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Presidential Address :

Journey towards greener pasture: Research on drought tolerance*

V. Rajagopal

Director, Central Plantation Crops Research Institute, Kasaragod - 671 124 Kerala, India

Honourable past Presidents of the Indian Society for Plantation Crops, distinguished members of the Executive Committee, delegates to the 16th PLACROSYM, Colleagues, ladies and gentlemen. It is now my privilege to deliver the address as the President of the Society during 2002-2004. I have devoted my whole time on drought research during the last three decades on different crops and gained an insight into the complex nature of responses to given stress conditions. As my aim was always to probe into the mechanisms of drought resistance/tolerance and strategies for amelioration of drought to ensure the recovery of crops with renewed vigour, I decided to give the above title to my lecture.

Introduction

Weather variables like rainfall, day/night temperature regimes, relative humidity, sunshine duration, vapour pressure deficits play pivotal role in determining the crop growth, development and yield. All plants do not show same response to changes in environmental variables . Some plant species are relatively more tolerant to stresses. Some plants "escape" stress period by completing their life cycle within short favourable period and are called "evaders". Some plants overcome stress through avoiding by adopting themselves for stress period e.g. root penetration for water uptake to avoid water stress and are called "avoiders". However, some plants are able to withstand stress owing to their physiological, biochemical, anatomical, morphological and phenological adaptations (Kramer, 1983). These are called tolerant/resistant types. In this I will be giving more emphasis on the stresses caused by abiotic factors.

Factors contributing to various stresses

There are both natural and anthropogenic factors, which are responsible for various types of stresses (Table 1). Excess water affects plant growth by hindering the water and mineral uptake. Similarly excess irrigation without proper drainage facilities cause salinity / alkalinity. It is estimated that India is losing about 10 thousand hectares annually due to salinity and alkalinity. Among the plantation crops, arecanut and pepper are sensitive to salt stress whereas coconut, cashew etc. are relatively tolerant. Plants possess chilling resistance mechanism by having ability to increase ratio of unsaturated to saturated lipids in cell membranes thus maintain cell membrane integrity where as plants that grow in hot conditions become succulent and some plants adopt Crassulacian Acid Metabolism (CAM). During stress period, plants produce some specific proteins called heat shock proteins (HSPs). These protect essential metabolic enzymes and nucleic acids from heat denaturing. Plants also accumulate compatible solute and possess antioxidant capacity.

Table 1. Stress factors

Natural stress factors	Anthropogenic stress factors
• High irradiance	• Herbicides
• Heat	• Pesticides
• Chilling	• Fungicides
• Frost	• ozone
• Water deficit	• Air pollutants
• Natural mineral deficiency	• Photo oxidants
• Long rainy periods	• Acid rains
• Insects	• Heavy metals
• Viral	• Increased CO_2 levels
• Fungal	• Increased UV radiation
• Bacterial pathogens	

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Plants tolerate high light intensities by developing mechanisms like thick cuticle (to reflect the light) thick leaves (so that the light intensities at the chloroplast level reduces), modifying the photosynthetic pigment concentrations, possessing antioxidant capacity, etc. Among the natural stress factors drought stress is the most prevalent abiotic stress, which affects the plant growth and productivity. In fact, deserts occupy 1/7 of global surface. According to FAO, among the cultivated land world wide, only 18% of land is irrigated. In India, about 72% of agricultural land is under rainfed condition (Table 2).

Table 2. Cultivable land in rainfed area in the World and in India

Land	World	India
Cultivable land	1474 m ha	142 m ha
Irrigated area	227 m ha	39.2 m ha
Rainfed area	1247 m ha	102.8 m ha
Irrigated area (%)	17.6%	28%
Rainfed area (%)	82.4%	72%

(Source: II International Crop Science Congress Proceedings (1998)

In spite of the development of irrigation facilities, it is expected that still 60% of land has to remain under rainfed condition. Inadequate water availability for plant growth due to low rainfall is termed "drought stress" and those low rainfall years are called "drought years". The region or a period is considered drought affected if it receives 20% or less of normal rainfall for that area or period. From agriculture point of view, drought can be defined as "the inadequacy of water availability, including precipitation and soil moisture storage capacity, in quantity and distribution during the life cycle of the crop to restrict expression of its full genetic potential". The food grain production during drought years also will be restricted. Plants developed, over generations, mechanisms to overcome drought stress. Thus the drought resistance is defined as "the mechanisms causing minimum loss of yield in water deficit environment relative to the maximum yield in a water constraint-free management of crop".

Drought, plant growth and development

Water stress is the main factor, which affects plant growth and development. Deficient in water in cells lead to loss of turgor thus causing closure of stomata, which in turn adversely affects the photosynthetic rates. This affects growth in general, decreases root growth, increases respiration and denatures enzymes and decreases Hill activity. These cause the formation of super oxide radicals, which damage the membrane integrity. All these adverse effects on physiology and cell structure of plant lead to poor growth and lower yields. Plants, which can with stand the water stress, are called "drought tolerant" types. These drought tolerant types are of importance in agricultural production point of view. These plants mainly possess the following drought tolerant characteristics.

1. Osmotic adjustment: in which plants lower osmotic potential by accumulating the compatible solutes like sugars and aminoacids.
2. Antioxidant capacity: to detoxify the active oxygen radicals by certain enzymes like super oxide dismutase, catalase, peroxidase, etc.
3. Desiccation tolerance *per se*: i.e. capacity of the cells to survive low leaf water status through mechanisms other than osmotic adjustment and anti oxidant capacity. e.g. by accumulating / synthesizing certain drought induced proteins like late embryo genesis (LEA) proteins, etc.

Chronology of drought research:

The drought research started way back in 1940s with ultimate aim to overcome the adverse impact of drought through technological developments; to ensure sustainability of food production to meet the demands of millions of humanity around the world. For the sake of convenience, the chronological order is given to highlight the progressive development that took place on drought research.

Prior to 1940	Soil-weather-plant relationship(Soil characteristics, water requirement, crop responses, root-leaf morphology etc)
1941 to 1950	Weather-crop-relationship(Agro-meteorological factors, definition of drought, yield variations among crops and varieties within the crop
1951 to 1960	Crop characteristics(Genotypic responses to water deficits, yield evaluation of varieties for plant characters, yield components, yield)
1961 to 1970	Development of techniques(Sensitivity of parameters, enumeration of desirable traits, screening methods, physiological characterization)
1971 to 1980	Stress tolerance(Identification of tolerant genotypes, biochemical characterization, selection criteria for breeding)
1981 to 1990	Breeding strategies(Perfection of breeding techniques, crosses with proven tolerant genotypes, evolving promising hybrids, evaluation, multiplication etc)
1991 to date	Biotechnological approaches(*In vitro* screening, molecular basis of tolerance, application of latest techniques of genetic engineering, production of transgenic plants

2000 & beyond	Crop improvement(Field evaluation of transgenic plants, further refinement of techniques, improved varieