, in general, the maximum yields are obtained under 50-60% FC and -0.3 to -0.4 bars of water tension (Reddy, 1988). The field experiment during rabi season has shown that crop coefficient (Kc) value was low initially, increased linearly with advancement of crop growth, attained peak value at reproductive growth period from flowering through pod initiation, and decreased towards maturity which is useful in developing a methodology for the determination of periodic and peak irrigation requirements (Hemalatha and Rao, 2006). The crop coefficient curve facilitates prediction of groundnut ET, the seasonal net, gross and peak irrigation requirement of groundnut were determined.

The scheduling of irrigation is based on the depletion of available soil moisture IW/CPE ratio. Using non-weighing lysimeters, a value of 1 times pan evaporation for the area covered by the canopy was determined to be an appropriate rate for the groundnut production of unstressed plants. The irrigation schedule recommended at various places is given in Table 3.

Table 3. Irrigation scheduling in groundnut at various locations

SN	Groundnut varieties	Soil type and Places	Critical stages of water stress and irrigations schedule	Conditions	References
1	TMV 2	Sandy loam soils AP, India	Supply adequate water during moisture-sensitive FL & PD by scheduling irrigation at 4 growth stages	In summer, moderate stress at VG and maturity stages, produced optimum yield (2.82 t/ha) and WUE (7.73 kg ha^{-1} mm^{-1})	Reddy and Reddy, 1993
2	GAUG-1	Medium black soil at Junagadh	Irrigations at 7-11 intervals	40 kg K2O/ha	Shahid Umar *et al.*, 1997
3	GG 2	Medium black soil at Junagadh	13 irrigations	Transient moisture-deficit stress during vegetative phase for 25 days, followed by weekly irrigations	Nautiyal *et al.*, 1999
4	GG-2 and Jl-24	—	8-days intervals	RWC, leaf water potential (psi), leaf diffusive resistance and transpiration	YC Joshi *et al.*, 1988
5	-	Parbhani	988 and 930 mm water consumption at IW:CPE 0.8 and 0.6, irrigating at IW:CPE ratio 1.0 throughout growth.	Irrigated at IW:CPE ratios of 0.4, 0.6 or 0.8 at different growth stages	Shinde and Pawar, 1984
6	SB XI	Akola, Maharashtra	Irrigation at IW:CPE 0.50 up to flowering, 0.65 FL to PD and 0.80 during PD to maturity	Pod yields increased by applying antitranspirants	Patil and Morey, 1993
7	-	—	Water stress for 20-25 days during the VG, relief with 2 irriga-	In summer crop increased the pod yields by 20% compared	Ravindra *et al.*, 1989

			tions at 5-d interval then normal irrigation at 10-d intervals	with yields of unstressed crops, besides savings of 2 irrigations.	
8	SB 11	—	Max. pod yield (3.06 t/ha) predicted with 1131 mm water	Using IW:CPE, 3 levels of water stress applied at 4 growth stages	Shinde and Pawar, 1982
9	Konkan Gaurav	—	11 irrigations at 10-day intervals.	The highest yield and net returns	Chavan *et al.*, 1999

A comprehensive field investigation was done on groundnut crop over a period of three years with five different irrigation treatments, to determine an efficient strategy for management of irrigation water under water stressed conditions in a sub-tropical region. Layer-wise soil moisture status was continuously monitored to determine the crop water extraction pattern and thereby the irrigation management depth. Five irrigation treatments maintained based on predefined levels of maximum allowable depletion (MAD) of ASW were 10% (T1), 30% (T2), 45% (T3), 60% (T4) and 75% (T5) maximum allowable depletion of ASW (measured periodically in 15-30, 30-45, 45-60, 60-90 and 90-120 cm soil profiles using a neutron probe). CROPGRO-Groundnut growth simulation model was calibrated and validated for further use. Thus, the plants extracted most of the soil moisture from 0-30 cm soil layer. The study shows that only 0-30 cm of soil profile be considered for scheduling of irrigation in case of groundnut grown in sandy loam soil in the sub-tropical regions. Measured and simulated results revealed that under water scarcity condition, plant extractable soil water depletion of more than 45% of ASW must be avoided even during non-critical growth stages to obtain high WUE and net return. The calibrated CROPGRO-Groundnut model was found to be quite efficient in simulation of yield parameters and layer-wise soil moisture extraction pattern (Panda and Behera, 2005).

In red sandy loam soils in Andhra Pradesh, a good relation was established by Reddy (1984) with class 'A' pan using a simple can evaporimeter and that irrigation of groundnut when cumulative can evaporation reached 2 cm with a depth of water equal to that lost in evaporation from the evaporimeter gave the highest yield of pods. In sandy loam soil of Tirupati, India, groundnut irrigated at IW/CPE ratio of 0.5 at 7 cm resulted in early flowering; however irrigation at IW/CPE ratio of 1.0 at 5 cm resulted in more filled pods, a greater volume weight of pods, a higher shelling percentage, and significantly higher pod and kernel weights, highest pod yield and net returns (Sree and Rao, 1998). The summer groundnut cv. TMV 2 grown by Reddy and Reddy (1993) with adequate soil moisture, 60% (moderate water stress) or 80% depletion (severe water stress) throughout the growing period, or 1 of 6 combinations of these irrigation schedules at 4 growth stages (vegetative, flowering, yield formation and maturity) found that scheduling irrigation to supply adequate water during the moisture-sensitive flowering and yield formation stages, yet allowing moderate stress in the vegetative and maturity stages, produced the optimum yield (2.82 t/ha) with maximum water-use efficiency (7.73 kg ha^{-1} mm^{-1}) and water economy. At times of water deficit, irrigations can be scheduled at 60% depletion of ASM throughout the growing period without reducing the cropping area for want of irrigation water. Yield response factors (k_y) which relate relative yield decrease to relative ET deficit were calculated. Lower k_y values due to no soil moisture stress at flowering and yield formation stages stress the need for an adequate water supply at these stages. For a relative ET of 0.71-0.74, the relative yield levels varied between 0.5 and 0.6, while for relative seasonal ET of 0.76-0.84, the groundnut yields varied from 0.74 to 0.86 (Reddy and Reddy, 1993). During summer, in Tamil Nadu, irrigation schedule at 0.75 IW/CPE led to highest yield (Lourduraj, 2000).

In Maharashtra, application of 80 mm depth of irrigation water at 0.40 IW/CPE ratio for first 40 days, at 0.90 ratio from 40-70 DAS and at 0.60 ratio from 70 DAS and onwards produced maximum pod yield in SB XI groundnut where the average consumptive use of 387 mm of water with consumptive use efficiency of 5.0 kg ha^{-1} mm^{-1} and ET/PE ratio of 0.71 (Dhonde *et al*., 1985). However, Patil *et al.* (1984) reported 5.48 kg ha^{-1} mm^{-1} as the comsumptive use efficiency of JL 24 (Phule Pragati) at 3.5 mm day ET, 0.85 ET/PE ratio and 416 mm PE in lysimeter experiment. Irrigation at 50% ASM depletion or at 1-week intervals, during summer season, gave pod yields of 4.98 and 4.83 t ha^{-1}, respectively, compared with 4.65, 4.13 and 3.47 t ha^{-1} with irrigation at 50, 75 and 100 mm CPE, respectively (Babalad and Kulkarni, 1988).

At Parbani, Shinde and Pawar (1984) observed that irrigation at 0.8 IW/CPE ratio at all the growth stages with 930-998 mm of water in 14 irrigations increased pod yield, but was detrimental at the ratio of 0.4. The crop sown in Feb the maximum pod yield was obtained by irrigation at IW: CPE ratio of 1.0 throughout growth. Irrigation at ratio 0.8 and 0.6 was most economic, with 3.07 and 3.16 kg dry pods/ha per mm water applied (Shinde and Pawar, 1984). Response of groundnut to different levels of IW: CPE ratio (treated as a stress day index) was observed during the summer seasons. The relationship between stress day index (x) and pod yield (y) was negative and quadratic in nature and was expressed by y = 31.1692 - 0.13133x + 0.0000721x2. The maximum yield obtainable was predicted to be 3.12 t/ha with an opt. irrigation (zero stress day index) (Shinde and Pawar, 1983). At Palghar, groundnut cv. Konkan Gaurav, grown with 7, 9 or 11 irrigations gave higher pod yield than 5 irrigations and the highest yield and net returns were with 11 irrigations at 10-day intervals (Chavan *et al*., 1999).

In medium black calcareous soil of Saurashtra, the FC and permanent wilting point were 24.8 and 9.9% soil moisture level in top 0-15 cm layer and irrigation at 1.0 IW:CPE ratio was suitable (Kachot *et al*., 1984). However, Gajera and Patel (1984) reported that irrigation at IW/CPE ratio of 0.8 yielded at par with than that of ratio 1.0 with total water applied 550 mm, and to maintain this ratio a total of 11 irrigations were provided to summer groundnut variety GAUG 1. Thorat *et al.* (1984) obtained highest yield when crop was irrigated at 50 mm at, IW: CPE ratio1.0 and the total number of irrigations were 14 (700 mm-ha water) during rabi season. The irrigation at 15 days intervals during germination to pegging and 10 days during pegging to pod formation and maturity gave highest yield in calcareous soils of Saurashtra, Gujarat during summer season (Dwivedi, 1986b).

In India, Khan and Datta (1990) reported that the I/E (irrigation/ CPE) ratio of 0.75 was optimum irrigation index for potential yield and WUE in SB XI cv. of groundnut, and to ensure adequate moisture in the effective root zone, 6 cm depth of irrigation is considered to be the best irrigation depth. In Eastern India, during summer, pod yield and DM increased with rate of K application (up to 30 kg K_2O ha^{-1}) and frequency of irrigation at 0.3, 0.55 and 0.8 atm. soil water tension increased pod yield by 112, 150 and 159%, respectively, compared with the rainfed treatment (Ghatak *et al.*, 1997). At Kharagpur, Jain *et al.* (1997) developed a water stress response function by imposing various degrees of stress at various physiological stages of crop growth in groundnut crop using 22 treatments of different combinations of IW: CPE ratio (depth of water applied per irrigation to the CPE during kharif which can be used for optimum allocation of water resources for maximum benefit of the groundnut crop. The study concluded that in case of limited water supply, water saving should be made during periods other than the flowering and pod formation stages, however WUE increased at a decreasing rate when deficiency in IW: CPE ratio was made at one stage only (Jain *et al.,* 1997).

Under semi-arid tropics often with low and erratic rainfall the groundnut yield and yield attributes, growth and development are affected by soil moisture deficit or water stress and maintenance of optimum soil moisture at critical growth stages is the key factor for achieving higher yields. The knowledge on physiological characters like photosynthesis, stomatal conductance, leaf water potential and water use efficiencies would certainly be helpful in making irrigation scheduling of groundnut and decision support systems that aim at higher productivity (Thiyagarajan *et al.*, 2009). Combinations of N, P and K fertilizers on growth and production of groundnut growing in the absence of water stress and at a modest rate of deficit irrigation (0.75 times pan evaporation for the canopy area) when studied for the high irrigation rate, crop water stress index (CWSI) values did not exceed 0.2. For the low rate water stress values frequently ranged from 0.5 to 0.7 (Worthington *et al*., 1995).

Nautiyal *et al.* (2001) synthesize the response of groundnut to various aspects of deficit irrigation practices during vegetative phase. The transient soil-moisture-deficit stress for 25 days, at the vegetative phase (20-45DAS) followed by two relief irrigations at an interval of 5 days, resulted in synchronized flowering, greater conversion of flowers to pods and higher pod yield and total biomass accumulation, but water deficit stress was highly detrimental when imposed at flowering (40-65 DAS) and pod development at (60-85 DAS) (Nautiyal *et al.,* 1999a)

Pressurized irrigation system found to be quite effective under less water availability not only in achieving higher productivity but also economizing other inputs such as fertilizers, pesticides, labour etc. compared to traditional irrigation methods (Keller and Bliesner, 1990). Drip irrigation system is a convenient and effective means of supplying water directly to soil and nearer to the plant without much loss of water resulting in higher water productivity (Parihar *et al.*, 2008; Singh *et al.,* 200, 2001; Man Singh *et al.,* 2012). Planting of groundnut on raised bed enhances pod yield and helps in achieving higher irrigation efficiency through higher pod yield compared to normal flat bed planting (Parihar *et al.*, 2008; Man Singh *et al.*, 2012).

The estimation of the water requirements (WR) of crop is one of the basic needs for crop planning on the farm and design of any irrigation system. The WR can be defined as the quantity of water, regardless of its source, required by crop or diversified pattern of crops in a given period of time for its normal growth at a given field conditions. The WR also includes the evapotranspiration (ET) losses or consumptive use (C_u) of the crop, unavoidable losses during irrigation, and the quantity of water required for special operations such as land preparation, transplanting, leaching, etc. Thus WR may be formulated as:

$$WR = ET / Cu + Unavoidable...losses + special..needs. \quad (1)$$

Water requirement is, therefore, a 'demand' and the 'supply' would consist of contribution from any of the source of water, the major source being the irrigation water (IR), effective rainfall (ER) and soil profile contributions (S) including that from shallow water tables. Therefore, water requirement is:

$$WR = IR + ER + S \quad (2)$$

The field irrigation requirement of a crop refers to the water requirement of crops, exclusively of effective rainfall and contribution from soil profile, and it may be given as:

$$IR = WR - (ER + S) \quad (3)$$

The plant canopies of young and wide-spaced crops shade only a portion of the soil surface area and intercept only a portion of incoming radiation. Conventional estimates of water requirement of young crops assume part of the applied water will be lost to non beneficial consumptive use. This loss is through evaporation from the wetted soil surface and through transpiration from undesirable vegetation. The plant canopies of young and medium spaced crops like groundnut shade only a portion of the soil surface area and gradually the canopy increases to full surface area as the crops attain its full vegetation stage. The daily crop water use rate under trickle irrigation is a function of the conventionally computed consumptive use rate and the extent of the plant canopy.

Trickle (drip) irrigation reduces evaporation losses to a minimum, so the transpiration by crop account for practically all the water consumed. Thus, estimates of consumptive use that assume the wetting of entire field surface should be modified for trickle irrigation. The transpiration rate under trickle irrigation is a function of conventionally computed consumptive rate and the extent of the plant canopy. A simple equation for estimating the average peak daily transpiration rate is:

$$T_d = U_d \left(0.1 \left(P_d\right)^{0.5}\right) \tag{4}$$

Where, T_d = Average daily transpiration rate during the peak – use month for a crop under trickle irrigation mm/day, U_d = Conventionally estimated average daily consumptive use rate during the peak–use month for the mature crop with a full canopy, mm/day, P_d = Percentage of soil surface area shaded by crop canopies at midday.

Equation is based on the observation that even when the plant canopy is very small and P_d is 1% or greater, the minimum $T_d > (0.1\ U_d)$. This is because there is an oasis effect and some additional vegetation usually grows in the area wetted by the emitters. Furthermore, as the canopies of the plants increase toward full converge, T_d approaches U_d, and at full coverage when P_d= 100%, $T_d = U_d$

While calculating depth of irrigation water required, the percentage wetted area was 100 based on the plant spacing, number of emitters per plant, and optimal emitters spacing. The following formula can be used for calculating the percentage wetted area:

$$P_w = \frac{N_p S_e W}{S_p S_r}$$

Where, P_w = percentage of soil area wetted along a horizontal plane (%), N_p = Number of emitters per plant, S_e = Optimum emitter spacing (m), W = Wetted width (m), S_p = Plant spacing (m), S_r = Row spacing (m)

Man Singh *et al.* (2012), using same amount of irrigation water for entire season, but with different amount and duration at each irrigation, reported an innovative method of estimation of water requirement of irrigated groundnut crop for two distinct seasons *kharif* (July-November) and summer (March-July) in the semi-arid region under the trickle system of irrigation using 5 irrigation schedules (irrigation depth: as per the estimated crop evapotranspiration; irrigation interval (s): 1, 2, 3, 4 and 5 days) where the estimated seasonal water requirements were 304-310 mm during *kharif* and 380-450 and mm during summer seasons at Delhi, India. During summer the irrigation were applied through drip at one day interval for 15 minutes duration (T_1), two days interval with 30 minutes duration (T_2), three days interval with 45 minutes duration (T_3), four days interval with 60 minutes duration (T_4), five days interval with 75 minutes duration (T_5) where the pod yields were significantly higher in case of daily irrigation, but it was reduced if irrigation were scheduled beyond 3 days interval. Daily irrigation based on crop water use rate maintained moist soil surface throughout the irrigation season and thus promoted penetration of more number of pegs into the soil easily resulting in more pods per plant.

The reference evapotranspiration is determined using the Penman-Montith equation for the crop growth period. These ETo determined for 1-25 days, 25-75 days and 75-105 days and estimated daily water requirements of per plant for the entire crop growth season (*Kharif)* for the semi arid region is presented in the Table 4.

Table 4. Daily water requirement of groundnut plant under drip irrigation (Man Singh *et al.,* 2012)

Crop growth stage	Duration of crop (days)	Percentage shaded area	Water requirement (L $day^{-1}plant^{-1}$)
Initial	0-25	1-33	0.10-0.25
Vegetative and flowering	25-75	33- 67	0.25-0.45
Pegging and pod formation	75-105	67- 100	0.45-0.60

Using the daily value of U_d and P_d in equation (1) the T_d was estimated for trickle/drip irrigation. The values of U_d are the reference evapotranspiration estimated from the local weather data.

The water requirements of the crop under trickle irrigation for the two consecutive seasons varied with prevailing temperatures and rainfall events which led to the variation in the crop ET from 450 mm in the year 2006 to 380 mm in 2007. Also a comparison of water requirements estimate of ground nut crop between conventional and new method is given in Table 5.

Table 5. Water requirements estimate of groundnut crop, a *comparison* (Man Singh *et al.,* 2012)

Season	Conventional Method, mm	New Method, mm
Monsoon *(Kharif)*	400 - 450	304 -310
Summer	650 -750	380 - 450

Leaf growth is a sensitive indicator of water deficit stress and LAI recorded at three different phases of reproductive development; early pod formation (76 DAS), pod filling (104 DAS) and at physiological maturity (120 DAS) was highest in T1 treatment and T2 to T5 experienced water deficit. Canopy Temperature Depression (CTD) of the crop canopy recorded at 60, 76 and 101 DAS showed maximum CTD as 7 at 60 DAS and mininmum of 1.5 at 101 DAS. As soil water becomes limiting, transpiration is reduced and leaf temperature increase, effect of irrigation scheduling on CTD was clearly observed among the treatments with stress condition. The pod and haulm yields were significantly higher in T1 treatment where irrigation for 15 minute was provided daily, but decreases with increasing interval and was lowest with T5 treatment (interval 5 days) due to reduced transpiration and low CTD, and LAI (Man

Singh *et al* 2012). Thus water requirement of a particular crop is not constant or fixed regardless to any irrigation method, it depends on the weather/climatic fluctuations during the crop growth season.

5.2 Early Season Stress

Early-season moisture deficit greatly reduced leaf area expansion, although the rate recovered following irrigation. The early moisture stress (EMS), imposed from emergence to initiation of pegs, reduced ET with no apparent reduction in LAI, pod and seed growth during the rainy as well as the post-rainy seasons on a medium deep Alfisol at Patancheru, India and the WUE was substantially higher for the EMS treatment compared with the control and despite the contrasting climatic conditions during the rainy and post-rainy seasons, groundnut response to EMS was fairly similar (Sarma and Sivakumar, 1990). Stirling *et al.* (1990) in controlled-environment, withholding water in groundnut between sowing to pod initiation showed the pod yield 5 times higher than withholding water between pod initiation and harvest concluded that field management should aim to optimize water availability at pegging. Osmotic adjustment occurred in expanding but not in mature leaves; the latter often lost turgor around midday and pegs retained turgor during water stress in both treatments.

The groundnut cv. Yueyou 5, grown in a growth chamber with irrigation suspended after 11 d to create water stress, when sprayed with 3000 ppm triadimefon, SEM examination revealed that triadimefon treatment induced stomatal closure, reduced transpiration and increased drought resistance of the seedlings. From the 4^{th} day after the suspension of irrigation, proline contents decreased and water contents increased in treated seedlings compared with the untreated controls. Treated seedlings withered on the 5th day and the control on the 4th day. Triadimefon also reduced plant height and increased photosynthetic rate and improved photosynthate distribution in favour of the sink, indicating that triadimefon, usually a systemic fungicide, may be a potential antitrans-pirant for groundnuts (Guo and Pan, 1989).

In greenhouse, groundnuts irrigated from sowing to pod intiation or from pod intiation to final harvest, when compared, the shoot DM yields were largely unaffected, but pod yields were 4-fold lower in early- than in late-irrigated crops. The insensitivity of pod yield to early moisture deficits reflected the extreme plasticity of growth and development in groundnut (Stirling, 1989). The effect of water stress on Tainan 9 groundnut cultivar studied on Warin soil series of the Agricultural Development Research Center (ADRC), Khon Kaen Province in Thailand during dry seasons by providing various treatments indicated that water stress plays an important role on the yield of groundnut and yield decreases due to water stress at different growth stages follows the following sequence: water stress at seed development > at early pod filling

> at early growth > at early pegging (Uthai-Arromratana *et al*., 1993).The groundnut is the most important oil and cash crop in the sub-Sahelian tropics and traits expressed at the early stages of the cycle that could reveal cv differences in drought adaptation in the field are useful as plant adaptation to drought, i.e. cultivars (cvs) that can maintain yield when water is limited, is a complex phenomenon and not yet fully understood.

The yield advantages due to moderate water deficit during the pre-flowering phase are associated with greater pod synchrony after the release of water stress, resulting in production of more mature pods (Nageswar Rao *et al*., 1988). When stress is released, the plant try to set more fruiting sites with the existing assimilates as the vegetative site demanding assimilate supply are reduced. To improve the conventional irrigation management practices to enhance yield and water use efficiency in groundnut during summer seasons a field experiment was conducted by Nautiyal *et al.* (2002) where dry matter partitioning among various plant parts, and leaf area index (LAI) varied significantly under water deficit and more dry matter accumulated in petiole and stem under stress. Transient water-deficit in vegetative phase resulted in higher dry matter accumulation in reproductive parts (peg+pod). Water use efficiency (Ef) was, however, higher under prolonged stress during vegetative phase; though cultivars response varied. Per cent reduction in total biomass under stress during flowering (F), and pod-development (P) ranged between 6 and 25%, this reduction in total biomass was mainly due to the reduction in the pod mass rather than in the vegetative mass. Water-deficit occurring during the vegetative stage, seedling stage until flowering, was most beneficial for the crop, and need to be utilized in irrigation scheduling (Nautiyal *et al.,* 2002).

5.3 Mid Season Stress

The mid-season drought (MSD) of common occurrence in groundnut in central India and AP in particular causing severe yield losses and reduction in yield attributes and quality, as against crop receiving full irrigation during the whole crop duration, revealed genotype differences, and genotype environment interaction for pod yield, shelling percentage and HI. There was maximum reduction in the number of mature pods (47%) under MSD, followed by pod yield (29.7%) while under ESD for pod yield (41%), followed by the number of mature pods (33%), indicating that number of mature pods was most sensitive to MSD and pod yield to ESD (Suvarna *et al.,* 2002).

Different drought management practices for groundnut were compared on shallow (15 cm depth) sandy loam soil with a loamy subsoil where pod yield was 1.36 t/ha in control plots, and with drought management practices it was 1.53 t with a 5% kaolin spray during mid-season stress and 1.68 t when mulched with 5 t groundnut shells/ha 10 d after sowing (Reddy, 1994). In a field at ICRISAT, Patancheru, during the rabi/summer season (Dec to April) screening of 20 groundnut genotypes under three drought conditions normal (with regular irrigation); mid-season drought (irrigation withheld 50-100 DAS); and end-season drought (irrigation withheld between 100 DAS to harvest) reveals that the genotypes, ICGV 86031 performed best under both normal and stress conditions, genotypes ICGV 93261, 93269, 93277 and KRG 1 had high yields and less percent yield reductions under the stress conditions (Suvarna *et al*., 2006). By adopting moisture conservative methods during July and September months enhanced the groundnut yields in the drylands of Tirupati (Sumathi and Subramanyam, 2007).

At Tirupati, with groundnut cv. JL 24 moisture stress induced for 45 d in 1986 and 35 d in 1987, after irrigation at 25 d after sowing in summer by Selvam *et al*. (1989) reported that stress did not affect plant population, but reduced number of filled pods/plant. The pod yields in treatment (a) control, (b) water spray twice during stress, (c) irrigation twice to prevent moisture stress, (d) 2% urea spray once after relieving stress, (e) 2% urea spray twice during stress, and (f) 2% urea + trace element compound Tracel-1 (13.2% S, 6.6% Zn, 5.3% Fe and 3.7% Mn) sprayed twice during stress, followed (f) > (e) > (d) = (c) > (b) > (a) and ranged from 0.80 t/ha in (a) to 1.82 t ha^{-1} in (f). Thus, foliar application of 2% urea with trace elements is a promising technique to overcome the adverse effects of mid-season moisture stress (Selvam *et al*., 1989).

Variations exist in the proportion of DM used for pod growth and large variations in the response of genotypes to midseason are due to recovery differences after the drought is relieved and a 3-factor interaction of genotype, gypsum, and drought exists because the gypsum may increase early pod development, thus providing escape effects (Williams *et al*., 1985). In a field trial in Rahuri, Maharashtra on mulching with sugarcane trash or white polyethylene in groundnut water stress at different growth stages (flowering, pegging or pod development stage) during summer, indicated that mulching with white polyethylene along with water stress at the pod development stage resulted in the greatest plant height (38 cm), plant spread (25 cm), number of functional leaves per plant (73), leaf area per plant (21 dm^{-2}), dry matter per plant (18 g), dry pod yield (2896 kg ha^{-1}), haulm yield (4741 kg ha^{-1}), dry kernel yield (2083 kg ha^{-1}), oil yield (989 kg ha^{-1}), net monetary returns (34 097 rupees/ha) and benefit: cost ratio (2.44) (Bodare and Dhonde, 2011).The oil content with polyethylene and sugarcane trash mulch in water stress at the pod development stage was 47.7% and 47.3%, respectively (Bodare and Dhonde, 2011).

5.4 Late Season Stress

A large spectrum of genotype duration is now available, from long to short and extra-short duration and matching genotype duration with likely period of soil water availability is the first strategy used against terminal-drought stress. Reddy *et al.* (2003) in a review summarized recent information on the drought resistance characteristics of groundnut with a view to developing appropriate genetic enhancement strategies for water-limited environments and suggested that a considerable gain has to be made in increasing and stabilizing yield in environments characterized by terminal drought stress and further exploiting drought escape strategy by shortening crop duration. Many traits conferring dehydration avoidance and dehydration tolerance are available, but integrated traits, expressed at a high level of organization, are likely to be more useful in crop improvement programmes. Possible genetic improvement strategies are outlined, right from empirical selection for yield in drought environments to a physiological-genetic approach. Increasing soil moisture storage by soil profile management and nutrient management for quick recovery from drought are some of the areas which need to be explored (Reddy *et al*., 2003).

Groundnut in the Sahel is often exposed to end-of-season drought and studies taking five new selected Spanish cultivars along with the control cultivar, 55-437 to identify traits associated with yield variation, indicated that earliness and general adaptation of the cultivars did not impair the expression of significant genetic variation for some traits relative to flowering, productivity and physiology (Clavel *et al.,* 2004). The partitioning coefficient and yield of the 5 cultivars under water stress were higher than those of cultivar 55-437, water deficit affected leaf area index, RWC and transpiration at approximately 2 weeks after the occurrence of water deficit at the soil level. Since genotypic differences seemed to be greatest at this time, measuring physiological traits during this period may be useful for breeding early groundnut for end-of-season water deficit conditions (Clavel *et al.,* 2004). In field during summer, 0.5% KCl spray reduced the effects of water stress imposed during seed growth stage (60-90 d after emergence) in groundnut cv. CO_2 suggesting that this may be useful in reducing water demand at critical growth stages (Mohandass *et al*., 1989).

Four groundnut lines (H 2030, H 2060, H 2063 and H 2095) showing resistance to aflatoxin contamination (caused by *Aspergillus flavus* and *A. parasiticus*) when evaluated for pre-harvest contamination by aflatoxins under end-of-season drought stress in field alongwith susceptible line 88-1202 by controling irrigation at 80 DAS when plants showed slight wilting symptoms due to water deficit. The plants were harvested at 120 DAS, and the seeds were analysed for aflatoxin contamination within 30 days after harvesting. In 88-1202, drought stress significantly increased the aflatoxin content of seeds, which was higher than that of the 4 genotypes. Drought treatment did not significantly enhance the aflatoxin content in the resistant lines. H 2030 had the lowest aflatoxin content (0.073µg g^{-1}) among the lines. These results confirmed that aflatoxin resistance in vitro could reduce pre-harvest contamination of seeds by aflatoxins (Yu *et al*., 2004).

Spanish type groundnut, due to relatively short duration, is preferred under lesser water availability environment. Field trials at DGR for three contrasting seasons with 30 Spanish groundnut cultivars showed wide genetic variability in physiological and yield components. The associations between pod yield and leaf area index during early crop growth stages, P_N and number of reproductive sink, and P_N and difference between T_{leaf} and T_{air} during pegging stage indicated that source is not a limiting factor. The lower SLA cultivars could be utilized under less water availability environment, the higher SLA types could be utilized in increasing early leaf area index and biomass, especially under irrigated condition. The P_N was higher during full pod (R4) (18 µmol $m^{-2}s^{-1}$) followed by beginning seed (R7) (17 µmol $m^{-2}s^{-1}$) and lower during full seed (R6) (8 µmol $m^{-2}s^{-1}$) and harvest maturity (R8) (8 µmol $m^{-2}s^{-1}$) showing enhanced P_N during beginning pod, to meet the additional requirement of photosynthates to developing reproductive sink (Nautiyal *et al.,* 2012).

5.5 Drought Tolerant Cultivars, QTLs and Breeding

Cultivated groundnut (*Arachis hypogaea* L.), an allotetraploid (2n=4x=40), is a self pollinated and widely grown crop in the semi-arid regions of the world. Improvement of drought tolerance is an important area of research for groundnut breeding programmes. The DGR, AICRP on groundnut and ICRISAT's research achievements for the past four decades in the domain of drought tolerance and present future perspectives in the genetic enhancement of crop water use and drought adaptation in the semiarid and arid tropics reveals that exploration of crop genetic variability and genotype-environment interactions have contributed significantly for developing suitable screening methods for specific drought-tolerant traits. Genetic sources of drought tolerance were also identified for groundnut, and some of the associated traits have been well characterized. A number of genotype with varied duration is now available, and matching genotype duration with likely period of soil water availability is the first strategy used against drought stress. Identification and genetic mapping of quantitative trait loci for specific drought-tolerant traits using molecular markers are currently receiving greater research focus. This approach provides a powerful tool for dissecting the genetic basis of drought tolerance. If validated with accurate phenotyping and properly integrated in marker-assisted breeding programmes, this approach will accelerate the development of drought-tolerant genotypes. Overall, the progress made at ICRISAT during the last three decades proves that it is realistic to develop varieties that have increased yield under drought-prone conditions, however further multidisciplinary research integrating plant breeding, simulation modelling, physiology and molecular genetics will realize the potential of these approaches and increase the efficiency of crop improvement in drought-prone environments (Serraj *et al*., 2003).

Breeding for drought resistance in groundnut has been done using empirical selection for yield under drought stress conditions. Selection for physiological traits contributing to superior performance of the crop under drought stress conditions, SLA and HI are physiological traits to be used for this purpose. The identified groundnut cultivars showing drought tolerance in various climatic conditions and soil types are summarized in Table 6 and the sensitive one in Table 7. The sensitivity of a genotype to drought increases with yield potential, increasing the closer the drought ends to final harvest. Genotypic variation in response to drought exists in the water-use ratio of genotypes, with some being able to accumulate up to 30% more shoot DM than others with the same total transpiration (Williams *et al*., 1985). Reddy *et al.* (2003) outlined possible genetic improvement strategies ranging from empirical selection for yield in drought environments to a physiological-genetic approach. For the choice of an efficient breeding procedure, a good knowledge on the types of gene action controlling the expression of these traits is needed. Field and laboratory studies conducted in Khon Kaen, Thailand, during the rainy season, to examine the various gene effects for SLA and HI in the groundnut crosses ICGV 86388 x IC 10, ICGV 86388 x KK 60-1 and IC10 x KK 60-1 showed that additive gene effects were predominant in determining the expression of SLA and HI in all 3 crosses, accounting for 80-95% of the total genetic variation for SLA and 63-73% for HI. The dominant gene effect for SLA was significant in one cross but its contribution was very small. Significant additive x dominant epistatic effects were also observed for SLA in all crosses, but additive x additive and dominant x dominant gene effects were significant in one cross each. Significant epistatic gene effects for HI were also detected in two crosses but were largely additive x additive, which is fixable. The predominance of additive gene effects for SLA and HI suggested that selection for the two traits in these crosses would be effective even in early segregating generations (Suriharn *et al*., 2005).

The choice of a genotype for production under irrigated or moisture stress condition should be based on the yield potential and moisture stress tolerance of the genotype. Izge and Olorunju (2000) evaluated 16 groundnut cultivars in greenhouse and found most of them sensitive to moisture stress, as evident in most of the parameters (plants at emergence, days to first flowering, maturity, pods per plant, pod and haulm yields, shelling percentage, 100-seed weight, protein and oil contents). Pod yield and other attributes, except protein and oil contents, were significantly affected by moisture stress. SAMNUT 18 (RRB) had the highest pod yield under both normal moisture and moisture stress conditions. Two Argentinian groundnut varieties Florman INTA (a drought-sensitive) and Manfredi 393 INTA (a drought-tolerant) when compared at two different water supply regimes the Manfredi 393 INTA demonstrated an adaptative advantage to drought, expressed in its higher pod production; due to either an earlier onset of beginning peg stage that affected differentially peg penetration into the dry soil upper layer, and an enhanced partitioning of assimilates to pods (Collino *et al.,* 2000).

Table 6. Drought tolerant groundnut varieties/cultivars reported in various soils and climate

SN	Tolerant cultivars	Soil type, Place	Crop Stage	Criteria used	Details of Drought tolerance	References
1.	GG-2	Black calcareous, Junagadh	VG, PD	Transpi-ration rates and low leaf psi at rela-tively higher RWC.	High transpiration in GG-2 at 1800 h under water stress a mechanism ada-ptive to compensate for reduced CO_2 fixation during day. GG-2 with low leaf psi at relatively higher RWC than JL-24.	Joshi *et al.,* 1988
2.	J11, GG 2	Black calca-reous, Junagadh	VG, FL or PD stages	Yield	Water stress during vegetative stage had less effect on pod yield, nodules, plant DM and N uptake than at later stages.	Kulkarni *et al.,* 1988
3.	GG-2, G-13 and G-20	-	-	Germination in field and PEGstress	Putrescine prevented the fall in tissue moisture in water-deficit seedlings.	Vakharia *et al.,* 2003
4.	Ex-Dakar, RRB12, RMP12, 91	-	Early growth stage	Germination in field	The germination in PEG, glucose or NaCl solutions at 1.8 Mpa a quick proc-edure for drought screening	Mensah and Okpere, 2000
5.	ICGV8603 1, TMV-2, TCGS-41	-	-	Germination in labora-tory	Germination and seedling growth in water stress situation (-1.0 MPa)	Prathap *et al.*, 2006
6.	RS 218	-	Seedling stage	better perfor-mance of seedlings	0.25% $CaCl_2$ for 8 h was ascribed to higher accu-mulation of proline and K in seedlings soil moisture stress conditions	Sashidhar *et al.,* 1981
7.	Kadiri	-	Sowing to PI and PI to harvest	Growth stages	The insensitivity of pod yield to early moisture deficits reflected the extreme plasticity of growth and development.	Stirling,198 9
8.	TMV 2, Acc 847, 55-437, GNP 1157	-	FI to PI (14 to 80 DAS)	Yield in pot study	Interactions between cul-tivar and water stress on stomatal resistance, leaf water potential & root DW.	DelRosario and Fajardo, 1988
9.	GAUG-1	Medium black soil Junagadh	-	growth and yield para-meters	K application decreased these negative effects of water stress by increasing yield parameters, oil and protein content.	Shahid-Umar *et al.,* 1997

10.	Dh-3-30 TMV-2	-	FL peg and pod formation	Leaf diffusive resistance, proline transpiration	Leaf diffusive resistance and proline accumulation highest and transpiration rate lowest with water stress at 70 DAS.	Koti *et al.,* 1994
11.	ICGV 86031 TMV2NL M	Andhra Pradesh	-	Soil moisture extraction, root length density	Efficient in soil water extraction and least losses (17-18%) in total DM production under moisture stress	Reddy, 1999
12.	CO 2, VRI2	Coimba-tore, TN	FL, PG, PD, PM stages	yield com-ponents and crop yield	Water stress at pod development had most effect on yield	Velu, 1998
13.	JL 24	-	5th sub-culture stage	Stress tolerance capacity of selected tissues	Tissues of JL 24 performed better than TMV 2 for growth, solute accumu-lation and water relation under PEG stress	Purushotha m *et al.,* 1998
14.	AK-12-24	-	All growth stages	Yield and water use efficiency	Highest WUE in plants stressed at pod developm-ent stage & lowest when st-ressed at peg penetration.	Kar *et al.,* 2002
15.	SAMNUT-18 (RRB)	Samaru, Zaria, Nigeria	EMI, FLI, 50% FL	Pod yield and attributes	Pod yield and other attributes were affected by moisture stress.	Izge and Olorunju, 2000
16.	Tatu	-	VG and RG stages like FL, PI	In Green house, flowering, pegging	Lesser Flower production by water stress.	Oliveira-Junior *et al.*, 2004
17.	JL 24	Kalyani, IND	FL, PI	In field, pod, haulm yield	Water stress at the pod initiation and development stages reduced yield by 13.4 & 44.2%, respectively.	Patra *et al.,* 1999
18.	ICGV 86707	Medium deep Alfisol at ICRISAT	PI or PF (83-113 DAS	Partitioning to DM to pods in drought	Partitioning to pods in drought ranged 0.56 in cv. ICGV 86707 to >0.95 in early maturing genotypes.	Rao *et al.,* 1993
19.	TMV 2	Sandy loam, Andhra Pradesh	VG, FL, MS throughou t growing	Yield	Produced optimum yield (2.82 t/ha) with maximum WUE (7.73 kg ha^{-1} mm^{-1}) and water economy	Reddy and Reddy, 1993
20.	JL-24	Akola, deep soil	VG and RP stages	Root respiration and yield	Cv. JL-24 was the most tolerant of water stress with 32.1% yield reduction compared with 47-67% yield reduction in TAG-24 the most susceptible cultivar.	Dhopte *et al.,* 1992

21.	GG-2	Junagadh, Gujarat	FL, PI, PD, PM stages	Pod yield, seed formation efficiency	Pod yield was reduced by reductions in fertility index, seed formation coefficient and seed formation efficiency and GG-2 was more drought tolerant than J-11.	Golakiya and Patel, 1992
22.	Q18801	Redland Bay, Queens-land, Australia	Early RP stage	Harvest index	Q18801, a Virginia cultivar with high HI yielded higher than Virginia Bunch and McCubbin (a Spanish).	Chapman *et al.,* 1993
23.	SB XI	-	0-40, 40-80, 80-120 d after sowing	IW: CPE ratios	WUE highest (5.23 kg ha-1 mm) with irrigation at IW:CPE ratio 0.5 0-40 DAS, 0.75 during 50-80 DAS and adequate moisture 80-110 DAS for obtaining maximum yields.	Patil and Gangavane, 1990
24.	GG2	DGR, Junagadh	All pheno-phases	Leaf transpi-ration rate, RWC, pod yield,	GG 2 showed develop-mental plasticity and gave the best pod yields even under stress at any growth phase,	Ravindra *et al.,* 1990
25.	TMV-2		VG, FL, PI, PD stages	Pod yield	High pod yield of 2.62 t/ha was unde moisture stress during the pod develop-ment and maturation stages.	Raju *et al.,* 1981
26.	Baisha 1016	Shandong, China	FL, FR and ripening stages	Protein content of seeds,	Drought at the flowering reduced protein content in seeds, while drought at seed development and ripening stages it gave seeds with higher protein than control.	Yao *et al.,* 1982
27.	Robut 33-1	-	EM to MI, Em to FL, start of SG to MI	Seed yield , evapo-transpir-ation	Evapotranspiration- yield relationships showed a strong interaction with timing of drought and greatest reduction in seed yield (28-96%) when stress imposed during seed growth	Rao *et al.,* 1985
28.	Robut 33-1	-	-	Pod:shoot wt. ratio (PWR), pod yield	Mild water stress promoted peg and pod production and increased PWR.	Ong, 1984

29.	GG-2	Medium black calcareous soil	FL, PI, PD, PF stages	Pod yield and nutrients (N, P, K) accumu-lation	Pod yield most affected due to water stress during pod development, nutrient accumulation increased with crop growth except K which showed maximum accumulation at 78 DAS	Sakarvadia *et al.,* 2010
30.	GG 6	Clay soil Junagadh	FL, PI, PD, PF stages	benefit: cost ratio, WUE	GG 6 recorded higher WUE and benefit: cost ratio.	Vaghasia *et al.,* 2010
31.	ICGS-11, ICGS-44 and Girnar-1	-	Fl stage	Stomatal conductance, proline content	The better performance under water stress was related to good stomatal conductance and increased proline level for osmotic adjustment.	Patil and Patil, 1993
32.	Florunner	Tifton, Georgia	Pre-flowe-ring, pod formation matu-ration	Fatty acid composition, O:L ratio, iodine value	Under water stress, long chain saturated fatty acids, eicosenoic acid [gadoleic acid], O:L ratio and alpha -tocopherol decreased in groundnuts and stress at maturity decreased O:L ratio, but increased iodine value.	Hashim *et al.,* 1993
33.	Giza 5	Egypt	Pod initiation and pod developm ent	Yield and yield attributes oil and protein content and yield	Water stress (skipping one irrigation) and potassium fertilizer application	Ali, 2001
34.	TAG 24	Jhargram, West Bengal, India, acid lateritic soils	VG and FL stages	WUE, Benefit: cost ratio	Maximum WUE under moisture stress during vegetative stage. Benefit: cost ratio was higher with moisture stress at vegetative stage.	Dutta and Mondal, 2006
35.	JL 24	Madurai, Tamil Nadu	At early PI, late PD stages and VG stges	Pod yield, seed quality, oil and protein content, nutrient uptake	Kaolinite (3%) spray reduced yield loss due to water stress.	Naveen *et al.,* 1992
36.	PI 165-3176	Ceara, Brazil, sandy soil	FL	Pod yield and transpiration	Pod yield was highest for PI 165-3176 under all water regimes.	Ferreira *et al.,* 1992

37.	Robut-33	Redland Bay, Queens land	-	Pod yield, harvest index (HI)	Robut-33 had the highest CGR and early and rapid pod growth and high HI more important in yield under water deficit.	Chapman *et al.,* 1993
38.	TMV2	-	-	Flowering , pod yield or oil content	Moisture stress reduced the number of gynophores formed from the 1st flush of flowers	Gowda, 1977
39.	Kadiri-3	Green-houses	At 28 °C (±5°) under CO_2 levels of 350 and 700 ppmv)	leaf water potential	Elevated CO2 affected growth and yield mediated by an increase in the conversion coefficient for intercepted radiation and maintenance of higher leaf water potentials during drought stress.	Clifford *et al.,* 1993
40.	J11, GG 2 and Robert, GAUG 1	-	Early growth period	Yield	Withdrawal of 2 irrigations in early crop growth followed by spraying of 50 ppm IBA at 40 and 60 DAS was economical.	Patel *et al.,* 1988
41.	JL 24	Vertisol and silty loam	-	Total DM, Pod yield	In water-stressed conditions, the cv. JL-24 partitioned more total DM to pods than susceptible cultivars	Dhopte and Ramteke,19 94
42.	JB 223 and 224	Junagadh, Gujarat	-	Yield	Recorded consistently superior and stable yield for the three years at all the locations.	Mandavia *et al.,* 2007
43.	ICGV8601 5	Sri Lanka	VG stage	Seed yield	highest seed yield under water-stressed condition	Costa *et al.,* 2001
44.	DVR50	-	PI stage	Drought index, Pod yields	highest yield under both natural and moisture-stress conditions.	Chavan *et al.,* 1992
45.	Robut-33	University of Queens land, Australia	Early RP stage	Harvest index	Robut-33 showed highly synchronous development and high HI and an ability to tolerate drought.	Chapman *et al.,* 1993
46.	GG 2	Junagadh, Gujarat	FL, PI, PD, PM stages	Pod yield	GG 2 was more tolerant to drought than J 11	Patel and Golakiya, 1991
47.	ICGV 87123	Niamey, Niger	-	pod yield	ICGV 87123 and 55-437 gave the highest yields over all irrigation treatments.	Greenberg and Ndunguru, 1989

48.	TG 17	-	FL, PI, PD stages	leaf area, pod yield, RWC	TG 17 tolerated water stress better than cv. GAUG 1.	Patel *et al.,* 1983
49.	Kadiri 3	-	PI stage	Filled - Pod wt/plant	Kadiri 3 intercropped with sorghum hybrid CSH-8, increased pod yield, in droughted stands.	Harris and Natarajan,1 987
50.	TG26	Southern Telangana, Alfisols, AP	PI to PD stage	pod yields	In rainy season, pod yields ranged from 0.58 (TCGS88) to 2.41 t/ha.	Thatikunta Ramesh *et al.,* 1996
51.	ICGV 86031	ICRISAT, Patan-cheru	VG and RP stages	yield	Performed best under both normal and water stress conditions .	Suvarna *et al.,* 2006
52.	Yueyou 5	-	11 d old seedling stage	Stomatal closure, tran-spiration, seedling growth	Triadimefon induced stomatal closure, reducing transpiration and increasing drought resistance of the seedlings.	Guo and Pan, 1989
53.	M 37	-	50 and 80 DAS	pod setting, oil content in seeds	The moisture stress suppressed pod setting, but not the oil content	Sharma *et al.,* 1987
54.	ICG-4504 and GPHY-35	-	-	Yield	The percentage of reduction in their yield under increasing moisture stress was less.	Shashikuma r *et al.,* 1988
55.	Robut 33-1	ICRISAT Patan-cheru, India	Emer-gence to maturity	Emergence, seedling vigour, pod and seed yields	Seeds from groundnut grown under stress from emergence to initiation of pegs gave higher field emergence, better seedling vigour pod yields.	Sarma and Sivakumar, 1987
56.	GG-2	Calcareous vertic Inceptisol	-	Vegetative growth	Lower fluctuations in leaf temperature, stomatal resistance and vegetative growth.	Patel and Golakiya, 1993
57.	PBS 11049	Junagadh	95 DAS after sowing	Epicuticular wax load	Wax load ranged from 0.91 mg dm^{-2} in Chico to 1.74 mg dm-2 in PBS 11049, with a mean of 1.27 mg dm-2.	Samdur *et al.,* 2003
58.	RD 14 , RD 22 and RD 25	-	19, 28 DAS etc.	Symptoms	Transgenic lines RD 14, RD 22 and RD 25 showed lesser symptoms than JL 24. RD 14 reached the end point in 29 days, and RD 4 in 52 days.	Mathur *et al.,* 2004

59.	Manfredi 393 INTA	-	47 and 113 days after sowing	Critical soil resistance and Peg and pod development	Manfredi 393 INTA had an adaptative advantage to drought, due to earlier onset of peg and enhanced partitioning of assimilates to pods.	Collino *et al.,* 2000
60.	Q18801	Redland Bay, Queensland		LAI, transpiration efficiency	Q18801 was able to maintain a higher LAI and a greater crop transpiration efficiency than McCubbin.	Chapman *et al.,* 1993
61.	ICGVs 88369, 88371, 88381, -82 , 88403	ICRISAT Patancheru	40 and 80 DAS, mid-season drought	Oil content,	In ICGVs 88369, 88371, 88381, 88382 and 88403, total oil content remained unaffected while oleic fatty acid content increased under end-of-season drought	Dwivedi *et al.,* 1996
62.	K-134	-	-	The protease activity	Protease activity of K-134 makes it a more drought-tolerant cultivar	Madhusudhan *et al.,* 2002
63.	GG-2	-	Growth stages	Carbohydrate concentration	After 30 days without irrigation, increase in total carbohydrate.	Kandoliya *et al.*, 2000
64.	GAUG- 1	Gujarat	Different growth stages	Palmitic acid	Increase in palmitic acid due to stress during pod development phase was observed only in GAUG 1.	Misra and Nautiyal, 2005
65.	K 3	-	-	Yield components	Cv. K 3, performed better than JL 24 and Gangapuri if sowing was delayed until July.	Padma *et al.,* 1991
66.	Florunner	-	-	Soluble and total carbohydrate, total protein and oil contents	Soluble and total carbohydrate increased in Jumbo showing the highest increase under drought and temperature stress.	Musingo *et al.,* 1989
67.	TPT-4	-	-	CaM, proline and activity proline oxidase	The CaM in cotyledons of water-stressed seedlings decreased, but $CaCl_2$ treated maintained higher CaM and proline oxidase activity.	Sulochana and Savithramma, 2001
68.	TPT-4	-	-	Acid phosphatase activity	External Ca^{2+} maintained higher levels of ACPH activity in the seedlings of TPT-4 than TPT-1.	Sulochana and Savithramma, 2003

69.	Dragon - type cultivars	-	-	SOD activity, protein content, water potential	Under drought, water potential was higher in the dragon-type cultivars than in the other types cultivar.	Jiang and XiaoPing, 2004
70.	Baipi No.1	-	-	RPMP, oxygen radical, MDA content, and SOD, POD, CAT activity and AsA.	Resistant to drought as evident from smaller increase in RPMP, oxygen radical generation and MDA content, and in slower decrease in SOD, POD and CAT activity and AsA content.	Chen-YouQiang *et al.,* 2000
71.	Jun-40 and GG-2	-	-	SOD, SOR, APX, lipid peroxidation	Jun-40 accumulated SOR, higher SOD activity and GG-2 showed less lipid peroxidation in water stress.	Mittal *et al.,* 2006
72.	M-13	-	10-day-old seed lings	Relative turgidity, protein and NR activity	M-13, during stress, was able to preserve its protein conc. and nitrate reductase activity	Saini and Srivastava, 1981
73.	TAG 24 and Somnath	Mumbai	-	Leaflet area, stomatal frequency on adaxial	Reduced leaf area, increase in stomatal frequency on adaxial surface are related to WUE in TAG 24 and Somnath	Badigannavar *et al.,* 1999
74.	ICGV 99029 and ICR 48	-	-	SCMR, SLA	ICGV 99029 and ICR 48, with higher SCMR and lower SLA values indicated higher WUE.	Nigam and Aruna, 2008
75.	Vemana and K 1375	-	-	Water stress-regulated proteins,	Vemana, K 1375 are able to maintain expression of certain proteins (MW 14 kDa and 70 kDa)	Ramesh-Katam *et al.,* 2007
76.	Kadiri-3	-	-	CMS, K value, membrane stabilty	Kadiri-3, maintained higher CMS and K values greater cell membrane stability than JL-24, the drought susceptible one.	Venkateswarlu and Ramesh, 1993
77.	Manfredi 420	-	-	Stomatal opening, membrane stability	Manfedi 420, could keep their stomata most open during drought stress, without major alterations in membrane stability.	Collino *et al.,* 1994
78.	TMV2 , Kadiri 3	Sandy loam soil (Alfisol)	-	assimilation and water loss	At peak flowering these had lower canopy temperature.	Subramanian *et al.,* 1993

79.	GG-2	-	-	RWC, proline, ascorbic acid and reducing sugars	GG-2 is characterized by high RWC & greater accumulation of proline, ascorbic acid and reducing sugars.	Dhruve and Vakharia, 2007
80.	TMV-2	-	-	Pod yield	The lowest water stress was experienced by TMV2 and highest by TAG-24.	Mukherjee *et al.,* 2010
81.	TMV2 and J11	-	-	Gypsum requirement	Drought susceptible varieties has more requirement of gypsum.	Rajendrudu & Williams, 1987
82.	ICG221	Vriddhachalam, TN	-		ICG221 performed best in the simulated stress environment (rain out shelter).	Arjunan *et al.*, 1997
83.	Nigeria 55437	-	-	Leaf water potential, transpiration and DR	Nigeria 55437 showed high diffusion resistance and proline and low leaf water potential and transpiration under stress.	Nogueira-RJMC *et al.*, 1998
84.	Manfredi 393 INTA	-	-	RUE	RUE values higher in Manfredi 393 INTA than in Florman INTA,	Collino *et al.*, 2001
85.	JUG-37, JUG-43 and TIR-46	Tirupati, AP, India	-	Pod yield	Parents, JUG-37, JUG-43 and TIR-46 were desirable general combiners for pod yield, drought tolerance.	Venkateswarlu *et al*, 2007
86.	Spancross and NC 3033	-	-	Pod yield	The increase in pod yield was 21 and 23% for the drought resistant cv. Spancross and NC 3033	Womble and Garren, 1978
87.	TMV2 (Tindivanam 2)	-	-	leaflet area, leaf closure	Leaflets under water stress reduced areas and showed greater movement (leaf closure) than control.	Babu *et al.*, 1983
88.	TIR-21,34, JAL-07 & CSMG 84-1	-	-	Yield	Genotypes TIR-21, TIR-34, JAL-07 and CSMG 84-1 are better under higher temperatures.	Babitha *et al*, 2006
89.	Yuhua 13 and FDR-S10 dragon-type				Under drought stress, water potential was higher in the dragon-type cultivars than other.	Jiang and XiaoPing, 2004
90.	X537B, Florunner & X487A			Thermo stability of cellular membranes	Genotype x date interactions observed, but Pearl Early Runner, X537B, Florunner and X487A were the most heat tolerant	Bennett and Hammond, 1982

Where, FL= Flowering, FR= Fruiting, PI= Pod initiation, PD= Pod development, VG= Vegetatitive, RP= Reproductive, M= maturity, MI= Maturity initiation stages, FI= Flower initiation, Pg I=Peg initiation

Under limited rainfall conditions, the crosses of GG 2 x NCAC 17135, GG 2 x PI 259747, J 11 x PI 259747 and S 206 x FESR 8, kisan x FESR-S-PI-B1-B and the genotypes JB 223 and 224 recorded consistently superior and stable yield for the three years and could be grown under regions of limited rainfall and may be used as parents in breeding programmes for developing drought tolerant groundnut cultivars (Mandavia *et al.,* 2007). Six groundnut cultivars grown on a deep Vertisol or a shallow silty loam in the kharif season showed highest pod and total DM yield/plant in cv. TAG 24 in deep soil, and in cv. JL 24 on shallow soil. In water-stressed conditions, the tolerant cv. JL 24 partitioned more of the total DM to pods than did drought susceptible cultivars (Dhopte and Ramteke, 1994).

The transpiration response of 14 transgenic groundnut genotypes to water deficit was studied under greenhouse along with JL 24 as control by exposing the plants to drought stress (absence of irrigation) at 19 DAS where JL 24 started showing wilting symptoms (loss of turgor) after 21 days of stress, with severe symptoms later on. JL 24 reached the stage III (normalized transpiration rate or NTR <0.1) after 27 days. Wilting symptoms were not observed in the transgenic lines even after 21 DAS but later on these lines exhibited different levels of wilting symptoms, with a few transgenic lines showing no symptoms, and lines RD 14, RD 22 and RD 25 showing reduced levels of symptoms compared to JL 24. The transgenic lines varied largely in the number of days to reach the end point. RD 14 reached the end point in 29 days, whereas RD 4 reached the end point in 52 days. Data on NTR, fraction of transpirable soil water, and number of days to end point were subjected to average linkage cluster analysis for the development of a dendrogram indicating that the lines could be classified into 4 groups, as the transgenic lines varied in their stomatal response to water deficit (Mathur *et al*., 2004).

The mechanism of water stress by leaflet angle variation when studied for cv. Tindivanam 2 (TMV 2) groundnut plants, radiation avoidance by leaf closure was exhibited to different degrees by water stressed plants and leaflets in plants under continuous water stress reduced areas and showed greater leaflet movement (leaf closure) compared to the amount of movement of leaflets on plants without water stress (Ramesh Babu *et al*., 1983). At Vriddhachalam, evaluation of 68 groundnut genotypes for agronomic characteristics during rainy season the ICGS 76 and TAG 24 performed better under irrigated conditions, ICG 221 performed best in the simulated stress environment (rain out shelter), and ICGV 86635, DH 43 and ICG 2716 performed best under rainfed conditions (Arjunan *et al*., 1997).

Relative drought tolerance of 17 groundnut genotypes when evaluated under six gradients of moisture stress using line-source irrigation, the JL 24 and ICG 5266 had high yield potential at all the moisture regimes but yield reduction with increasing moisture stress was higher than in other genotypes. On the other hand the ICG 4504 and GPHY 35 showed low yield potential under control as well as lesser yield reduction under increasing moisture stress (Shashikumar *et al*., 1988). In groundnut cv. JL 24 grown in pot, water stress reduced number of nodules, leaf area, total DW and total chlorophyll and leaf protein contents and Ca application increased growth parameters and chlorophyll and protein contents (Mohan and Rao, 1989).

During February-May, the variation of micrometeorological parameters when assessed within different groundnut cultivars TG 51, ICGS 44, TAG 24, TMV 2 and AK 12-24 and their yield potentiality the ICGS 44 recorded the highest net radiant energy (490-540 w/m^2) irrespective of the dates of observation and TG 51 showed the lowest value. Based on the average canopy temperature value the cultivars are arranged in the following order TAG 24> ICGS 44> AK 12-24> TG 51> TMV 2. The lowest water stress was experienced by TMV 2 and highest by TAG 24. The highest and lowest pod yield was produced by TAG 24 and AK 12-24 cultivar, respectively (Mukherjee *et al*., 2010).

Table 7. Drought sensitive groundnut cultivars/varieties reported in various soils and climate

SN	Sensitive varieties/ cultivars	Soil type, Place	Phenophase	Criteria used	Details of Drought tolerance	References
1	JL 24	Medium black, Junagadh	VG, PD	Transpiration and leaf psi and RWC.	Drought sensitive variety	Joshi *et al*., 1988
2	Florman INTA	-	-	yield and oleic/linoleic ratio,	Nine variables along with yield and its compone-nts, and oleic/ lino-leic ratio, showed drought sensitive	Collino, 2000
3	M-13	-	FL stage (30 DAS)	RuBP carboxylase, PEP carboxylase	PEP carboxylase activities increased with stress RuBP carboxylase & NADP-glyceral-dehyde-3-phospha-te dehydrogenase decreased gradually.	Sharma *et al*., 1993
4	Cultivar 55-437	Sahel	flowering	Partitioning coefficient, yield, LAI RWC and T	The partitioning coefficient & yield under water stress reduced, affected LAI, RWC & tran-spiration at 2 wee-ks of water deficit at the soil level	Clavel *et al*., 2004
5	SB XI and UF 70103	-	12 d after sowing	Yield	UF 70103 and SB XI gave av. yields of 3.28 and 2.43 t/ha, resp.	Jadhao, *et al*., 1989

6	AK-12-24	Bhubaneswar, Orissa, India	15 DAS of sowing	Crop coefficient value	Plants stressed at vegetative stage exhibited the lowest crop coefficient value (0.61) at initial stage and the highest value (1.33) at peak growth stage and lesser water evaporation from the soil surface.	Kar *et al.*, 2001
7	Chitra	-	30 DAS, 60 DAS	Proline, peroxidase, seed yield	Proline content and peroxidase activity increased with the simulated drought	Neelam-Yadav *et al.*, 2007
8	Ak 12-24, J-11, GAUG-1 and GG-3		pod initiation/ development stage	Viability, vigour, seed membrane integrity, dehydrogenase	Water stress at the PI, PD stages reduced germinability, vigour, seed membrane integrity, embryo RNA content, and dehydrogenase activity in cotyledons during germination	Nautiyal *et al.*, 1991
9	Florunner	Yoakum, Texas	-	Yield	Water stress increased proportion of small seeds.	Schubert and Sanders, 1985
10	Florigiant and Florunner	-	Germination	Seed weight of sound mature seed	Drought reduced the av. seed wt. of sound mature seed in Florigiant and Florunner but not in Tifspan	Pallas JE Jr *et al.*, 1977
11	JL-24	-	-	Proline , K content	Proline accumulation and tissue K content.	Venkateswarlu *et al.*, 1993
12	JL-24	-	-	Cell membrane stability	Kadiri-3, the drought tolerant cultivar maintained higher CMS than JL-24, the drought susceptible one.	Venkateswarlu and Ramesh, 1993

13 ICGS 44	-	Reproductive stage		The reproductive stage (35-115 days after sowing) was the most sensitive.	Reddy *et al.*, 1996
14 GG 11	Gujarat	-	Yield	Water stress during the late crop growth stages resulted in low yields	Sahu *et al.*, 2004
15 Konkan Gaurav	Palghar	-	Pod yield	Applying 7-11 irrigations gave higher pod yield than 5 irrigations.	Chavan *et al.*, 1999

Where, FL= Flowering, FR= Fruiting, PI= Pod initiation, PD= Pod development, VG= Vegetatitive, RP= Reproductive, M= maturity, MI= Maturity initiation stages, FI= Flower initiation, Pg I=Peg initiation

A combining ability analysis for drought tolerance and yield traits was conducted during rabi in Tirupati, AP, involving 8 parents (TIR 46, JUG 37, ICR 45, TIR 10, K 134, JAL 6, JUG 43 and JL 24) of groundnut in all possible combinations excluding reciprocals, where mean squares for both general combining ability (GCA) and specific combining ability (SCA) were significant for all the characters indicating the involvement of both additive and non-additive gene action in the inheritance of characters (Venkateswarlu *et al*, 2007). In general, high magnitude of GCA variance depicted the greater importance of additive gene action in the inheritance of traits and the parents, JUG 37, JUG 43 and TIR -46 emerged as desirable general combiners and the crosses K 134 x JUG 43, K 134 x JL 24 and TIR 46 x JAL 6 were the most desirable specific combinations for pod yield, drought tolerance and yield attributes (Venkateswarlu *et al.*, 2007).

For the identification of candidate QTLs for drought tolerance, a comprehensive and refined genetic map containing 191 SSR loci based on a single mapping population (TAG 24 x ICGV 86031), segregating for drought and surrogate traits was developed by Ravi *et al*, (2011) and genotyping and phenotyping data for more than ten drought related traits in 2-3 seasons were analyzed in detail for identification of main effect QTLs (M-QTLs) and epistatic QTLs (E-QTLs) using QTL Cartographer, QTL Network and Genotype Matrix Mapping (GMM) programmes. A total of 105 M-QTLs with 3.48-33.36% phenotypic variation explained (PVE) were identified using QTL Cartographer, while only 65 M-QTLs with 1.3-15.01% PVE were identified using QTL Network. A total of 53 M-QTLs were such which were identified using both programmes. On the other hand, GMM identified 186 (8.54-44.72% PVE) and 63 (7.11-21.13% PVE), three and two loci interactions, whereas only 8 E-QTL interactions with 1.7-8.34% PVE were identified through QTL Network. Interestingly a number of co-localized QTLs controlling 2-9 traits were also identified.

The identification of few major, many minor M-QTLs and QTL x QTL interactions in the study confirmed the complex and quantitative nature of drought tolerance in groundnut and study suggests deployment of modern approaches like marker-assisted recurrent selection or genomic selection instead of marker-assisted backcrossing approach for breeding for drought tolerance in groundnut (Ravi *et al*, 2011).

Five years of study on drought at DGR during 2005-2010 developed a concept on ideotype for water use efficiency and drought tolerance in groundnut and efficient root systems for maximum productivity under both irrigated and rain-dependent systems (DGR, 2010, 2009; Nautiyal *et al*., 2012). In groundnut, compact canopy showed lesser leaf and canopy temperatures. The SLA, distance between two leaflets and petiole length were inversely associated with P_N and WUE. Number of branches and LAI during vegetative and early reproductive stages were directly associated with higher productivity (r = 0.62**), and JAL 42 an advance breeding line was ideal plant type under irrigated condition of summer season. The groundnut is characterized with degree of leaf folding to avoid the incidental radiations, especially under water deficit stress to avoid the water loss through leaf surfaces, i.e., higher the degree of leaf folding more drought tolerance (DGR, 2010). The large water storage cells, high stomatal density with small stomatal cell on both upper and lower surfaces of the leaf, higher palisade and spongy parenchyma cell thickness, higher number of xylem rows and number of cells are associated with drought tolerance, in groundnut. The epicuticular wax load accumulated under water deficit conditions cause drought avoidance mechanism. Plant height under water stress was associated positively with thickness of epidermis and inversely with thickness of palisade cell and number of xylem rows (DGR, 2010).

Uniform field emergence, early ground cover and synchronized flowering are desirable. The crop maturity period is positively associated with total biomass production, but inversely with harvest index (HI). The increase in pod yield, has been achieved is mainly due to increased HI. The groundnut cultivar with lower SLA and higher leaf area index and higher rate of biomass production during vegetative and early reproductive stage is a desirable trait (DGR, 2010). Water deficit stress is also associated with high temperature and in groundnut, a tolerant type is efficient in maintaining cell membrane integrity under high temperature stress, and accumulates less reserve food in stem but higher proline contents under water-deficit stress.

During rainy season under moisture-deficit, the low SLA groundnut cultivars were able to maintain higher RWC, P_N and stomatal conductance (g_s) with significant relationship between RWC and P_N (r= 0.91, P<0.01), and RWC and g_s (r=0.65, P<0.01) and a significant inverse association between SLA and RWC (DGR, 2010). The low SLA types (water use efficient) were drought tolerant in terms of total dry mass production and maintenance of higher RWC under water-deficit. Drought tolerant cultivars with higher biomass and pod yield could be made by combining high HI and WUE in terms of lower SLA. A superior rate of biomass accumulation and actual yield accumulation in order to acquire a higher HI is needed (DGR, 2010). The cultivar TAG 24 is most promising under summer season as it has higher P_N, g_s, HI and lower ΔT and higher stability in pod yield, stand close to the ideotype suitable for cultivation during summer season (DGR, 2010, 2009; Nautiyal *et al.*, 2012).

In a recent field study with six Spanish groundnut cultivars ('SG 99', 'ICGS 44', 'ICGV 86031', 'AK 159' and 'DRG 1') during summer season, Kalariya *et al.* (2012a) reported that water deficit stress at 30-60 DAS (WS1) and 60-85 DAS (WS2) reduced leaf RWC, Membrane Stability Index (MSI), but increased chlorophyll content, as compared to control plot irrigated at weekly interval. Under water deficit stress the leaf RWC reduction in 'ICGV 86031' (6.4% under WS1) and 'DRG 1' (10% in WS2) and reduction in MSI was highest in 'SG 99' and 'DRG 1' (22%). Under water deficit condition at Junagadh, the minimum fluorescence (F_0) and NPQ increased but the maximum quantum yield of PS II (Fv/Fm) and photosynthesis decreased (Kalariya *et al.,* 2012b). The rate of photosynthesis which was 29 and 36 μ mol m^{-2} s^{-1} in control plots decreased to 26 and 28 μ mol m^{-2} s^{-1} by imposing water deficit condition between 31-61 DAS and 61-87 DAS, respectively. The variety TAG 24 showed better stress recovery capacity with high photosynthesis under well watered as well as under water deficit condition whereas, data on chlorophyll fluorescence showed that variety ICGS 44 was least affected to damage via photoinhibitory action. Stress susceptibility index (STI) revealed that 'ICGS 44', 'TAG 24' and 'SG 99' were superior varieties compared to others.

In groundnut, WUE is correlated with SPAD chlorophyll meter reading (SCMR) and specific leaf area (SLA). These two traits, SCMR and SLA, can be used as surrogate traits for selecting for WUE. In order to improve SCMR and SLA, and in turn WUE in groundnut, a good knowledge of the genetic system controlling the expressions of these traits is essential for the selection of the most appropriate and efficient breeding procedure.

The Photosynthesis, Chlorophyll fluorescence and SPAD Chlorophyll meter reading (SCMR) were studied in 30 groundnut minicore germplasms during 70-90 Days after sowing during *Rabi-summer* 2012 where photosynthesis rate ranged from minimum of 18.3 µmol m^{-2} s^{-1} in NRCG 14327 to maximum of 34.2 µmol m^{-2} s^{-1} in NRCG 14338, while SCMR readings ranged from lowest value of 31 in NRCG 14332 to highest value of 41 in NRCG 14331, and the chlorophyll fluorescence highest Fv/Fm among the genotypes was 0.85 for NRCG 14347 (Nakar, *et al.,* 2012). Averages for Fv/Fm, SCMR and Photosynthetic rate in these groundnut genotypes were, 0.9, 37.3 and 28.1 respectively. On the basis of three physiological parameters studied, the physiologically efficient groundnut genotypes indentified were NRCG 14329, 14328, 14324, 14338, 14331, 14337, 14354 and 14348 accessions while the genotypes with NRCG accessions, 14351, 14347, 14332, 14343, 14344, 14335, 14327, 14351 and 14350 were physiologically less efficient. A positive correlations with r value of 0.28 between Fv/Fm and Photosynthetic rate, 0.67 between SCMR and Fv/Fm and 0.36 between Photosynthetic rate and temperature was observed indicating that these parameters account for physiological efficiency in groundnut.

5.6. Land configuration, Spacing and Intercropping

The land configuration, plant spacing and crop intercropping play an important role in increasing water use efficiency and finally pod yield as decreasing irrigation rates increases stomatal resistance, soil moisture tension and PAR penetration, and decreased transpiration rate, LAI, Pod yield and total DM (Dwivedi *et al.,* 1986d). Four type of canopy orientations S-N, E-W, radial and cross, at full, two-thirds or half the conventional irrigation rate (2.5 cm water applied at intervals of 10, 15 and 20 days, resp, giving totals of 30, 20 and 15 cm) were studied taking a Spanish bunch groundnuts cv. J 11 in Gujarat, The cross orientation favoured soil moisture storage compared with others (Dwivedi *et al.,* 1986d). Energy harvesting efficiency decreased with increasing water stress but the adverse effect was lower in cross than in the other treatments. The highest harvesting efficiency occurred in radial at the high irrigation rate. concluded that cris-cross was the most favourable orientation in terms of pod yields and energy harvesting by groundnuts (Dwivedi *et al.,* 1986d).

In an alfisol at Hyderabad the groundnut cv. TMV 2 grown in rows 35, 70 or 120 cm apart, the transpiration of ground cover (which varied 3-fold between spacings) and root: shoot ratio, was substantially greater in the wider row spacings; when the soil was wet, both the transpiration rate (T) and the canopy conductance (gc) were approximately proportional to the fraction (f) of incident radiation intercepted by foliage, but when the soil water content decreased below a threshold value, T/f and gc/f decreased because of an increase in stomatal resistance (Simmonds and Azam-Ali, 1989). Stomatal closure in response to soil water stress occurred sooner in the denser stands, because of more rapid depletion of soil water, also the sparser stands (which had a relatively large root: shoot ratio) had a greater capacity to keep stomata open as the soil water deficit increased (Simmonds and Azam-Ali, 1989).

In Japan, Runkulatile *et al*. (1998) characterized intercropping advantages in groundnut-finger millet (*Eleusine coracana*) intercrops in relation to crop combination ratios, soil moisture and nitrogen (N) availability taking three intercrops in 1:2, 1:1 and 2:1 alternating rows of groundnut and finger millet, their growth and yield in comparison with single crop and also the effect of adequately watered (W) and water stressed (D) conditions on the intercropping advantage for 1:1 intercrops revealed that the total aboveground biomass (DM) and its land equivalent ratio (LER) were highest in the 1:1 combination ratio. Intercropped groundnut exhibited significantly higher DM production after finger millet harvesting. The LERs were consistently higher under D than W conditions. Water stress severely reduced the leaf area index (LAI) of finger millet at the lower N rate, especially in the later stages, whereas higher N alleviated the water stress effect. A close linear relationship was observed between LAI and leaf area (LA) per unit leaf N both for groundnut and finger millet, with intercrops producing larger LA per unit leaf N than single crops. Intercropping maintained leaf net photosynthesis and transpiration of groundnut up to the later stages, and reduced water evaporation from soil surface compared with single cropping of finger millet (Runkulatile *et al*., 1998).

An intercrop consisting of 1 row of sorghum between 2 rows of groundnut grown under two irrigation treatments a 'wet' (water stress was kept to a minimum by frequent irrigation) and a 'dry' treatment which received less water reveals that total crop performance ratio in wet intercrop was only 3% more total DM than the 2 crops separately, whereas in the dry treatment the advantage was 21%, the reproductive yield advantages were 14% and 88% in the wet and dry treatments, respectively, showing larger harvest indices in the intercrops (Harris *et al*., 1987). Intercropped sorghum produced more TDM, but intercropped groundnut produced less, while leaf area indices were lesser than expected in all intercrop components. Sorghum intercepted more radiation in the intercrop than in the sole crop, but used it to produce DM less efficiently when water was plentiful. Groundnut intercepted less radiation than expected, but used it with greater efficiency in both wet and dry treatments. As well as intercepting more radiation, intercropped sorghum also used it more efficiently when water was limited, suggesting that sorghum was able to compete more successfully for soil water with groundnut in the intercrop than with itself in the sole crop (Harris *et al*., 1987).

Further studies in a replacement series, intercrop of two rows of groundnut cv. Kadiri 3 alternating with one row of sorghum hybrid CSH-8, increased grain and filled-pod wt/plant due to intercropping were large, especially in drought stands sorghum, grain yields were 38 and 93% higher per unit row in the irrigated and drought treatments, respectively, while groundnut produced 81% more filled-pod wt per unit row than did sole stands during drought (Harris and Natarajan, 1987). Harvest index was larger for both species in the intercrops, by 8% and 33% in sorghum, and by 12% and 68% in groundnut in irrigated and drought treatments, respectively. In groundnut, HI was increased in the irrigated intercrop because individual pods were heavier, whereas the intercrop subjected to drought produced twice as many pods per plant in comparison with the sole crop. Large differences in plant temperature and water status between irrigated and drought stands throughout the post-rainy season, but mean differences between sole crops and intercrops within each water regime were small. Shading of groundnut by sorghum in the intercrop ameliorated to some extent the effects of high temperature and water stress, in the droughted stands. This was particularly important during peg production. It is suggested that less damage to flowers in the drought intercrop resulted in more pegs forming pods than in the sole crop, leading to the observed advantage in HI in groundnuts (Harris and Natarajan, 1987).

Using a line-source irrigation Natarajan and Willey, (1986) tested the range of moisture regimes (S1 to S5 in order of increasing moisture stress) on sole crops of sorghum cv. CSH 8R, *Pennisetum americanum* cv. BK 560 and groundnut cv. Robut 33-1, and intercrops of sorghum:groundnut at 1:2-3 rows, and *P. americanum*:groundnuts with 1:1-3 rows showed DM yield advantages of intercropping over sole cropping 8 to 30% for the *P. americanum*: groundnut systems and 0-19% for the sorghum/groundnut systems; moisture stress had no consistent effect on these DM advantages. For reproductive yields, all the intercropping systems showed some increase in relative advantages with increase in stress because of higher harvest indices in intercropping than in sole cropping. Largest advantages were 93% for sorghum + 2 rows of groundnut at S5 moisture regime and 78% for *P. americanum* + 2 rows groundnuts at S4 moisture regime, both of these being greater than at S1. The level of stress giving peak advantages depended on crop combinations and crop proportions (Natarajan and Willey, 1986).

Herbaceous legumes are becoming increasingly important for the crop-livestock farming systems in the moist and semi-arid regions of West Africa as these crops cover the ground quickly, check erosion, contribute to soil fertility and provide nutritious food and fodder to human beings and livestock. However, one of the major constraints in this region is the long dry season, which limits the productivity and duration of crop growth. A concerted effort was made to identify most suitable species and varieties with desirable agronomic traits including drought tolerance and high yield potential taking 72 accessions/varieties of relevant herbaceous legumes along with 3 cereals-millet, sorghum and maize for their relative drought tolerance in the wooden box method (130 cm long, 65 cm wide and 15 cm deep filled with soil of loamy composition). The number of days taken to first, 50% and 100% plant deaths as a measure of drought tolerance for different accessions/varieties showed that soybean variety TGX 1445-1D was the most susceptible as all plants were dead in 13 days while the lablab variety TLN 13 was the most drought tolerant which survived up to 46 days after stopping water. Based on the number of days taken to attain 100% plant death, the most drought tolerant group comprised of lablab, horse gram, centrosema and cowpea followed by chamaecrista and pearl millet as the second group; velvet bean, joint vetch, crotolaria, stylosanthes, sorghum and groundnut formed the third group and blue pea and soybean as the most drought susceptible group (Ewansiha and Singh, 2006).

On a well-drained Millhopper fine sand, maize, sorghum, groundnuts and sorghum-groundnuts intercropping subjected to four water treatments (optimum irrigation, irrigation allowing 2 d of wilting on sorghum or on groundnuts, and rainfed and visible crop water stress symptoms and daily soil water budgets using soil water depletion method) reveals that yields of maize, sorghum and groundnut increased linearly with seasonal irrigation and ET, with the respective slopes of the irrigation production functions 511, 204, and 160 kg ha-1 cm for DM and 341, 177, and 67 kg ha-1 cm for grain yields respectively and slopes of ET functions were 627, 486, and 383 for DM and 417, 397, and 198 for grain yields respectively (Omoko, 1990). The Irrigation-use efficiencies (IUE) were 82, 45, and 34% for maize, sorghum and groundnut, respectively. Yield levels in the irrigated treatments reached their near optimum potentials for all 3 crops and using LER concept, sorghum-groundnut intercrop yielded 15-36% more than pure stands, and the yield advantages increased with increasing irrigation, however, these advantages partially or completely disappeared when the analysis was done on the land water-use equivalency ratio (LWUER) concept. Similarly, intercropping did not provide any WUE superiority when its conjugate water production functions were compared with those of its equivalent sole crop and also intercropping did not improve yield stability (Omoko, 1990).

The WUE of groundnut sole (GG), sorghum sole (SS) and sorghum-groundnut intercrop (SG) were compared by Omoko and Hammond (2010) for two consecutive years with sorghum (*Sorghum bicolor* L. Moench) and groundnut on a loamy, Grossarenic Paleudult, using four water managements (T_1 Optimum irrigation, T_2 deficit irrigation allowing stress on sorghum, or T_3 on groundnut, T_4 rainfed, and crops seeded in rows at a density of (256000 (SS), 160000 (GG), 256000 + 160000 (SG, year 1), 157000+102000 (SG, year 2) plants/ha), sorghum grain yield (GY) range 3.55 (T_4) to 8.03 (T_1) Mg/ha in sole crop, and 2.71 to 6.27 Mg/ha in intercrop whereas the groundnut grain yield was 3.76 to 6.54 Mg/ha sole crop, but decreased in intercrop (0.13-3.26 Mg/ha). The mean Total Land Equivalent Ratio (TLER) was 1.14 for DM and 1.11 for grain yield (GY), showing a 14 and 11% advantages over sole cropping. But these advantages disappeared when the amount of water used was taken into account in the Total Land Water Use Equivalency Ratio (TLWUER). The overall mean TLWUER were 1.01 (irrigation) and 0.99 (seasonal ET) for DM, 0.98 and 0.96 for GY, indicating no advantage of intercropping over sole cropping. Nevertheless, based on water use ratios, intercropping was more water use efficient than sole crops. The contrasting results between the TLER and TLWUER may imply that the yield advantage of intercropping was not attributable to its overall improved water use ratio but rather to its higher seasonal water use (Omoko and Hammond, 2010).

5.7. Crop Modeling and its Simulation

A highly flexible and user-friendly method, with provisions to modify each input variable based on actual site and management requirements, was developed by Parekh and Shete (2008) using data on agro meteorological parameters (max and min temperature, dry and wet bulb temperature, sunshine h, pan evaporation, wind velocity, RH and rainfall) for 1991-2004 to estimate the daily water balance for summer groundnut and determine the optimum irrigation scheduling based on the daily crop water requirement (Reference crop ET calculated using meteorological data and daily crop water requirement calculated using the dual crop coefficient approach), where the crop coefficient varied with the crop growth stage and climatic condition in the area, and accordingly the irrigation scheduling can be planned using a computer programme based on MS Excel to avoid soil water stress.

The phenotype models utilized by plant breeders are partition traits reproductive yield (Y), and components of genetic (G), environmental (E), and GE interaction as yield commonly has large GE interaction. Breeders often have little information concerning the physiological basis of this GE interaction, without a clear idea of how to exploit the material further. Better knowledge of the physiological basis for the differential responses of genotypes to specific environments should improve the efficiency with which the breeder can characterize material for its G, and GE interaction, and hence increase the speed at which superior genotypes can be identified. Wright *et al.* (1996) described a simple physiological model to improve the understanding of the basis of GE interactions in groundnut under drought conditions. The physiological model, proposed by Passioura (1977) was used to define the yield (Y) as the product T x TE x HI, where T = amount of water transpired, TE = transpiration efficiency and HI = harvest index. Past and current studies have attempted to quantify these components in easily measurable ways. TE in groundnut was measured via carbon isotope discrimination and specific leaf area. T was estimated by substituting estimates of Y, TE, and HI in the identity above. The components analysed from an experiment consisting of 50 genotypes grown across multiple environments (seven locations) indicated selection of parents/genotypes with specific adaptive traits, highlight negative associations between yield determining traits. The sp. assumptions were further verified in an international collaborative project involving Indian and Australian scientists (Wright *et al.,* 1996).

Increased atmospheric CO_2 concentration will benefit the yield of most crops as two free air CO_2 enrichment (FACE) meta-analyses have shown increases in yield between 0 and 73% for C_3 crops. A novel perturbed-parameter method of crop model simulation based on peanut version of the general large-area model for annual crops (GLAM) was proposed by Challinor and Wheeler, (2008) where increases in yield simulated by GLAM for doubled CO_2 were between 16 and 62%. The difference in percentage increase between well-watered and water-stressed simulations was 6.8. These results were compared using CROPGRO and the groundnut model of Hammer *et al.*, (1995). The relationship between CO_2 and water stress in the models when examined, study shows that from a physiological perspective water-stressed crops are expected to show greater CO_2 stimulation than well-watered crops. However, this result is not seen consistently in either the FACE studies or in the crop models. In contrast, leaf-level models of assimilation do consistently show this result. The evidence from these models and from the data suggests that scale (canopy versus leaf), model calibration and model complexity are factors in determining the sign and magnitude of the interaction between CO_2 and water stress and the statement that 'water-stressed crops show greater CO_2 stimulation than well-watered crops' cannot be held to be universally true. Further the relationship between water stress and assimilation varies with scale (Challinor and Wheeler, 2008).

Deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield. Models can play a major role in developing practical recommendations for optimizing crop production under conditions of scarce water supply. The applicability of FAO CROPWAT model on deficit irrigation scheduling for groundnut, was assessed at Bhavanisagar, Tamil Nadu during summer and Rabi where moisture stress imposed during flowering and pod formation stages were more sensitive than other stages and CROPWAT model can effectively simulate yield reduction as a result of moisture stress imposed by deficit irrigation at various growth stages (Thiyagarajan, and Ranghaswami, 2010).

In crop modelling, one of the most important problems is the model calibration for different cultivars (Gauch, 1988). In order to make a predictive model reliable it is necessary to find ways to calibrate it efficiently for different cultivars. Significant variability of photosynthesis rates between groundnut cultivars suggests that gas exchange parameters should be analyzed. Farquhar's model is often used to simulate photosynthesis on both levels of organization, single leaf and canopy. Ferreyra *et al.* (2000) showed that the simulated differences in both transpiration and photosynthesis qualitatively agree with observations of biomass vs. LAI and water consumption vs. LAI of experimental plots. With the inclusion of additional relevant phenomena such as heliotropism and canopy light distribution, the 2-dimensional model of leaf gas exchange 2D LEAF may be used to explain differences in water stress tolerance between different cultivars, and serve as a fine-tuning tool for other applications such as crop-scale peanut simulation models. A Theoretical model of water stress tolerance in groundnut proposed by Kameswara Rao *et al.* (2009) is given in Figure 1.

Representative model depicting the pathways implicated in water-deficit tolerance in groundnut leaves. Proteins identified in this study are displayed on the corresponding metabolic pathways. Solid arrows indicate induction of a particular protein, and dashed lines represent reduction. Dark, thick arrows show the signal molecules generated downstream of a pathway. ABA, NDK1 (nucleoside diphosphate kinase 1), TPR (tetratricopeptide repeat), DREB (water-deficit stress response element-binding protein).

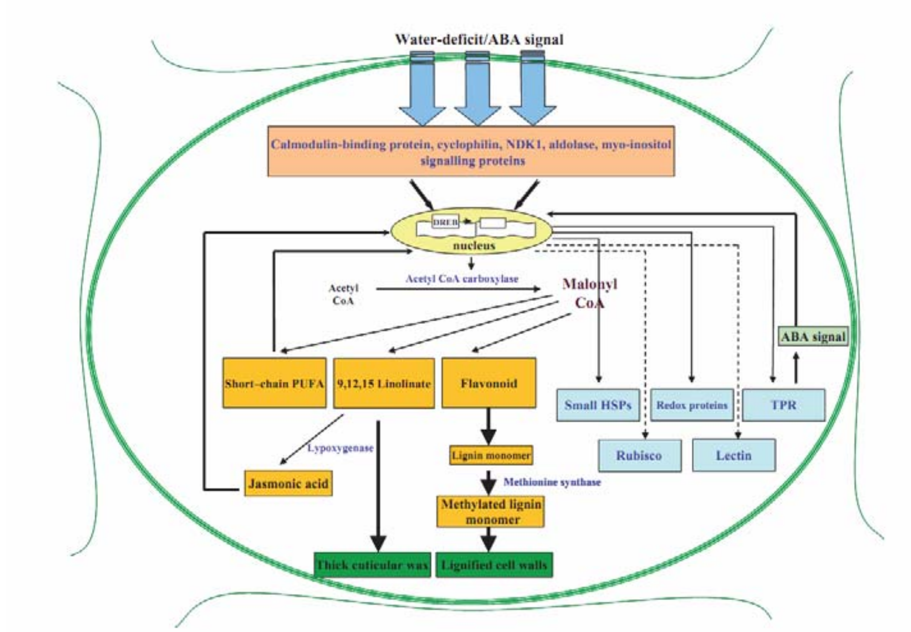

Fig. 1. Theoretical model of water stress tolerance in groundnut (Kameswara Rao *et al.,* 2009).

The PNUTGRO model calibrated and validated for a subhumid climate and sandy loam soil of Kharagpur, West Bengal by performing multiple year simulation to recommend a set of alternate decisions with different levels of assurance for effective management of water in groundnut crop, using actual weather data for 10 years and the study reveals that under limited water availability, a soil water depletion of more than 60% of plant extractable soil water should be allowed during the non-critical stages, but, 30% of ASW depletion can be allowed during critical stages of crop growth, at a moderate risk level of 50%, without affecting the crop yield where full irrigation is recommended for risk levels up to 30% (Panda *et al*., 2003).

In NE Thailand the MACROS crop model evaluated for its utility to generate information on land suitability for dry season groundnut cropping based on water availability at the regional scale indicated that the model was specific for the condition where crop growth is limited by water stress, and evaluated using both calibration and validation phases in sequence (Katawatin *et al.*, 1996). The dynamics of observed and corresponding simulated values of shoot dry weight agreed in every condition involved in this validation study also the simulated pod yields agreed with the field data. For the validation B, where model was further validated using data from 35 farm trials conducted at 5 different test sites, a high positive correlation (r=0.91) existed between observed and simulated pod yields (Katawatin *et al.*, 1996).

In another study in Thailand the CSM-CROPGRO-Groundnut model in simulating the responses of groundnut cultivars Tainan and KK 60-3 to three levels of soil moisture regimes (FC, and 2/3 and 1/3 available water) when evaluated and data collected on the growth and development compared with the corresponding simulated data, the model performed fairly in simulating the phenological development and patterns of dry matter accumulation but performed reasonably well in predicting the final biomass and pod yields (Dangthaisong *et al.*, 2006). The model predicted the relative yield reductions from drought stress of the individual groundnut cultivars quite accurately and provided information on the time of occurrence and severity of water stress during the cropping period. Thus, the CSM-CROPGRO-Groundnut model is sufficiently capable to be used in generating the required information for determining appropriate management during drought stress (Dangthaisong *et al.*, 2006).

A crop weather model to predict the growth and pod yield of groundnut based on the dry matter accumulation at each growth stages was developed Rajegowda *et al.* (2010) where multiple linear regression equations relating to GDD, SSH and AET with the dry matter production during each growth stages and also the final pod yield of kharif crop were generated by using the field experimental data for the period of 2000-2008. The coefficient of determinants indicate that the climatic parameters and the initial TDM used to estimate the final TDM in each stage could predict an extent of 77 to 98 per cent (coefficients of determinants) in different growth stages. Comparison of the observed and the predicted yields indicates the close agreement between them in all the stages. Considering the observed TDM up to the first four stages and predicted the Total Dry Matter at the harvesting stage when model was validated for the year 2009, and there was a good agreement between the observed and the predicted crop yield. The favourable influence of AET at the beginning of peg initiation and peg formation stage, and higher GDD during pod formation and harvest stages were noticed. The increase in AET during pod filling stage did not favour to the pod yield (Rajegowda *et al*, 2010).

Improved management (high yielding cultivars, balance crop nutrition and control of pest and diseases) in high rainfall regimes and rainfall conservation and supplemental irrigations in low rainfall regimes are essential components of the improved technologies aimed at bridging the yield gaps of groundnut (Bhatia *et al.*, 2009). To assess the scope for enhancing productivity of groundnut in India, well-calibrated and validated CROPGRO-Peanut model used to assess potential yields (water non-limiting and water limiting) and yield gaps of groundnut for 18 locations representing major groundnut growing regions of India where the average simulated water non-limiting pod yield of groundnut was 5440 kg ha^{-1}, and the water limiting yield was 2750 kg ha^{-1} indicating a 49% reduction in yield because of deficit soil moisture conditions (Bhatia *et al*., 2009). As against this, the actual pod yields of the locations averaged 1020 kg ha^{-1}, which was 4420 and 1730 kg ha^{-1} less than the simulated water non-limiting and water limiting yields, respectively. Across locations, the simulated water non-limiting yields were less variable than water limited and actual yields, and strongly correlated with solar radiation during the crop season (R^2=0.62, P<=0.01). Simulated water limiting yield showed a positive, but curvilinear relationship (R^2=0.73, P<=0.01) with mean crop season rainfall across locations. The relationship between actual yield and the mean crop season rainfall across locations was not significant, whereas across seasons for some of the locations, the association was found to be significant. Total yield gap (water non-limiting minus actual yields) ranged 3100-5570 kg ha^{-1}, and remained more or less unaffected by the quantity of rainfall received across locations. The gap between simulated water non-limiting and water limiting yields, which ranged from 710-5430 kg ha^{-1}, was large at locations with low crop season rainfall, and narrowed down at locations with increasing quantum of crop season rainfall. On the other hand, the gap between simulated water limiting yield and actual farmers yield ranged from 0 to 3150 kg ha^{-1}. It was narrow at locations with low crop season rainfall and increased considerably at locations with increasing amounts of rainfall indicating that type of interventions to abridge the yield gap will vary with the rainfall regimes (Bhatia *et al*., 2009).

5.8. Pre and Post Season Sowing

The effects of sowing time and rainfall distribution on the yield of groundnut cv. GG 11 were studied in Junagadh, Gujarat, India, during 1975-2003 by sowing the crop after sufficient amount of rainfall received during or after the 25th standard meteorological week (SMW) by Sahu *et al.* (2004) dividing the sowing time into two periods, i.e., timely sowing (25th and 26th SMW) and late sowing (after 27th SMW) and classifying each year as low rainfall year (<590 mm), moderate rainfall year (590-740 mm) or high rainfall year (>940 mm) where the yield varied from 100 kg ha^{-1} during dry year of 1987 to 1784 kg ha^{-1} during moderate rain fall of 1975. The correlation between rainfall during vegetative period and pod formation period was negative, indicating that moderate rainfall had synergistic effects on the yield under timely sowing. Under late sowing, rainfall during the vegetative and flowering stages had positive effects on the yield. It was concluded that the timely onset of monsoon and commencement of sowing in the 25th SMW resulted in moderate and high rainfall and good and moderate yields, whereas the late commencement of sowing resulted in low rainfall and low yields and water stress during the late crop growth stages (Sahu *et al.,* 2004).

The effects of moisture stress on yield components of 4 groundnut cultivars when studied at 2 irrigation levels (rainfed and irrigated) and 3 sowing dates the cv. Kadiri 3 followed by M 13, performed better under rainfed conditions than JL 24 and Gangapuri if sowing was delayed until July. If delayed further, to August, JL 24 and K 3 gave the best performances. Irrigation improved yields in both the seasons, the values for K 3, M 13, JL 24 and Gangapuri being 4.74, 3.53, 3.01 and 2.85 t ha^{-1}, respectively, during kharif and 5.17, 7.62, 3.85 and 5.8 t ha^{-1}, respectively, during rabi (Padma *et al.*, 1991). In summer withholding irrigation for up to 10, 15, 20, 25 or 30 DAE gave av. yields of 2.58, 3.02, 3.10, 3.15 and 2.41 t ha^{-1}, respectively in two groundnut cultivars. Yields increased linearly with a delay in applying irrigation up to 25 and 20 DAE, resp in SB XI and UF 70103 with av. yields of 2.43 and 3.28 t ha^{-1}, with the highest yields of 2.68 and 3.65 t, respectively (Jadhao *et al.*,1989).

In peninsular India at Hyderabad, four groundnut genotypes studied across a drought-stress gradient to determine the influence of insect distribution in the post-rainy season reveals that gelechiid leaf-miner *Aproaerema modicella* was most abundant on the most stressed plants, *Cicadellid empoasca* kerri had the reverse distribution, the thrips *Frankliniella schultzei* and *Scirtothrips dorsalis* were at first densest where drought stress was least and their distribution subsequently became reversed and, as the condition of their hosts worsened, they again became most abundant at the wetter end of the gradient (Wheatley *et al.,* 1989). Bud necrosis disease caused most mortality where drought stress was highest (Wheatley *et al.,* 1989).

5.9. Fertilizer, Organic Manures, Mulching and Others

The effects of moisture stress and gypsum on pod development and yield of groundnut when examined, the gypsum increased the pod and kernel yields of Samaru 38 variety as moisture stress at 9-13 weeks after sowing coincide with the period of peg and pod development, lowered the uptake of nitrogen and increased the proportion of unfilled pods, drastically reducing yield (Balasubramanian and Yayock, 1981). As gypsum increases early pod development, it provides an escape mechanism from drought (Singh and Chaudhari, 1995; Williams *et al.*, 1986). Gypsum applied at flowering increased yield of genotype subjected to drought but there was no response if there was no drought since soil contained adequate amount of available calcium of about 600 ppm (Rajendrudu and Williams, 1987).

The cyclic dry spells in calcareous Vertic Inceptisol, caused up to 75% reduction in pod yield and potassium at 60 kg K_2O ha^{-1} enhanced the level of production and could also restore the loss in pod yield to a noticeable extent. A marked increase in the diffusive resistance of leaves with K fertilization supports the contention that potassium plays an important physiological role in counteracting adverse conditions caused by drought (Golakiya and Patel, 1988). In a field experiment in Gujarat, groundnut cv. GAUG 1, the solar energy harvesting efficiency was highest with 20 kg K and decreased with increasing water stress (Umar and Umar, 1997). Excised leaves of groundnut cv. J 11 exposed to normal and moisture stress conditions showed proline accumulation and KCl enhanced proline accumulation. The KCl pretreatment enhanced conversion of arginine to proline under non-stress conditions. In groundnut proline accumulation was high in the leaves and levels of all the precursors were also high (Rao, 1979).

In acid lateritic soils at Jhargram, India, the response of groundnut cv. TAG 24 to moisture stress and application of organic manure (FYM) and fertilizer with and without gypsum studied during summer reveals that moisture stress at vegetative stage (10-30 DAS) gave 34% higher pod yield than that at flowering stage (30-50 DAS), but this moisture stress at vegetative stage was on a par with no moisture stress for pod yield, yield attributes, oil content and nutrient uptake (Dutta and Mondal, 2006). The highest use of water was recorded with no moisture stress, as a result maximum WUE was obtained under moisture stress during vegetative stage. Farmyard manure at 7.5 tonnes ha^{-1} resulted in better yield attributes, yield, oil content, nutrient uptake and WUE than the control. Recommended dose of fertilizer (RDF), i.e., 30 kg N ha^{-1}, 60 kg P_2O_5 and 40 kg K_2O when applied with gypsum 500 kg ha^{-1} increased the pod yield by 17 and 11.5% over 100 and 125% RDF alone respectively. However nutrient uptake and oil content were also influenced with increase in fertilizer level in combination with gypsum. Benefit:cost ratio was higher with moisture stress at vegetative stage and application of 7.5 tonnes FYM/ha or 100% RDF+500 kg gypsum/ha respectively (Dutta and Mondal, 2006).

On the sandy soils at Ismailia Research Station, two long-term field trials were conducted to investigate the effect of sulfate of potash (SOP) and muriate of potash (MOP) at 70 and 140 kg K_2O ha^{-1}. Sprinkler irrigation was used in one trial with rotations of wheat-groundnut, berseem (*Trifolium alexandrinum)*-sesame and berseem-groundnut; and drip irrigation in the other with sesame, faba bean-sesame, onion-groundnut, and faba bean-fodder maize rotations. In sandy soils, the amounts of total soluble salts and chloride in the surface layer of the soil slightly increased with sprinkler irrigation irrespective of whether K was added as SOP or MOP. However, with drip irrigation addition of MOP at 140 kg K_2O ha^{-1} increased the total soluble salts under the dripper area by 18 times and chloride by 35 times compared to the concentration at the beginning of the experiment. In sandy soils using sprinkler irrigation, increased yields 140 kg K_2O ha^{-1} by SOP, were approximately 14% for wheat, 40-43% for groundnut, 17-18% for berseem, and 23% for sesame (Hadi *et al.*, 2003).

In Rahuri, Maharashtra, during the summer the effects of mulching and water stress at different growth stages was studied on the performance of groundnut by mulching with sugarcane trash or white polyethylene along with water stress at the flowering, pegging or pod development stage. Mulching with white polyethylene along with water stress at the pod development stage resulted in the greatest plant height (37.77 cm), plant spread (25.23 cm), number of functional leaves per plant (72.59), leaf area per plant (21.17 dm^{-2}), dry matter per plant (17.77 g), dry pod yield (2896 kg ha^{-1}), haulm yield (4741 kg ha^{-1}), dry kernel yield (2083 kg ha^{-1}), oil yield (989 kg ha^{-1}), net monetary returns (34 097 rupees ha^{-1}) and benefit:cost ratio (2.44). The highest oil contents were obtained with polyethylene mulch along with water stress at the pod development stage (47.79%) and mulching with sugarcane trash along with water stress at the pod development stage (47.31%) (Bodare and Dhonde, 2011).

5.10. Hormones and Growth Regulators

Plant hormones are involved in multiple processes. Phytohormones are essential for the ability of plants to adapt to abiotic stresses by mediating a wide range of adaptive responses as it play central roles in the ability of plants to adapt to changing environments, by mediating growth, development, nutrient allocation, and source/sink transitions (Santner and Estelle, 2009). Plant growth substances have key role in different physiological processes related to growth and development of crops. The changes in the level of endogenous hormones due to biotic and abiotic stress alter the crop growth and any sort of manipulation including exogenous application of growth substances would help for yield improvement or at least sustenance of the crop. Hormones usually move within plant from a site of production to site of action. Phytohormones are physiological intercellular messengers that are needed to control the complete plant lifecycle, including germination, rooting, growth, flowering, fruit ripening, foliage and death. In addition, plant hormones are secreted in response to environmental factors such as abundance of nutrients, drought conditions, light, temperature, chemical or physical stress. Hence, levels of hormones will change over the lifespan of a plant and are dependent upon season and environment. Cross-talk between the different plant hormones results in synergetic or antagonic interactions that play crucial roles in response of plants to abiotic stress (Peleng and Blumwald, 2011). Although ABA is the most studied stress-responsive hormone, the role of cytokinins, brassinosteroids, and auxins during environmental stress is now being emphasised.

The key role of ABA, jasmonic acid (JA) and salicylic acid (SA) as primary signals in the regulation of plant defense has been well established (Bari and Jones 2009). These hormones generate a signal transduction network that leads to a cascade of events responsible for the physiological adaptation of the plant to stress. The degree of drought tolerance varies with developmental stages in most plant species (Reddy *et* *al*., 2004; Rassaa *et al*., 2008). ABA is well known hormone for its regulatory role in integrating environmental adversity with the developmental programs of plants. Thus, it affects a wide range of processes at different developmental stages such as embryo and seed development, acquisition of desiccation tolerance and dormancy, flowering and organogenesis (De Smet *et al*., 2006; Liang *et al*., 2007). ABA also promotes plant growth under non stressful condition and has shown to be essential for vegetative growth in several organs (Sharp *et al*., 2000; Chen *et al*., 2002).

Similarly, SA is an endogenous regulator of growth involved in a broad range of physiologic and metabolic responses in plants (Hayat *et al*., 2010). During the last few years, SA has been intensively studied as a signal molecule mediating local and systemic defense responses against pathogens. Currently, it has been reported that this compound plays also a role in plants responses to abiotic stresses, such as drought, low and high temperatures, heavy metals, and osmotic stress (Nemeth *et al*., 2002; Munne-Bosch and Peñuelas, 2003; Shi and Zhu, 2008; Rivas-San Vicente and Plasencia, 2011). SA was also shown to influence a number of physiological processes, including seed germination, seedling growth, fruit ripening, flowering, ion uptake and transport, photosynthesis rate, stomata conductance, biogenesis of chloroplast (Fariduddin *et al*., 2003; Khodary, 2004; Hayat *et al*., 2005; Shakirova, 2007).

JA, and its cyclic precursors and derivatives constitute a family of bioactive oxylipins that regulate plant development and responses to environmental cues (Turner *et al*., 2002; Devoto and Turner, 2003). This family of compounds is formed by 12-oxophytodienoic acid (OPDA), methyl jasmonate (Me-JA) are collectively receive the name of jasmonates (JAs). These molecules are involved in a variety of processes related to plant development and survival, including direct and indirect defense responses (e.g., defense against insects and necrotrophic pathogens, abiotic stresses viz. drought, salinity etc.), secondary metabolism, reproductive processes (e.g., pollen maturation and anther dehiscence, ovule development), and fruit development, among others (Seo *et al*., 2001; Wasternack and Hause, 2002; Liechti and Farmer, 2006; Wasternack, 2007). The participation of JA in response to abiotic stress, such as drought and salinity, has been reported in several species. For instance, the treatment of barley leaves with sorbitol or mannitol (compatibles solutes to simulate water stress) increased JAs endogenous contents, followed by synthesis of jasmonate-induced proteins (Lehmann *et al*., 1995).

The yield and quality of GAUG 1 groundnut under water stress during summer by withdrawing two irrigations in the first 30 DAE and various growth regulator treatments (50 ppm GA, 40 ppm NAA, 50 ppm IBA, 250 ppm daminozide, 500 ppm chlormequat chloride) applied alone or in combination and the effects of 12 irrigations + 50 ppm IBA on pod yields of cv. J11, GG 2 and Robot study reveals maximum pod yield (2.17 t/ha) by 250 ppm daminozide + 50 ppm GA treatment followed by 12 irrigations + 50 ppm IBA (2.15 t) and water stress + 50 ppm IBA (2.06 t), spraying with 50 ppm IBA at 40 and 60 DAS increased pod yield by 11-29% and gave the highest net return, but least cost:benefit ratio. Withdrawal of two irrigations in early growth followed by spraying of 50 ppm IBA at 40 and 60 DAS was economical (Patel *et al*., 1988).

Groundnut seeds soaked in 100 ppm GA_3 for 1 h and PEG for 24 h and subjected to drying for 0, 3, 5, 7 or 9 d when sown in soil containing 70, 40, 30, 21 and 14% moisture (w/w) to give 0, -0.1, -0.3, -0.6 and -15.0 bar, respectively, drying seeds for 9 d and growing in soil at 0 bar soil moisture decreased percentage seed germination to 80% compared with 91% with no drying (Golakiya, 1992). At -0.3 bar soil moisture, seed germination was 86% with no drying and 47% with 9 d drying. Pelleting seeds with polyvenyl alcohol, polyacryliamide and polyacrelic acid improved seed germination at low soil water potential the most effective germination was 78% with 7 d drying and -6.0 bar soil moisture when pelleted with polyacreliamide (Golakiya, 1992). Four groundnut varieties during summer and ten varieties during the rainy season grown, using seed pretreated with calcium chloride (1%) or ascorbic acid (50 ppm) the pod yield increased by calcium chloride in four varieties, more particularly in RS 218 which showed high proline accumulation under stress and then effect of seed hardening results into the ability of plants from treated seeds to produce proline when under stress (Sashidhar *et al*., 1977).

In Vertisol at Dharwad, groundnut cv. Dh 3-30 sprayed with different antitranspirants at 45DAS and withholding irrigation for 17 d during summer, among the antitranspirants, proline content was highest with 1500 ppm B-9 (daminozide), 20 ppm PMA (phenyl mercury acetate), 6% silica powder and 5% China clay, the reducing sugar was lowest in irrigated plants and highest with 0.2% Sunguard and 20 ppm alachlor, whereas non-reducing sugars were highest in irrigated crops, the leaf K content was lowest with irrigation and highest with Sunguard, alachlor and 100 ppm Cycocel (chlormequat), and among the antitranspirant, yield was highest with alachlor, Sunguard and Rallidhan (long chain fatty alcohol derivative), while spraying with PMA decreased yield (Amaregouda *et al*., 1994a). The pod yield increased by all antitranspirants except PMA and B-9, with Sunguard and alachlor giving the highest yields (1.71 and 1.70 t/ha, respectively) (Amaregouda *et al*., 1994). Also the antitranspirants and plant water relations when studied, stomatal resistance was lowest and greatest in plants treated with B-9 (1500 ppm) and PMA (20 ppm), respectively and Alachlor (20 ppm), Sunguard (0.2%), China clay (6% w/v) and silica powder (6% w/v) maintained moderate stomatal resistance compared with the control (Amaregouda *et al*., 1994b). In another field study on a Vertisol at Akola, groundnut cv. SB XI irrigated at IW: CPE ratios of 0.50, 0.65 or 0.80 up to flowering, flowering to pod development or pod development to maturity stages, stress up to flowering and pod formation stages decreased pod yield which were increased by foliar application of 400 ppm aspirin and/or 8% kaolin at 62 DAS as antitranspirants (Patil and Morey, 1993).

In summer two groundnut cultivars, irrigated at 12 or 8 days intervals (water stressed and non-stressed conditions, respectively), no mulch and mulched with 5 t wheat straw/ha, with and without 5 sprays of kaolin treatment reveal that, pod yields under non-stressed and stressed conditions were 3.23 and 2.76 t ha^{-1}, respectively. Yields without mulch, with mulch and mulch + kaolin sprays were 2.66, 2.99 and 3.34 t ha^{-1}, respectively. The WUE was highest with mulch + kaolin spray (Joshi *et al*, 1987). At Bambey the water balance in fallow soils and soils cultivated with groundnuts when examined groundnut gave pod yields at 2.26 and 3.43 t ha^{-1} in first year and 1.22 and 3.70 t ha^{-1} in second year, without and with irrigation, respectively (Dancette *et al*., 1979). In plot groundnut cv. Nonghua No. 5 protected from rain during the early flower bud stage decreased root and shoot dry matter, main stem length, total root length and leaf area (Yao *et al*., 1999).

Water logging is one of the most serious ecological restricting factors for groundnut in southern China. By exploring the correlation between main characteristics and pod yield in groundnut under natural water-logging stress, this study aimed to provide a theoretical basis for higher tolerance breeding in waterlogging conditions. Twenty characteristics including yield of 21 Spanish type germplasm lines were recorded. The bivariate correlation showed that the high-yielding groundnut lines had lower plant height, more sub-branches, less physiological defoliation, higher root biomass and lower shoot biomass (higher root/shoot ratio, i.e. R/S ratio), more fully developed pods $plant^{-1}$ (FDPP) and larger pods with bigger kernel, but lower fully developed pod ratio (FDPR) and fully developed kernel ratio, higher harvesting indexes (HI), and the correlation coefficients were in the rank of total pod number > HI > less developed pod plant-1 (LDPP) ~ FDPP > 100-seed mass (Ms) > 100-pod mass > R/S ratio. With multiple-factor stepwise regression analysis, however, only 5 characteristics were significantly related to pod yield, and they were in the rank of FDPP > Ms > LDPP >> FDPR > R/S ratio in standardized regression coefficients; meanwhile the partial correlation coefficients were in the rank of Ms > FDPP > LDPP > FDPR > R/S ratio. Path analysis indicated that FDPP and Ms directly affected pod yield, R/S ratio affected less on yield but had considerable indirect effect on yield, and FDPR had less direct effect on yield but strong indirect negative effect on yield. Thus, Ms, FDPP and LDPP can be used as criteria for screening high-yielding waterlogging-tolerant groundnut; apart from these parameters, R/S ratio may also be used as a reference (Li *et al*., 2008).

During rabi seasons, presoaking of TAG 24 groundnut seeds in solutions of CFL and CCC (both 10^{-6} M) for 6 h resulted in higher yield under drought conditions and drought indices like RWC, proline accumulation and transpiration supported the antitranspirant action of these chemicals (Mathew and Pandey, 2006). During kharif seasons, at Madurai, India, water stress in groundnut cv. JL 24, imposed during flowering and pegging stages produced the greatest reduction in pod yield followed by water stresses at early pod stage, late pod stage and vegetative stages where Kaolinite (3%) spray reduced yield loss due to water stress. Seed quality, oil and protein contents and N, P and K uptake were correlated with pod yields (Naveen *et al*., 1992).

6. CONCLUSIONS AND FUTURE RESEARCH STRATEGIES

Drought is the major abiotic constraint affecting productivity and quality of groundnut worldwide. There are three major aspects of drought, duration, intensity and timing relative to crop phenophases which vary independently. Water deficit stress delay pod initiation, and the major cause of variability in pod yield and HI is the delay between peg initiation and onset of rapid pod growth. The period of reproductive growth stages occurs over a period of nearly two months and moisture stress has a depressing effect on flowering, stem growth and nodulation. No flowering occurs during the stress, but once the stress is relieved, there is a flush of flowering depending on the growth stages and sometimes it results in more flowers. The Virginia type groundnuts, due to their longer duration, are more tolerant to drought than Spanish and Valencia, however, the Spanish and Valencia due to short duration escape the late season drought. The flush of late flowers, following mid season drought, delay maturity and hence late harvesting, where late season rain helps. The fruiting occurs once the gynophores enter into the soil and soil physical condition is important and must be wet during the gynophore entering the soil as the gynophore can exert a force equivalent to 3-4 g only.

The water flow in intact plant under high soil moisture condition is for growth and transpiration and two concepts are expressed about the driving force for transpiration water flow, the water potential differences between the root and leaf as the primary force and hydrostatic and osmotic pressure differences, as the factors determining water flow. The management practices should aim to optimize the availability of resources at the time of pegging to ensure timely pod initiation. In order to sustain plant growth and hydration, water must be continuously supplied to the leaves as it is lost by transpiration which becomes difficult under low soil moisture condition.

The groundnut is relatively drought tolerant and an important crop of the semi-arid regions, however the plant water-status the balance between water uptake and loss has been less understood in groundnut. Though different growth stages have different sensitivity to water deficit, none of these can proceed normally below some minimum water. The water requirement of groundnut is lowest from germination to flower formation and reaches maximum during pod formation. However, the utilization of available moisture is greatest during flowering and pod formation and the crop receiving adequate water during these stages only can give equal yield to the well watered crop. During these stages if stress is given and later on water supply is resumed only the vegetative growth is benefited not the reproductive growth of crop. The period of maximum sensitivity to drought occurs baetween 50-80 days after sowing, the period of maximum flowering and vegetative growth.

The timing of drought has a large impact on the variation. The sensitivity of a genotype to drought increases with yield potential, increasing the closer the drought ends to final harvest. Genotypic variation to drought exists in the water-use ratio with some, being able to accumulate up to 30% more shoot DM with the same total transpiration and HI, and large variations in genotypes to midseason are due to recovery differences after the drought is relieved.

The yield is a function of many plant and environmental factors and moisture stress play an important role particularly the stage at which stress occurs. The water stress affects the vegetative, root and reproductive growth and a proper scheduling of irrigation is required. Moisture stress at flowering reduced phytobiomass and pod yield by limiting the number of mature pods per unit area as compared to stress at pegging and pod formation stages. The variation in HI account for the large proportion of variation in yield, and hence recommended to make selection for high HI. As reproductive development is sensitive to drought resulting to poor yield, the strategies to combat drought in groundnut genotypes are (i) early production of flowers pegs, and pods, with subsequent filling of the pods at a moderate, but essentially at constant rate despite the drought, (ii) faster development of later developed pegs into pods once water become available after drought late in the season.

Drought stress effects on groundnut depends primarily on the stress pattern because genotypic variation is usually of secondary significance. In a 110-120 days crop water deficit stress at 45-70 DAS (flowering) and pod development (60-90 DAS) phases was highly detrimental to leaf area development, dry matter production, pod formation causing 40-60 and 50-70% yield reductions, respectively. However, in a 140-150 days crop maximum reduction in kernel yield was when stress was imposed during seed filling phase, i.e., 93 DAS onwards. The early and continuous availability of water until the start of pod filling result in large canopy and which increases transpirational demand. The transient soil-moisture-deficit stress for 20-25 days as pre-flowering drought during vegetative phase (20-45 DAS) results in synchronized flowering, increases 10-20% pod yield and save 10-15% water mainly due to promotion of root growth during water stress and inhibition of number of vegetative sites (leaves and branches).

Pod yield is a function of transpired water (T), transpiration efficiency (TE) and harvest index (H) and the TE derived from measurements of carbon isotope discrimination in leaves indicated only small variation. The yield losses (%) due to drought are estimated as: Yield loss (%) = 100 (1 - D_y/W_y), where, W_y is the pod yield under adequate irrigation and D_y is the pod yield under drought. The reported yield reductions ranged 10-15, 15-30, 40-50 and 50-70%, when drought was imposed from 10-30, 30-50, 50-

80 and 80-120 DAS, respectively. The greatest yield reduction corresponds to peak flowering to early pod filling stage and adequate moisture during this period is critical for obtaining maximum yield. Under water stress there is poor pod filling that reduced kernel size, shelling, SMK% and lipid content of kernel.

Plant population, planting pattern, land configurations and minerals influence both the temporal and spatial patterns of water use, with high density crops extracting water from lower depths sooner than low density crop. High water use prior to early pod filling in high density crop was associated with more rapid leaf area development. The more rapid water extraction in a high, compared with a low, population density groundnut crop is associated with greater root production at depth. Minerals Ca and K play important role in the moisture stress tolerance. Gypsum increase early pod development and provides an escape mechanism from drought and hence it must be applied at flowering to increase yield of groundnut subjected to drought. Potassium also improve input use efficiency through interaction and quality of produce.

The groundnut crop of about 120 days duration, requires 400-450 mm of water in normal soil and 600-700 mm in sandy soil. The levels of irrigation have a major effect on the amount of water consumed, and it is 300-350 mm in non irrigated field and 500-600 mm in field irrigated at 40-60% moisture availability at 30 cm depth. The irrigation at a depth of 100 mm showed highest yield. The yield decreases due to water stress at different growth stages are in order of water stress at seed development > at early pod filling > at early growth > at early pegging. The pod yield and quality of groundnut are reduced when less than 30 cm water was received by the crop. Water deficit during seed production affected C_2H_2 and CO_2 production during subsequent germination. Water stress at pod initiation and development phase reduced germinability, vigour, seed membrane integrity and affects subsequent growth of seedlings and could pose a problem in establishment for the succeeding crop.

Seasonal water requirement for groundnut crop were 300-350 mm during *kharif* and 380-450 and mm during summer seasons for semi arid region. The best irrigation scheduling criteria would be to irrigate as per the daily use rate of the crop. A minimum of 350 and 500 mm of water in 120 and 140 days duration crops, respectively is necessary to produce seeds with high potential for germination and high proportion of vigorous seedlings. Many a time the superiority of genotype with high yield, in water stress is not reflected in their ancillary characters. As the technology is likely to increase pod yield more than two folds in addition to water saving farmers may adopt drip irrigation method for groundnut crop at large field scale.

Genetic improvement of crop resistance to drought stress is one component and will provide a good perspective on the efficacy of control strategy through genetic improvement. Selection for drought adaptation under rainfed conditions, though commonly practiced, could be misleading, since it may not reflect the ability of the genotype if the stress occurs during the critical stages of plant development. More efficient selection would require simulated drought conditions, and the use of other indirect selection methods that give a good indication of drought adaptation. When water deficit during seed filling phase, genotypic yield potential accounted for approximately 90% of the variation in pod yield sensitivity to water deficit, and it is unlikely that breeders will be able to combine high yield potential with low sensitivity to drought spanning the seed filling phase, therefore other important strategies are necessary. The pod yield potential accounted for less of the variation in drought sensitivity (15-64%) in the early and mid-season droughts. For these circumstances it may be possible to identify genotypes with both high yield potential and relatively low drought sensitivity.

Agrometeorological studies must include an awareness of the relationship between environment, crop phenology, maturity, and postharvest quality. The seed composition changes dramatically as the crop matures and also has relation with environment, postharvest quality of groundnut is the resultant of the particular set of environmental and cultural practices during pod growth and maturation. A biochemical basis exists for inferior quality in immature groundnut. Drought stress and soil temperature influence maturation rate and thus had an indirect effect on postharvest quality. *Aspergillus flavus* invasion and aflatoxin contamination in groundnuts are related to drought stress, soil temperature and maturity and small, immature seeds are more likely to be contaminated with *A. flavus* than larger, mature seeds.

Most breeding programmes in groundnut follow an empirical approach to drought resistance breeding, largely based on kernel yield and traits of local adaptation, resulting in slow progress. Recent advances in the use of easily measurable surrogates for complex physiological traits associated with drought tolerance encouraged breeders to integrate these in their selection schemes. However, there is no direct comparison of the relative efficiency of a physiological trait-based selection approach *vis-a-vis* an empirical approach to ascertain the benefits of the former. The drought tolerance contributing factors in groundnuts are, an extensive root system established before maximum leaf area to meet the transpirational demand, recurred and synchronized flowering once stress was relieved, water storage cells in the abaxial side of the leaves to provide water when transpiration was greater than the roots extraction of soil moisture; leaf folding during stress to reduce solar incidence; and transpiration regulated by high stomatal resistance during stress.

REFERENCES

Ahmad, A., Kirda, C., Moutonnet, P., Hera, C. and Nielsen, D.R. (1999). Yield response of groundnut grown under rainfed and irrigated conditions. *In:* Crop Yield Response to Deficit Irrigation, 128-135.

Ali, E.A. (2001). Effect of water stress and potassium fertilization on yield and yield components of peanut (*Arachis hypogaea* L.). *Annals of Agricultural Science.* 39: 1425-1434.

Amaregouda A., Chetti, M.B., Salimath, P.M. and Gowda, M.V.C. (1994a). Influence of antitranspirants on osmoregulants in summer groundnut (*Arachis hypogaea* L.). *Annals of Plant Physiology*. 8: 114-120.

Amaregouda, A., Chetti, M.B., Salimath, P.M. and Kulkarni, S.S. (1994b). Effect of antitranspirants on stomatal resistance and frequency, relative water content and pod yield in summer groundnut (*Arachis hypogaea* L.). *Annals of Plant Physiology*. 8: 18-23.

Annerose, D.J. (1988). Physiological criteria for improving groundnut adaptation to drought. *Oleagineux Paris*. 43: 217-222.

Arjunan, A., Senthil, N. and Dharmalingam, V. (1997). Selection of groundnut genotypes for irrigated and rainfed environments. *Indian Journal of Plant Physiology*. 2: 118-122.

Asalatha, M., Reddy, P.V. and Ramana Rao, D.V. (1999). Relationship of specific leaf area and carbon isotope discrimination with dry matter production and pod yield in groundnut genotype under moisture stress. *Indian Journal of Plant Physiology*. 4: 161-166.

Asif, M. A., Yusuf Zafar, Javaid Iqbal, Iqbal, M. M., Umer Rashid, Ali, G. M., Arif A., Nazir, F. (2011). Enhanced expression of AtNHX1, in transgenic groundnut (*Arachis hypogaea* L.) improves salt and drought tolerence. *Molecular Biotechnology*. 49(3): 250-256.

Babalad H.B. and Kulkarni G.N. (1988). Effects of irrigation frequencies on growth and yield of summer groundnut. *Journal of Maharashtra Agricultural Universities*. 13: 189-191.

Babitha, M. and Reddy, P.V. (2001). Physiological traits related to water use efficiency in groundnut under stress and non-stress conditions. Journal of Research ANGRAU. 29:9-15.

Babitha, M., Sudhakar, P., Latha, P., Reddy, P.V. and Vasanthi, R.P. (2006). Screening of groundnut genotypes for high water use efficiency and temperature tolerance. *Indian Journal of Plant Physiology*. 11: 63-74.

Babu, V.R., Murty, P.S.S., Reddi, G.H.S. and Reddy, T.Y. (1983). Stress day index and pod yield relationship in groundnut. *Environmental and Experimental Botany*. 23(2): 183-188.

Badigannavar, M., Kale, D.M., Bhagwat, S.G. and Murty, G.S.S. (1999). Genotypic and seasonal variation in stomatal characters in Trombay groundnut varieties. *Tropical Agricultural Research and Extension.*, 2: 10-12.

Bailey, E and Boisvert, R N (1989) A risk evaluation of groundnut genotypes in drought prone areas of India. A. E. Research, Department of Agricultural Economics, Cornell University. 89 (11,iv): 95.

Balasubramanian, V. and Yayock, J.Y. (1981). Effect of gypsum and moisture stress on growth and pod-fill of groundnut (*Arachis hypogaea* L.). *Plant and Soil*. 62: 209-219.

Bari R. and Jones J. D. G. (2009). Role of hormones in plant defense responses. *Plant Molecular Biology.* 69: 473-488.

Bennett, J.M. and Hammond, L.C. (1982) Soil moisture and genotypic effects on the heat tolerance of peanut. *Proceedings: Soil and Crop Science Society of Florida*. 41: 97-100.

Bhatia, V.S., Singh, P., Rao, A.V.R.K., Srinivas, K. and Wani, S.P. (2009). Analysis of water non-limiting and water limiting yields and yield gaps of groundnut in India using CROPGRO-Peanut model. *Journal of Agronomy and Crop Science*. 195: 455-463

Billaz, R. and Ochos, R. (1961). The stage of susceptibility to drought in groundnut. *Oleagineux* 16: 605-609.

Bindumadhava, H., Sheshshayee, M.S., Shashidhar, G., Prasad, T.G. and Udayakumar, M. (2005). Ratio of stable carbon and oxygen isotope discrimination (Delta 13C/ Delta 18O) reflects variability in leaf intrinsic carboxylation efficiency in plants. *Curr. Sci*. 89: 1256-1258.

Bodare, C.A. and Dhonde, M.B. (2011). Effect of water stress on growth, yield and economics of summer groundnut. *Journal of Maharashtra Agricultural Universities*. 36: 152-155.

Challinor, A.J. and Wheeler, T.R. (2008). Use of a crop model ensemble to quantify CO_2 stimulation of water-stressed and well-watered crops. *Agricultural and Forest Meteorology*; 148: 1062-1077.

Chapman, S.C., Ludlow, M.M. and Blamey, F.P.C. (1993a). Effect of drought during early reproductive development on the dynamics of yield development of cultivars of groundnut (*Arachis hypogaea* L.). *Field Crops Research*. 32: 227-242.

Chaudhari, K.N. and Dadhwal, V.K. (2004). Assessment of impact of drought - 2002 on the production of major kharif and rabi crops using standardized precipitation index. *Journal of Agrometeorology*.; 6 (Special Issue): 10-15.

Chavan, A.A., Dhoble, M.V. and Khating, E.A. (1992). Effect of artificial water stress on different genotypes of groundnut (*Arachis hypogaea*) in dryland. *Indian Journal of Agricultural Sciences*. 62: 376-381.

Chavan, L.S., Patil, K.D. and Patil, B.P. (1999). Effect of water stress and nitrogen levels on yield of groundnut. *Journal of Maharashtra Agricultural Universities publ*. 24:309-310.

Chen S., Li J., Wang T., Polle A. and Hüttermann A. (2002). Osmotic stress and ion-specific effects on xylem abscisic acid and the relevance to salinity tolerance in poplar. *J. Plant Growth Reg*. 21: 224-233.

Chen YouQiang, Ye BingYing, Zhu-JinMao, Zhuang WeiJian, Chen, Y.Q., Ye, B.Y., Zhu, J.M. and Zhuang, W.J. (2000). Effects of osmotic stress on active oxygen damage and membrane peroxidation in young leaves of groundnut (*Arachis hypogaea*). *Chinese Journal of Oil Crop Sciences*. 22: 53-56.

Chung, SiYin., Vercellotti, J.R., Sanders, T.H. and Chung, S.Y. (1997). Increase of glycolytic enzymes in peanuts during peanut maturation and curing: evidence of anaerobic metabolism. *Journal of Agricultural and Food Chemistry*. 1997, 45: 4516-4521

Chuni Lal, Hariprasanna, K., Rathnakumar, A.L., Misra, J.B., Samdur, M.Y., Gor, H.K., Chikani, B.M. and Jain, V.K. (2009). Response of peanut genotypes to mid-season moisture stress: phenological, morpho-physiological, and yield traits. *Crop and Pasture Science*. 60: 339-347.

Clavel, D., Sarr, B., Marone, E., and Ortiz, R. (2004). Potential agronomic and physiological traits of Spanish groundnut varieties (*Arachis hypogaea* L.) as selection criteria under end-of-cycle drought conditions. *Agronomie*. 24: 101-111.

Clifford, S.C., Stronach, I.M., Mohamed, A.D., Azam Ali, S.N. and Crout, N.M.J. (1993). The effects of elevated atmospheric carbon dioxide and water stress on light interception, dry matter production and yield in stands of groundnut (*Arachis hypogaea* L.). *Journal of Experimental Botany*. 44: 1763-1770.

Collino, D., Biderbost, E. and Racca, R. (1994). Identification and characterization of physiological variables for the selection of drought-resistant material in groundnut (*Arachis hypogaea* L.). *Avances en Investigacion INTA Estacion Experimental Agropecuaria Manfredi*.1: 25-31.

Collino, D.J., Dardanelli, J.L., Sereno, R. and Racca, R.W. (2001). Physiological responses of argentine peanut varieties to water stress. Light interception, radiation use efficiency and partitioning of assimilates. *Field Crops Research*., 70: 177-184.

Collino, D.J., Dardanelli, J.L., Sereno, R. and Racca, R.W. (2000). Physiological responses of argentine peanut varieties to water stress. Water uptake and water use efficiency. *Field Crops Research*. 68:133-142.

Costa, W.A.J.M.de. and Nayakarathne, N.M.R.S. (2001). Effect of two different water regimes on growth and yield of different groundnut (*Arachis hypogaea* L.) genotypes in Sri Lanka. *Tropical Agricultural Research and Extension*. 4: 29-35

Craufurd, P.Q., Wheeler, T. R., Ellis, R.H., Summerfield, R.J. and Prasad, P. V. V. (2000). Escape and tolerance to high temperature at flowering in groundnut (*Arachis hypogaea* L.). *Journal of Agricultural Science*. 135: 371-378.

Dancette, C., Hamon, G. and Vachaud, G. (1979). Comparative study of water dynamics in fallow and cultivated sandy soils: modes of extraction of water by millet and groundnut crops in conditions of insufficient rainfall, in Senegal. Isotopes and radiation in research on soil plant relationships International Atomic Energy Agency, Vienna. 213-234.

Dangthaisong,, P., Banterng, P., Jogloy, S., Vorasoot, N., Patanothai, A. and Hoogenboom, G. (2006). Evaluation of the CSM-CROPGRO-Peanut model in simulating responses of two peanut cultivars to different moisture regimes. *Asian Journal of Plant Sciences*. 5: 913-922.

De Smet I., Zhang H., Inze D. and Beeckman T. (2006). A novel role for abscisic acid emerges from underground. *Trends Plant Sci*. 11: 434–439.

De Vries, J. D., Bennett, J. M., Albrecht, S. L. and Boote, K. J. (1989). Water relations, nitrogenase activity and root development of three grain legumes in response to soil water deficits. *Field Crop Res*. 21: 215-226.

Devi, K.B.S. and Rao, V.P. (2003). Crop coefficients for prediction of irrigation requirements of groundnut. *Journal of Research ANGRAU*. 31:1-8.

Devoto A. and Turner J.G. (2003). Regulation of Jasmonate mediated plant responses in Arabidopsis. Ann. Bot. 92: 329-337.

DGR, 2010. Annual report 2010-11. Directorate of groundnut Research, ICAR, Junagadh.

DGR, 2011. Annual report 2011-12. Directorate of groundnut Research, ICAR, Junagadh.

Dhonde, P.W., Shinde, S.H., Patil, B.B. and Pawar, A.D. (1985). Irrigation scheduling for kharif groundnut. *J. Maharashtra Agric. Univ*. 10: 28-30.

Dhopte, A.M. and Ramteke, S.D. (1994). Relative variation in dry matter partitioning of peanut genotypes under moisture stress conditions. *Annals of Plant Physiology*. 8: 174-178.

Dhopte, A.M., Ramteke, S.D. and Thote, S.G. (1992). Effect of soil moisture deficit on root growth and respiration, nodulation and yield stability of field grown peanut genotypes. *Annals of Plant Physiology*. 6:188-197.

Dhruve, J.J. and Vakharia, D.N. (2007). Amelioration of polyethylene glycol simulated water deficit stress by benzyladenine in groundnut. *Indian Journal of Agricultural Biochemistry*. 20: 53-58.

Duruoha, C., Piffer, C.R. and Silva, P.R.A. (2008). Root volume and dry matter of peanut plants as a function of soil bulk density and soil water stress. *IRRIGA*.13: 170-181.

Dutta, D. and Mondal, S.S. (2006).Response of summer groundnut (*Arachis hypogaea*) to moisture stress, organic manure and fertilizer with and without gypsum under lateritic soil of West Bengal. *Indian Journal of Agronomy*. 51: 145-148.

Dwivedi, R. S., Joshi, Y.C., Nautiyal, P. C., Singh, A. L., Ravindra, V., Thakkar, A. N., Koradia, V.G., and Dhapwal, G.S. (1986a). Developing parameters to predict drought resistance in groundnut genotypes. Transactions of Indian Society of Desert Technology and University Centre of Desert Studies. 11: 59-65.

Dwivedi, R.S. (1986b). Drought resistant plant attributes and breeding for drought resistance in groundnut. Ibid. pp. 66-67.

Dwivedi, R.S., Joshi, Y.C., P.C. Nautiyal, A.L. Singh, V. Ravindra, A.N. Thakkar, V.G. Koradia and G.S. Dhapwal, 1986c. Detection of drought resistance in peanut (*Arachis hypogaea* L.). Oleagineux, 41(6): 281-285.

Dwivedi, R.S., Joshi, Y.C., Saha, S.N., Thakkar, A.N., and Koradia, V.G.(1986d). Canopy orientations and energy harvests in groundnut (*Arachis hypogaea* L.) under water stress. *Oleagineux*, 41: 451-455

El Hadi, A.H.A., Khadr, M.S. and Johnston, A.E. (2003). Efficiency of potassium fertilization under saline and drought conditions in Egyptian soils. Potassium and water management in West Asia and North Africa. Proceedings of the Regional Workshop of the International Potash Institute, Amman, Jordan, 5-6 November 2001. 85-96.

Ewansiha, S.U. and Singh, B.B. (2006). Relative drought tolerance of important herbaceous legumes and cereals in the moist and semi-arid regions of West Africa. *Journal of Food Agriculture and Environment*. 4: 188-190.

FAO, 2012. FAOSTAT, FAO Statistics Division 2012, 26 September 2012.

Fariduddin Q., Hayat S. and Ahmad A. (2003). Salicylic acid influences net photosynthetic rate, carboxylation efficiency, nitrate reductase activity and seed yield in Brassica juncea. *Photosynthetica.* 41: 281-284.

Ferreira, L.G.R., Santos, I.F. dos, Tavora, F.J.F., Silva, J.V.da., Dos Santos, I.F., Da Silva, J.V. (1992). Effect of water deficit on groundnut (*Arachis hypogaea* L.) cultivars. Physiological reactions and yields. *Oleagineux Paris*. 47: 523-530.

Ferreyra, R.A., Ludmila B., Pachepsky, b., Collino, D., Acock B., (2000). Modeling peanut leaf gas exchange for the calibration of crop models for different cultivars. *Ecological Modelling.* 131: 285–298.

Gajera, M.S., Patel, J.C. (1984). Response of summer groundnut to irrigation scheduling based on cumulative irrigation under varying fertility levels. *Ind. J. Agron*. 29: 394-395.

Gauch, H.G. Jr, (1988). Model selection and validation for yield trials with interaction. *Biometrics.* 44: 705–715.

Ghatak, S., Sounda G,. Maitra S., Saren B. K., Roy D. K., Panda P. K. (1997). Effect of irrigation and potassium on growth and productivity of summer groundnut. *Environ and Ecology*. 15(2): 469 473.

Golakiya, B.A. (1992). Drought response of groundnut: VI. Hormonal treatment & seed pelleting to combat the drought. *Advances in Plant Sciences*. 5: 511-514.

Golakiya, B.A. (1993).Drought response of groundnut: VII. Identification of the critical growth stages most susceptible to water stress. *Advances in Plant Sciences*. 6: 20-27.

Golakiya, B.A. and Patel, M.S. (1988). Role of potassium in counteracting the effect of cyclic drought on groundnut. *Journal of Potassium Research*. 4: 163-167.

Golakiya, B.A. and Patel, M.S. (1992). Growth dynamics and reproductive efficiency of groundnut under water stress at different phenophases. Indian Journal of Agricultural Research. 26:179-186.

Gowda, A. (1977). Moisture stress and hormonal influence on the flowering and yield in groundnut (*Arachis hypogaea* Linn.).

Gowda, A. and Hegde, B.R. (1986). Moisture stress and hormonal influence on the flowering behaviour and yield of groundnut (*Arachis hypogaea* L.). *Madras Agricultural Journal*. 73: 82-86.

Greenberg, D.C. and Ndunguru, B.J. (1989). Groundnut drought-simulation studies at ICRISAT Sahelian Centre. *International Arachis Newsletter*. 6: 10-12.

Guo, Z.F. and Pan, R.Z. (1989). Effects of triadimefon on increasing drought resistance in groundnut seedlings. *Oil Crops of China.* 2: 14-18.

Hammer *et al*., 1995. A peanut simulation model. I. Model development and testing. Agronomy Journal. 87, 1085-1093.

Hammond, L.C., Boote, K.J., Varnell, R.J. and Robertson, W.K. (1978). Water use and yield of peanuts on a well-drained sandy soil. *Proceedings of American Peanut Research and Education Association, Inc*., 10: 73.

Harris, D. and Natarajan, M. (1987). Physiological basis for yield advantage in a sorghum/groundnut intercrop exposed to drought. *Field Crops Research*. 17: 273-288.

Harris, D. and Natarajan, M. and Willey, R.W. (1987). Physiological basis for yield advantage in a sorghum/groundnut intercrop exposed to drought. I. Dry-matter production, yield, and light interception. *Field Crops Research*. 17: 259-272.

Hashim, I.B., Koehler, P.E., Eitenmiller, R.R. and Kvien, C.K. (1993). Fatty acid composition and tocopherol content of drought stressed Florunner peanuts. *Peanut Sci.* **20**: 21-24.

Hayat S., Fariduddin Q., Ali B. and Ahmad A. (2005) Effect of salicylic acid on growth and enzyme activities of wheat seedlings. *Acta Agron Hung.* 53:433–437.

Hook, J.E. (1994). Using crop models to plan water withdrawals for irrigation in drought years. *Agricultural Systems*. 45: 271-289.

Huang, M.T. and Ketring, D.L. (1985). Studies of water relations of peanut under rainfed and irrigated conditions. Proceedings, American Peanut Research and Education Society, Inc., 17: 65.

Hubick, K.T. (1990). Effect of nitrogen sources and water limitation on growth, transpiration efficiency and carbon isotope discrimination in peanut cultivars. *Aust. J. Plant. Physiol*. 17: 413-430.

Hubick, K.T., Farquhar, G.D. and Shorter, R. (1986). Correlation between water use efficiency and carbon isotope discrimination in diverse peanut (*Arachis*) germplasm. *Aust. J. Plant Physiol*. 13: 803-816.

Hubick, K.T., Shorter, R. and Farquhar, G.D. (1988). Heretibility and genotype environment interaction of carbon isotope discriminate and transpiration efficiency in peanut (*Arachis hypogaea* L.). *Aust. J. Plant Physiol.* 15: 799-813.

ICRISAT. (1986). Annual Report, 1985. ICRISAT, Patancheru, A.P. 502 324, India.

Izge, A.U. and Olorunju, P.E. (2000). Response of groundnut genotypes to moisture stress in the greenhouse. *Journal of Sustainable Agriculture and the Environment.* 2: 182-187.

Jadhao, P.N., Bhalerao, P.D., Fulzele, G.R., and Thorve, P.V. (1989). Response of peanut to water stress during seedling stage under summer season. *Annals of Plant Physiology*. 3: 146-151.

Jain, L.L., Panda, R.K., and Sharma, C.P. (1997). Water stress response function for groundnut (*Arachis hypogaea* L.). *Agricultural Water Management*. 32: 197-209

Jiang HuiFang and Ren-XiaoPing (2004). SOD activity and protein content in groundnut leaves as affected by drought stress. *Acta Agronomica Sinica*; 30: 169-174

Joshi, A.C., Patil, J.R. and Umrani, N.K. (1987). Use of mulch and anti-transpirant on groundnut under water stressed and non-stressed conditions. J. of Maharashtra Agricultural Universities. 12: 247-249.

Joshi, Y.C., Nautiyal, P.C., Ravindra, V., Dwivedi, R.S. (1988). Water relations in two cultivars of groundnut (*Arachis hypogaea* L.) under soil water deficit. *Tropical Agriculture*. 65: 182-184

Kachot, M. A., J. C. Patel, and Malviya, D.D. (1984). Response of Summer groundnut to irrigation scheduling based on IW/CPE ratio under varying levels of nitrogen and phosphorus. *Indian J. Agronomy*. 29:411-412.

Kalariya, K.A. Singh A.L. and K. Chakraborty, 2012a. Influence of water deficit stress on chlorophyll fluorescence in groundnut. In: National Seminar on New Frontiers of Plant Science for Sustainable development, 25-26 Feb 2012, PN College Khurda, Orissa p 20.

Kalariya, K.A., Singh, A.L, Chakraborty, K. Zala, P.V. and Patel, C.B. 2012b. Physiology of Groundnut (*Arachis hypogaea* L.) under water stress: I Chlorophyll Fluorescence and Photosynthesis, *Indian Journal of Plant Physiology (in press)*.

Kameswara Rao Kottapalli, Rakwal, R., Shibato, J., Gloria Burow David Tissue, John Burke, Puppala, N., Burow, M. And Payton, P. (2009). Physiology and proteomics of the water-deficit stress response in three contrasting peanut genotypes. *Plant, Cell and Environment*. 32: 380–407.

Kandoliya, U.K., Parameswaran, M., and Vakharia, D.N. (2000). Effect of drought on kernel carbohydrates and lipids in groundnut (*Arachis hypogaea* L.). *Advances in Plant Sciences*, 13: 573-579.

Kar, D.N., Ray, M. and Garnayak, L.M. (2002). Effect of moisture stress on yield & water use by rabi groundnut. *Annals of Agricultural Research*, 23:159-161.

Kar, D.N., Ray, M. and Garnayak, L.M. (2001). Determination of crop coefficient of groundnut for modified Penman method. *Environment and Ecology.* 19: 474-476.

Kar, G. and Kumar, A. (2007). Surface energy fluxes and crop water stress index in groundnut under irrigated ecosystem. *Agricultural and Forest Meteorology*. 146: 94-106.

Katawatin, R., Crown, P.H. and Grant, R.F. (1996). Simulation modelling of land suitability evaluation for dry season peanut cropping based on water availability in Northeast Thailand: evaluation of the MACROS crop model. *Soil Use and Management*., 12: 25-32.

Keller, J. and Bliesner, R.D. 1990. *Sprinkle and Trickle Irrigation,* Van Nostrand Reinhold, New York.

Ketring, D.L. (1986). Physiological response of groundnut to temperature and water deficits - breeding implications. Agrometeorology of groundnut. Proceedings of an international symposium, ICRISAT Sahelian Center, 21-26 August 1985: 135-143.

Khan, A.R. and Datta, B. (1990). Response of peanut to moisture stress and irrigation. Agrochimica 24: 15-23.

Khodary S.F.A. (2004). Effect of salicylic acid on the growth, photosynthesis and carbohydrate metabolism in salt stressed maize plants. *Int. J. Agric. Biol.* 6: 5-8.

Koti, R.V., Chetti, M.B., Manjunath, T.V.and Amaregowda, A. (1994). Effect of water stress at different growth stages on biophysical characters and yield in groundnut (*Arachis hypogaea* L.) genotypes. *Karnataka Journal of Agricultural Sciences*. 7: 158-162.

Krishnamurthy, L., Vadez, V., Devi, M.J., Serraj, R., Nigam, S.N., Sheshshayee, M.S., Chandra, S., Aruna, R. (2007). Variation in transpiration efficiency and its related traits in a groundnut (*Arachis hypogaea* L.) mapping population. *Field Crops Res*. 103: 189-197.

Kulkarni, J.H., Joshi, Y.C., and Bhatt, D.M. (1988) Effect of water stress on nodulation and nitrogen content of groundnut (*Arachis hypogaea* L.). *Zentralblatt fur Mikrobiologie.* 143: 4, 299-302.

Kulkarni, J.H., Ravindra, V., Sojitra, V.K. and Bhatt, D.M. (1988). Growth, nodulation and N-uptake of groundnut (*Arachis hypogaea* L.) as influenced by water deficit stress at different phenophases. *Oleagineux Paris*. 43: 415-419

Kvien, C.S., Branch, W.D., Sumner, M.E. and Csinos, A.S. (1988). Pod characteristics influencing calcium concentrations in the seed and hull of peanut. *Crop Science*. 28: 666-671.

Lehmann J., Atzorn R., Brückner C., Reinbothe S., Leopold J., Wasternack C. and Parthier B. (1995). Accumulation of Jasmonate, abscisic acid, specific transcripts and proteins in osmotically stressed barley leaf segments. *Planta.* 197: 156-162.

Li Lin, Liu DengWang, Zou Dong Sheng and Liu Fei (2008). The correlation between main characteristics and pod yield in peanut genotypes under natural waterlogging stress. *Chinese Journal of Oil Crop Sciences*. 30: 62-70.

Liang Y., Mitchell D.M. and Harris J.M. (2007). Abscisic acid rescues the root meristem defects of the Medicago truncatula latd mutant. *Dev Biol.* 304: 297–307.

Liechti R. and Farmer E.E. (2006). Jasmonate biochemical pathway. *Sci. STKE* 322: 1-3.

Lourduraj C. A. (2000). Effect of irrigation and manure application on the growth and yield of groundnut. *Acta Agronomica Hungarica.* 48(1): 83-88.

Madhusudhan, K.V., Giridarakumar, S., Ranganayakulu, G.S., Reddy, P.C., Sudhakar, C. (2002). Effect of water stress on some physiological responses in two groundnut (*Arachis hypogaea* L.) cultivars with contrasting drought tolerance. *Journal of Plant Biology*, 29: 199-202.

Mandavia, C., Dhruj, I.U., Chattrabhuji, B.J., Rajani, J.C. and Bharodia, P.S. (2007). Identification of drought tolerant groundnut (*Arachis hypogaea* L.) genotypes. *Indian Journal of Agricultural Research.* 41: 17-22.

Man Singh, S.S. Parihar Manoj Khanna, A.K. Singh and A.L. Singh 2012. Seasonal Water Requirements and Irrigation Scheduling of Groundnut (*Arachis hypogaea* L.) Crop under trickle irrigation *Journal of water management* (inpress).

Mante, E.F.G. (1976). Suitable soils for grain legume production. Proceedings of the joint University of Ghana Council for Scientific and Industrial Research symposium on grain legumes in Ghana [Doku, E.V. (Editor)]. 7-23.

Maphanyane, G.S., Ndunguru B.J .(ed.), Hildebrand, G.L. (ed.); Subrahmanyam, P. (1994). Selecting groundnuts for adaptation to drought under rainfed conditions in Botswana. Sustainable groundnut production in southern and eastern Africa: proceedings of a Workshop, 5-7 July 1994, Mbabane, Swaziland: 32-36.

Mathew, T. and Pandey, D.P. (2006). Protection of groundnut plants from water stress by chlorflurenol and cycocel. *Indian Journal of Plant Physiology*. 11: 209-212.

Mathur, P.B., Devi, M.J., Serraj, R., Yamaguchi Shinozaki, K., Vadez, V. and Sharma, K. K. (2004). Evaluation of transgenic groundnut lines under water limited conditions. *International Arachis Newsletter*. 24: 33-35.

Matthews, R. B., Harris, D., Nageswara Rao, R. C., Williams, J. H. and Wadia, K. D.R. (1988a). The physiological basis for yield differences between four genotypes of groundnut (*Arachis hypogaea*) in response to drought I. Dry matter production and water use. *Exp. Agric.* 24: 191-202.

Matthews, R. B., Williams, J. H., Nageswara Rao, R. C. (1988b). The physiological basis for yield differences between four genotypes of groundnut (*Arachis hypogaea*) in response to drought II. Solar radiation interception and leaf movement. *Expl. Agric*. 24: 203-213.

Meisner, C.A. (1991). Peanut roots, shoot, and yield under water stress. Dissertation-Abstracts-International-B,-*Sciences and Engineering*. 52: 3B-4B.

Meisner, C.A. and Karnok, K.J. (1992). Peanut root response to drought stress. *Agronomy Journal*. 84: 159-165.

Mensah, J.K. and Okpere, V.E. (2000). Screening of four groundnut cultivars from Nigeria for drought resistance. *Legume Research*. 23: 37-41.

Misra, J.B. and Nautiyal, P.C. (2005). Influence of imposition of soil moisture-deficit stress on some quality components of groundnut, *Arachis hypogaea* L. kernel. *J. of Oilseeds Res*. 22: 119-124

Mittal, G.K., Arunabh Joshi, Rajamani, G., Mathur, P.N. and Sharma (2006). A Water-deficit induced generation of reactive oxygen species and antioxidants in two Spanish groundnut cultivars. *National Journal of Plant Improvement*. 8: 7-10.

Mohan, C.V.K. and Rao, G.R. (1989). Influence of foliar application of calcium on growth performance, chlorophyll and protein contents in groundnut under water stress. *Narendra Deva Journal of Agricultural Research*. 4: 7-11.

Mohandass, S., Radhakrishnan, R., Panchanathan, R.M., Kandaswamy, P. (1989). Diurnal pattern of plant water relations of groundnut under water stress and potassium nutrition. *Journal of Agronomy and Crop Science*. 163: 18-20

Mukherjee, A., Moitra, R. and Chakravarti, A.K. (2010). Variation of micrometeo-rological environment within different groundnut cultivars. *Environment and Ecology*. 28(3A): 1842-1844.

Munne-Bosch S. and. Peñuelas J. (2003). Photo- and antioxidative protection, and a role for salicylic acid during drought and recovery in field-grown Phillyrea angustifolia plants. *Planta*. 217: 758–766.

Musingo, M.N., Basha, S.M., Sanders, T.H., Cole, R.J. and Blankenship, P.D. (1989). Effect of drought and temperaturestress on peanut (*Arachis hypogaea* L.) seed composition. *J. Plant Physiol.* **134:** 710-715.

Muthumanickam, D., Kannan, P., Kumaraperumal, R., Natarajan, S., Sivasamy and R., Poongodi, C. (2011) Drought assessment and monitoring through remote sensing and GIS in western tracts of Tamil Nadu, India. *International Journal of Remote Sensing*. 32(17/18): 5157-5176.

Nageshwar Rao, R.C. and Wright, G.C. (1994). Stability of the relationship between specific leaf area and carbon isotope discrimination across environment in peanut. *Crop Sci.* 34:98-103.

Nageshwar Rao, R.C. (2003). Environmental characterisation of experimental sites in India and Australia. Breeding of drought resistant peanuts Proceedings of a Collaborative Review Meeting Hyderabad, Andhra Pradesh, India, 25-27-February, 2002.; 61-66.

Nageshwar Rao, R.C., Reddy, L.J., Nigam, S.N. and Subrahmanyam, P. (1992). Influence of soil type on the adaptation of groundnut genotypes. Proceedings of the fifth regional groundnut workshop for Southern Africa, 9-12 March, 1992, Lilongwe, Malawi , 15-17.

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

Nageshwar Rao, R.C., Williams, J.H., Wadia, K.D.R., Hubick, K.T. and Farquhar, G.D. (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.

Nakar R.N., A.L. Singh, Nisha Goswami, K.A. Kalariya, K. Chakraborty 2012. Physiological efficiencies in minicore groundnut germplasm accessions. In: Proceeding of the National Conference on "Research in Plant Sciences: Changing pathways, changing lives" Oct 29-30, 2012 at Talod, Sabarkantha, Gujarat P

Natarajan, M. and Willey, R.W. (1986). The effects of water stress on yield advantages of intercropping systems. *Field Crops Research*. 13:117-131.

Nautiyal, P.C., Ravindra, S. and Joshi, Y.C. (1991). Moisture stress and subsequent seed viability. Physiological and biochemical basis for viability differences in Spanish groundnut in response to soil moisture stress. *Oleagineux*. 46: 153-158.

Nautiyal, P.C., Ravindra, V., Zala, P.V. and Joshi, Y.C. (1999). Enhancement of yield in groundnut following the imposition of transient soil-moisture-deficit stress during the vegetative phase. *Exp Agric.* 35:371-385.

Nautiyal, P.C. Rajgopal, K. P.V. Zala, Dipti S. Pujari, Manojit Basu, Bhuwaneshwariba Dhadhal and Bharat M. Nandre, 2008. Evaluation of Wild *Arachis* species for abiotic stress tolerance: I Thermal stress and leaf water relations. *Euphytica*, 159:43-57.

Nautiyal, P.C., P.V. Zala, Rukam Singh, Paresh Sodavadiya, and Bhavesh Tavethia, 2011. A Evaluation of water use efficient new developed varieties of groundnut in on-farm trials in two different rain-fall areas in Gujarat, *Journal of SAT Agricultural Research, Dec, 9: 1-6.*

Nautiyal, P.C., Ravindra V, Rathnakumar, A.L., Ajay, B.C. and Zala, P.V. 2012. Genetic variation in photosynthetic rate, pod yield and yield components in Spanish groundnut cultivars during three cropping seasons. *Field Crop Research, 125:83-89.*

Naveen, P., Daniel, K.V., Subramanian, P. and Kumar, P.S. (1992). Response of irrigated groundnut (*Arachis hypogaea*) to moisture stress and its management. *Indian Journal of Agronomy*. 37: 82-85.

Neelam Yadav, Yadav, V.K. and Yadava, C.P.S. (2007). Influence of simulated whitegrub damage of roots on water relation parameters in groundnut. *Indian Journal of Plant Physiology*.12: 173-177

Nemeth M., Janda T., Horvath E. , Paldi E. and Szalai G. (2002). Exogenous salicylic acid increases polyamine content but may decrease drought tolerance in maize. *Plant Sci*. 162: 569-574.

Nigam, S.N. and Rupakula Aruna (2008). Stability of soil plant analytical development (SPAD) chlorophyll meter reading (SCMR) and specific leaf area

(SLA) and their association across varying soil moisture stress conditions in groundnut (*Arachis hypogaea* L.). *Euphytica*. 160: 111-117.

Nogueira, R.J.M.C., Santos, R.C.dos, Bezerra Neto, E., Santos, V.F. dos., dos Santos R.C. dos and Santos, V.F. (1998). Physiological response of two groundnut cultivars subjected to different water regimes. *Pesquisa Agropecuaria Brasileira.*, 33: 1963-1969.

Oliveira Junior, J. O. L. de., Tavora, F.J.A.F. and Barbosa Filho,-M (2004). Phenology of peanuts cultivars submitted to water stress. *Cientifica Jaboticabal*. 32: 25-29.

Omoko, M. (1990). Influence of crop-water managements on yield-water use relationships. Dissertation Abstracts International B, *Sciences and Engineering*. 51: 1050B

Omoko, M. and Hammond, L.C. (2010). Biological and water-use efficiencies of sorghum-groundnut intercrop. *Cameroon Journal of Experimental Biology*. 6: 1-10.

Ong, C.K. (1984). The influence of temperature and water deficits on the partitioning of dry matter in groundnut (*Arachis hypogaea* L.). *Journal of Experimental Botany*. 35: 746-755.

Padma, V., Rao, D.V.M. and Rao, I.V.S. (1991). Response of groundnut cultivars to time of sowing in different seasons. *Journal of Oilseeds Research*. 8: 275-279.

Padmanabhamurty, B., Saxena, N,. Sastry, P.S.N. (ed.), Rao, P.S. (ed.), Shekh, A.M. (ed.) and Pandey, V. (2001). Variation of residual energy fluxes in relation to plant height and biomass in groundnut. National workshop on preliminary results of Land Surface Processes Experiment (LASPEX-97) over Sabarmati River Basin, Anand, India, 18-20 November 1999. *J. Agrometeorology*. 3:119-126.

Pallas, JE Jr., Stansell, JR and Bruce, RR (1977). Peanut seed germination as related to soil water regime during pod development. *Agronomy Journal*. 69: 381-383

Panda, P.K. and Behera, S.K. (2005). Irrigation water management strategy for peanut under deficit conditions. *Zeitschrift-fur-Bewasserungswirtschaft*. 40: 91-114.

Panda, R.K., Kumar, P. and Kashyap, P.S. (2003). Effective management of irrigation water in a sub-humid region using PNUTGRO model. *Zeitschrift-fur-Bewasserungswirtschaft*. 38: 41-55.

Parekh, F.P. and Shete, D.T. (2008). Irrigation scheduling for summer groundnut considering agrometeorological parameters and dual crop coefficient approach. *Journal of Agrometeorology*. 10(Special Issue 2): 309-313.

Parmar, J.V., Patel, C.L. and Polara, K.B. (1989). Influence of soil-moisture stress at different stages of growth on yield response and nutrients in groundnut. *Annals of Arid Zone*. 28: 267-270.

Parihar, S.S., Man Singh, Manoj Khanna and A.K. Singh. 2008. Response of Summer Groundnut (*Arachis hypogaea* L.) to Method of Planting and Irrigation Regime under Drip Irrigation in Semi Arid Region. *Journal of water management*. 16(2): 101-113.

Passioura, J.B. (1977) Grain Yield, harvest index and water use of wheat. *J. Aust. Inst. Agric. Sci.* 43:117-121.

Patel, C.L. and Padalia, M.R. (1980). Nutrient accumulation and nutrient-use-efficiency in groundnut under different sequences of soil-water potential. *Legume Research*. 3: 45-50.

Patel, C.L., Padalia, M.R. and Babaria, N.B. (1983). Growth and plant-water relation in groundnut grown under different soil-moisture stresses. *Indian Journal of Agricultural Sciences*. 53: 340-345.

Patel, M.S and Golakiya, B.A. (1988). Effect of water stress on yield attributes and yield of groundnut (*Arachis hypogaea*). *Indian Journal of Agricultural Sciences*. 58: 701-703

Patel, M.S. and Golakiya, B.A. (1991). Effect of water stress on yield and yield attributes of groundnut (*Arachis hypogaea* L.). *Madras Agricultural Journal.* 78: 178-181.

Patel, M.S. and Golakiya, B.A. (1993). Moisture stress effects at different phenophases on biophysical parameters of groundnut cultivars. *Indian Journal of Agricultural Research*. 27: 126-130.

Patel, M.S., Gundalia, J.D., Davaria, R.L. and Vadher, P.G. (1988). Yield and quality of summer groundnut (*Arachis hypogaea*) as influenced by growth retardants and promoters. *Indian Journal of Agricultural Sciences*. 58: 773-775.

Patil, B.P. and Gangavane, S.B. (1990). Effects of water stress imposed at various growth stages on yield of groundnut and sunflower. *Journal of Maharashtra Agricultural Universities*. 15: 322-324.

Patil, N.A. and Patil, T.M. (1993). Physiological responses of groundnut genotypes to water stress. *Legume Research*.16: 23-30.

Patil, R.G., Radder, G.D., Patil V.C. and Ramachandrappa B.K. (1984). Dry matter production and distribution in bunch groundnut varieties as influenced by the time of sowing and foliar application of nitrogen and iron. *Madras Agricultural Journal*. 71: 177-181.

Patil, S.M. and Morey, D.K. (1993). Growth and yield of summer groundnut as influenced by antitranspirants and water management practices. *Journal of Soils and Crops*. 3: 18-22.

Patra, A.K., Tripathy, S.K. and Samui, R.C. (1999). Effect of sowing date, irrigation and spacing on nodulation, dry matter and yield of summer groundnut (*Arachis hypogaea*). *Indian Journal of Agronomy*., 44: 800-804

Peleg Z. and Bluwald E. (2011) Hormone balance and abiotic stress tolerance in crop plants *Current Opinion in Plant Biology.* 14:290–295.

Prathap, S., Reddy, S.S. and Swamy, G.N. (2006). Effect of water stress on germination and seedling growth of groundnut genotypes. *Crop Research Hisar*. 31: 58-60.

Purushotham, M.G., Patil, V., Raddey, P.C., Prasad, T.G., Vajranabhaiah, S.N. and Patil, V. (1998). Development of *in vitro* PEG stress tolerant cell lines in two groundnut (*Arachis hypogaea* L.) genotypes. *Indian Journal of Plant Physiology*. 3:49-51.

Rajegowda, M.B., Janardhangowda, N. A., Ravindrababu, B. T., Girish, J. (2010) Crop weather model for sustainable groundnut production under dry land condition. *J. of Agrometeorology*. 12(2): 221-224.

Rajendrudu, G and Williams, J.H. (1987). Effect of gypsum and drought on pod initiation and crop yield in early maturing groundnut (*Arachis hypogaea*) genotypes. *Experimental Agriculture*. 23: 259-271.

Raju, A.P., Reddi, G.H.S. and Reddy, T.B. (1981). Studies on the productivity of rainfed groundnut under moisture stress using neutron moisture probe. *J of Nuclear Agriculture and Biology*. 10: 131-133.

Ramachandrappa, B.K. and Nanjappa, H.V. (1994). Prediction of pod yield and quantification of stress effect to delineate sensitive stages in groundnut - A mathematical model. *Crop Research Hisar*. 8: 437-441.

Ramesh Babu, V., Murty, P.S.S., Sankara Reddi, G.H. and Reddy, T.Y. (1983) . Leaflet angle and radiation avoidance by water stressed groundnut (*Arachis hypogaea* L.) plants. *Environmental and Experimental Botany*. 23:183-188.

Ramesh Katam, Basha, S.M., Vasanthaiah, H.K.N. and Naik, K.S.S. (2007). Identification of drought tolerant groundnut genotypes employing proteomics approach. *Journal-of-SAT-Agricultural-Research*. 5: 1-2.

Ramesh Thatikunta, Durgaprasad, M.M.K. and Thatikunta, R. (1996). Identifying groundnut genotypes for the Southern Telangana Zone in India. International Arachis Newsletter., No. 16: 19-20.

Rassaa N., Ben Haj Salah H. and Latiri, K. (2008). Thermal responses of Durum wheat *Triticum durum* to early water stress. Consequence on leaf and flower development. *C. R. Biologies* 331: 363–371.

Rathore, A.L., Pal, A.R., Sahu, R.K. and Chaudhary, J.L. (1996). On-farm rainwater and crop management for improving productivity of rainfed areas. *Agricultural Water Management*. 31: 253-267.

Ravi, K., Vadez, V., Isobe, S., Mir, R.R., Guo, Y., Nigam, S.N., Gowda,M.V.C., Radhakrishnan, T., Bertioli, D.J., Knapp, S.J., Varshney, R.K. (2011) Identification of several small main-effect QTLs and a large number of epistatic QTLs for drought tolerance related traits in groundnut (*Arachis hypogaea* L.). *Theoretical and Applied Genetics*. 122(6): 1119-1132.

Ravindra, V., Nautiyal, P.C. and Joshi, Y.C. (1990). Physiological analysis of drought resistance and yield in groundnut (*Arachis hypogaea* L.). *Tropical Agriculture*. 67: 290-296.

Ravindra, V., Nautiyal, P.C., Koradia, V.G. and Joshi, Y.C. (1989). Manipulation of water stress to increase productivity in groundnut. *Groundnut News*. 2: 5.

Reddy A.R., Chaitanya K.V. and Vivekanandan M. (2004). Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. *J. Plant Physiol.* 161: 1189–1202.

Reddy, C.R. and Reddy, S.R. (1993). Scheduling irrigation for peanuts with variable amounts of available water. *Agricultural Water Management*. 23: 1-9.

Reddy, P.R.R., Reddy, B.B., Rao, V.P. and Sarma, P.S. (1996). Effect of water deficits at different crop growth periods on growth and yield of groundnut. *Journal of Research APAU*., 24: 147-149

Reddy, P.V., Asalatha, M., Babhita, M. (1999). Soil water extraction and root growth in five groundnut genotypes under different soil moisture regimes. *Legume Res*. 22: 94-98.

Reddy, P.V., Asalatha, M. and Babitha, M. (2000). Relationship of mineral ash and chlorophyll content with transpiration efficiency in groundnut under different moisture regimes. *Indian Journal of Plant Physiology*. 5: 59-63.

Reddy, S.R. (1984). Scheduling irrigation with can evaporation for groundnut. *Ind. J. Agron*. 29: 51-54.

Reddy, T.Y. (1994). Management practices for amelioration of moisture stress in groundnut (*Arachis hypogaea*) in arid tropics. *Indian Journal of Agronomy*. 39: 489-490.

Reddy, T.Y., Reddy, V.R. and Anbumozhi, V. (2003). Physiological responses of groundnut (*Arachis hypogaea* L.) to drought stress and its amelioration: a review. *Acta Agronomica Hungarica*., 51: 205-227

Reddy, T.Y., Reddy, V.R. and Anbumozhi, V. (2003). Physiological responses of groundnut (*Arachis hypogea* L.) to drought stress and its amelioration: a critical review. *Plant Growth Regulation*. 41: 75-88

Rivas-San Vicente M. and Plasencia J. (2011). Salicylic acid beyond defence: its role in plant growth and development. *J. Exp Bot*. doi: 10.1093/jxb/err 031.

Rosario, D.A.del. and Fajardo, F.F.(1988). Morphophysiological responses of ten peanut (*Arachis hypogaea* L.) varieties to drought stress. *Philippine Agriculturist*. 71: 447-459

Runkulatile, H., Homma, K., Horie, T., Kurusu, T. and Inamura, T. (1998). Land equivalent ratio of groundnut-finger millet intercrops as affected by plant combination ratio, and nitrogen and water availability. *Plant Production Science*., 1: 39-46

Sahu, D.D., Patra,B. K. and Patoliya, B.M. (2004). Effect of sowing time and rainfall distribution on groundnut yield. *International Arachis.Newsletter*.24: 39-42.

Saini, H.S. and Srivastava, A.K. (1981). Osmotic stress and the nitrogen metabolism of two groundnut (*Arachis hypogaea* L.) cultivars. *Irrigation Science*. 2: 185-192.

Sakarvadia, H.L. and Yadav, B.S. (1994). Effect of water stress at different growth phases of groundnut on yield and nutrient absorption. *Journal of the Indian Society of Soil Science*. 42: 147-149.

Sakarvadia, H.L., Parmar, K.B., Jetpara, P.I. and Kalola, A.D. (2010). Effect of cyclic water stress and potassium on dry matter and nutrients accumulation in summer groundnut.*Advances in Plant Sciences*. 23: 193-196.

Samdur, M.Y., Manivel, P., Jain, V.K., Chikani, B.M., Gor, H.K., Desai, S. and Misra, J.B. (2003). Genotypic differences and water-deficit induced enhancement in epicuticular wax load in peanut. *Crop Science*, 43:1294-1299.

Santner A, and Estelle M (2009). Recent advances and emerging trends in plant hormone signalling. *Nature*. 459:1071-1078.

Sarma, P. S. and Sivakumar, M.V.K. (1990). Evaluation of groundnut response to early moisture stress during the rainy and the post-rainy seasons. *Agricultural and Forest Meteorology*. 49: 123-133

Sarma, P.S. and Sivakumar, M.V.K. (1987). Productivity of groundnut as influenced by use of seed from a crop with moisture stress history. *Field Crops Research*. 15: 207-213.

Sashidhar, V.R., Mekhri, A.A., and Krishna Sastry, K.S. (1977). Proline accumulation in relation to seed hardening in groundnut genotypes. *Indian Journal of Agricultural Sciences*. 47: 595-598

Sashidhar, V.R., Mekhri, A.A. and Sastry, K.S.K. (1981). Potassium content and proline accumulation following seed treatment with calcium chloride in groundnut varieties. *Indian Journal of Plant Physiology*. 24: 89-92.

Schubert, A.M. and Sanders, T.H. (1985). Irrigation scheduling using a canopy temperature stress degree day index to induce variable water stress in field-grown Florunner peanut. *Proceedings, American Peanut Research and Education Society*. 17: 65.

Selvam, V.S., Rao, G.N.S. and Rajan, M.S.S. (1989). Mid-season correction for groundnut (*Arachis hypogaea*) during moisture-stress period. *Indian Journal of Agricultural Sciences*. 59: 795-796.

Seo H.S., Song J.T., Cheong J.J., Lee Y.-H., Lee Y.-W., Hwang I., Lee J.S. and Choi Y.D. (2001) Jasmonic acid carboxyl methyltransferase: a key enzyme for jasmonate-regulated plant responses. *Proc. Natl. Acad. Sci.* USA. 98:4788-93.

Serraj, R., Bidinger, F.R., Chauhan, Y.S., Seetharama, N., Nigam, S.N., Saxena, N.P., Kijne, J.W. (ed.), Barker-R (ed.), and Molden, D. (2003). Management of drought in ICRISAT cereal and legume mandate crops. Water productivity in agriculture: limits and opportunities for improvement. 127-144

Shahid Umar and Umar, S (1997). Influence of potassium on solar energy harvesting efficiency of groundnut under different soil moisture stress. *Indian Journal of Plant Physiology*. 2: 315-317.

Shahid Umar, Bansal, S.K. and Umar, S. (1997). Effect of potassium application on yield and quality of water stressed groundnut. *Fertiliser News*. 42: 27-29.

Shakirova F.M. (2007). Role of hormonal system in the manifestation of growth promoting and anti-stress action of salicylic acid. In: Salicylic Acid. A Plant Hormone (Eds.) Hayat S., Ahman A. Springer. ISBN 978-1-4020-5183-8. Dordrecht, Netherlands.

Sharma, K., Gurbaksh Singh and Sharma, H.L. (1987).Effect of simulated water stress by polyethylene glycol (PEG) on germination and some enzymes of groundnut (*Arachis hypogaea* L.). *Annals of Biology*. 3: 77-82

Sharma, K., Gurbaksh Singh and Singh, G. (1985). Seedling growth and sugar metabolism of groundnut under polyethylene glycol induced water stress. *Indian Journal of Ecology*. 12:252-256.

Sharma, K., Gurbaksh Singh and Singh, G. (1987). Effect of water stress on yield and quality of groundnut. *Environment and Ecology*. 5: 647-650

Sharma, P., Nisha., Malik, C.P. (1993). Photosynthetic responses of groundnut to moisture stress. *Photosynthetica*., 29:157-160.

Sharp R. E., LeNoble M. E., Else M. A., Thorne E. T. and Gherardi F. (2000). Endogenous ABA maintains shoot growth in tomato independently of effects on plant water balance evidence for an interaction with ethylene. *J. Exp. Bot.* 51: 1575-1584.

Shashikumar, M.R., Gowda, T.C.C., Prasad, T.G., and Kumar, M.U. (1988). Assessment of relative drought tolerance in groundnut genotypes using line-source technique. *Narendra Deva Journal of Agricultural Research.* 3: 48-54.

Sheshshayee, M.S., Bindumadhava, H., Ramesh, R., Prasad, T.G., Lakshminarayana, M.R. and Udayakumar, M. (2005). Oxygen isotope enrichment (Delta^{18}O) as a measure of time-averaged transpiration rate. *J. Exp. Bot*. 56: 3033-3039.

Shi Q. and Zhu Z. (2008). Effects of exogenous salicylic acid on manganese toxicity, element contents and antioxidative system in cucumber. *Environ. Exper. Bot.* 63: 317-326.

Shinde, G.G. and Pawar, K.R. (1984). Effects of water stress at critical growth stages on growth and yield of groundnut in summer season. *Journal of Maharashtra Agricultural Universities*. 9: 26-28.

Shinde, G.G. and Pawar, K.R. (1982). Effect of irrigation on the pod yield of groundnut. *Indian Journal of Agricultural Sciences*. 52: 576-578.

Shinde, G.G. and Pawar, K.R. (1983). Growth and plant-water relation in groundnut grown under different soil-moisture stresses. *Journal of Maharashtra Agricultural Universities*. 8: 32-34.

Shinde, G.G. and Pawar, K.R. (1984). Effect of water stress at critical growth stages on growth and yield of groundnut in summer season. *J. Maharashtra. Agric. Univ*. 9: 26-28.

Simmonds L.P. and Azam Ali S.N. (1989). Population, growth and water use of groundnut maintained on stored water. IV. The influence of population on water supply and demand. *Experimental Agriculture*. 25: 87-98.

Singh, A.L. 2004a. Growth and physiology of groundnut. pp 178-212. In: Groundnut Research in India (Eds. M.S. Basu and N.B. Singh) National Research center for groundnut (ICAR), Junagadh, India.

Singh, A.L. (2004b). Mineral nutrient requirement, their disorders and remedies in groundnut. pp 137-159. In: Groundnut Research in India (Eds. M.S. Basu and N.B. Singh) National Research center for groundnut (ICAR), Junagadh, India.

Singh, A.L. (2011). Physiological basis for realizing yield potentials in Groundnut. *In*: Advances in Plant Physiology (Ed. A. Hemantaranjan) Vol. 12 pp. 131-242. Scientific Publishers (India), Jodhpur, India.

Singh, A.L. and Vidya Chaudhari, 1995. Source and mode of sulphur application on groundnut productivity. *Journal of Plant Nutrition*, 18: 2739-2759

Singh, A.L., Ajai and Vidya Chaudhari. (2001). Drip irrigation- a potential system for micronutrient application in groundnut in semi-arid region. pp 501-507. *In*: Micro-irrigation (Eds. H.P. Singh, S.P. Kaushish, Ashwani Kumar, T.S. Murthy and J.C. Samuel), proceeding International Conference on Micro and Sprinkler Irrigation Systems, 8-10 February 2000, Jain irrigation Hills Jalgaon, India. Published by Central Board of Irrigation and Power, New Delhi, India.

Singh, A.L., Ajay, Vidya Chaudhari and J.B. Misra, 2000. Drip irrigation-an efficient system for micronutrient application in groundnut in calcareous soils of semi-arid region. In: Proc. GAU-PRII-IPI National Symposium on Balanced Nutrition of Groundnut and other Field Crops in Calcareous Soils of India (B.A. Golakiya, J.D. Gundalia, S.K. Bansal. and Patricia Imas eds) pp 194-198.

Sree, P.S.S. and Rao P.G. (1998). Response of groundnut to irrigation schedules based on IW/CPE ratios. *Journal of Oilseeds Research*. 15(2): 315 319.

Stirling, C.M. (1989). Environmental effects on partitioning and development in groundnut. Dissertation Abstracts International B, *Sciences and Engineering*. 50: 1726B

Stirling, C.M., Black, C.R. and Ong, C.K. (1990). Response of groundnut to timing of irrigation. *Monograph British Society for Plant Growth Regulation*. 21: 374-380.

Subramanian, V.B., Reddy, G.J. and Maheswari, M. (1993). Photosynthesis and plant water status of irrigated and dryland cultivars of groundnut. *Indian Journal of Plant Physiology*. 36: 236-238.

Sulochana, C. and Savithramma, N. (2003). Effect of calcium on acid phosphatase activity in groundnut (Arachis hypogaea L.) seedlings during water stress. *Indian Journal of Plant Physiology*. 8:186-188

Sulochana, C. and Savithramma, N. (2001). Effect of calcium in amelioration of PEG (6000) induced water stress in groundnut (*Arachis hypogaea* L.) cultivars during seedling growth. *Journal of Plant Biology*. 28: 257-263.

Sulochana, C.H., Rao, T.J.V.S. and Savithramma, N. (2002). Effect of calcium on water stress amelioration through calmodulin and scavenging enzymes in groundnut. *Indian Journal of Plant Physiology* (India). (Apl-Jun. v. 7(2) p. 152-158.

Sumathi, V. and Subramanyam, D. (2007). Analytical studies on drought categorization and its effects on rainfed groundnut yields. *Crop Research Hisar* .34: 88-91.

Suriharn, B., Patanothai, A. and Jogloy, S. (2005). Gene effects for specific leaf area and harvest index in peanut (*Arachis hypogaea* L.). *Asian Journal of Plant Sciences*. 4: 667-672.

Suvarna, Kenchanagoudar, P.V., Nigam, S.N. and Gowda, M.V. C (2006). Genotypic evaluation for yield and its attributes under imposed moisture stress conditions in groundnut (*Arachis hypogaea* L) *Research on Crops*. 7: 221-228.

Suvarna, Kenchanagoudar, P.V., Nigam, S.N. and Chennabyregowda, M.V. (2002). Effect of drought on yield and yield attributes of groundnut. *Karnataka Journal of Agricultural Sciences*. 15: 364-366.

Thiyagarajan, G. and Ranghaswami, M. V. (2010) Modeling yield response of groundnut to deficit irrigation at different growth stages by FAO CROPWAT. *Madras Agricultural J.* 97(4/6): 145-148.

Thiyagarajan, G., Rajakumar, D., Kumaraperumal, R., Manikandan, M. (2009) Physiological responses of groundnut (*Arachis hypogaea* L.) to moisture stress: a review. *Agricultural Reviews*. 30(3): 192-198.

Thiyagarajan, G., Ranghaswami, M.V., Rajakumar, D., Kumaraperumal, R. (2010). Deficit irrigation effects on groundnut (*Arachis hypogaea* L.) with micro sprinklers. *Madras Agricultural J.* 97: 40-42.

Thorat, S.T., Kalra, G.S., Pawar, A.B. (1984). Responses of groundnut varieties to different irrigation schedules. *Indian Journal of Agronomy*. 29: 43-45.

Tiwari, K.N. (2005). Meeting the challenges of oilseeds production through balanced use of potash. *Fertiliser Marketing News*. 36: 5-14, 19, 21-23.

Turner J.G., Ellis Ch. and Devoto A. (2002). The jasmonate signal pathway. *Plant Cell*. 14: 153-164.

Umar, S., Afridi, M.M.R.K. and Dwivedi, R.S. (1991). Influence of added potassium on the drought resistance of groundnut. *Journal of Potassium Research*. 7: 53-61.

Upadhyaya, H. D., Sharma S., Singh S. and Singh M. (2011) Inheritance of drought resistance related traits in two crosses of groundnut (*Arachis hypogaea* L.). *Euphytica*. 177(1): 55-66.

Uthai Arromratana, Tawatchai Na Nakara, Seri Sukakit, Boonlert Boonyoung (1993). Effect of water stress at different growth stages on yield of groundnut. Department of Agricultural Extension, Bangkok (Thailand). *Proceedings of the eleventh Thailand national groundnut meeting. Raingan kan sammana thua-lisong haeng chat khrang thi 11 na rongraem Chansomthara, Ranong 17-21 Phrusaphakhom 2536. Bangkok (Thailand).* 568: 273-278.

Vadez, V., Krishnamurthy, L., Kashiwagi, J., Kholova, J., Devi, J.M., Sharma, K.K., Bhatnagar Mathur, P., Hoisington, D.A., Hash, C.T., Bidinger, F.R., Keatinge, J.D.H. (2007). Exploiting the functionality of root systems for dry, saline, and nutrient deficient environments in a changing climate. *Journal of SAT Agricultural Research*. 4: 1-61.

Vaghasia, P.M., Jadav, K.V. and Nadiyadhara, M.V. (2010a). Effect of soil moisture stress at various growth stages on growth and productivity of summer groundnut (*Arachis hypogaea* L.) genotypes. *International Journal of Agricultural Sciences*. 6: 141-143.

Vaghasia, P.M., Jadav, K.V., Jivani, L.L. and Kachhadiya, V.H. (2010b). Impact of water stress at different growth phases of summer groundnut (*Arachis hypogaea* L.) on growth and yield. *Research on Crops*. 11: 693-696.

Vakharia, D.N., Kukadia, A.D. and Parameswaran, M. (2003). Polyamines in response to artificial water stress in groundnut seedlings. *Indian Journal of Plant Physiology*. 8: 383-387

Varshney, R.K., Bertioli, D.J., Moretzsohn, M.C., Vadez, V., Krishnamurthy, L., Aruna, R., Nigam, S.N., Moss, B.J., Seetha, K., Ravi, K., He, G., Knapp, S.J., Hoisington, D.A. (2009) The first SSR-based genetic linkage map for cultivated groundnut (*Arachis hypogaea* L.). *Theoretical Applied Genetics.* **118:** 729-739.

Velu, G. (1998). Effect of water stress on yield potential of groundnut (*Arachis hypogaea*). *Indian Journal of Agricultural Sciences.* 68: 284-286.

Venkateswarlu, B. and Ramesh, K. (1993). Cell membrane stability and biochemical response of cultured cells of groundnut under polyethylene glycol-induced water stress *Plant Science Limerick*. 90: 179-185.

Venkateswarlu, B., Mukhopadhyay, K. and Ramesh, K. (1993). Effect of PEG induced water stress on cell cultures of groundnut in relation to the response of whole plants. *Oleagineux*, 48: 463-468.

Venkateswarlu, O., Reddy, K.R., Reddy, P.V., Vasanthi, R. P., Reddy, K.H.P and Reddy, N.P.E. (2007). Identification of superior donor parents for drought tolerance and yield through combining ability analysis in groundnut. *Legume Research*. 30: 128-132.

Vivekanandan, A. S. and Gunasena, H. P. M. (1976) Lysimetric studies on the effect of soil moisture tension on the growth and yield of maize (*Zea mays* L.) and groundnut (*Arachis hypogaea* L.). *Beitrage zur Tropischen Landwirtschaft und Veterinarmedizin*. 14:269-378

Wang Sheng Yu, Liao BoShou, Lei Yong; Li Dong and Xiao DaRen (2004). Role of in vitro resistance to aflatoxin contamination in reducing pre-harvest aflatoxin contamination under drought stress in groundnut. *International Arachis Newsletter*. 24: 38-39.

Wasternack C. and Hause B. (2002). Jasmonates and octadecanoids: signals in plant stress responses and development. *Prog. Nucleic Acid Research Molecular Biology*. 72: 165-221.

Wasternack C. (2007). Jasmonates: an update on biosynthesis, signal transduction and action in plant stress response, growth and development. *Annals of Botany*. 100: 681-697.

Wheatley, A. R. D., Wightman, J. A., Williams, J. H., and Wheatley, S. J. (1989). The influence of drought stress on the distribution of insects on four groundnut genotypes grown near Hyderabad, India. *Bulletin of Entomological Research*. 79: 567-577.

Williams, J.H., Rao, R.C.N., Matthews, R and Harris, D. (1986). Responses of groundnut genotypes to drought. Agrometeorology of groundnut. Proceedings of an international symposium, ICRISAT Sahelian Center, 21-26 August 1985. 99-106.

Womble, B.A. and Garren, K.H. (1978). Sodium azide offers some promise for control of Cylindrocladium black rot (CBR) of peanuts. *Proceedings of American Peanut Research and Education Association, Inc*., 10:52.

Worthington, J. W., Schmidt, J. R., and Lamm, F. R. (1995). A microirrigation system for peanut research plots. Microirrigation for a changing world: conserving resources-preserving the environment. Proceedings of Fifth International Microirrigation Congress, Orlando, Florida, USA, 2-6 April 1995. 664-668.

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

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

Wright, G.C., Hubick, K.T., Farquhar, G.D. and Nageswara, R.C. (1993). Genetic and environmental variation in transpiration efficiency and its correlation with carbon isotope discrimination and specific leaf area in peanut. *Stable Isotopes And Plant Carbon Water Relations*. 247-267.

Wright, G.C., Rahmianna, A., and Hatfield, P.M. (1988). A comparison of thermocouple psychrometer and pressure chamber measurements of leaf water potential in peanuts. *Exerimental Agriculture*. 24: 355-359.

Wright, G.C., Rao, R.C.N., Basu, M.S., Passioura, J.B., Cooper, M (ed.) and Hammer, G.L. (1996). A physiological approach to the understanding of genotype by environment interactions - a case study on improvement of drought adaptation in groundnut. *Plant Adaptation and Crop Improvement*: 365-381.

Yao ChunMei, Yang PeiLing, Hao ZhongYong, Wang QuanHai, Yao, C.M., Yang, P.L., Hao, Z.Y. and Wang, Q.H. (1999). Dynamic analysis of root/shoot development in groundnut under different water regimes. *Journal of China Agricultural University*. 4: 40-44.

Yao, J.P., Luo, Y.N. and Yang, X.D. (1982). Preliminary report on the effects of drought on seed development and quality of early groundnut. *Chinese Oil Crops Zhongguo Youliao*., 3:50-52.

Zaharah, H. (1986). The effect of water deficit at different growth phases on the performance of groundnut. Miscellaneous Crops Res. Div., MARDI, Serdang, Selangor, Malaysia. *MARDI Research Bulletin*. 14: 126-131.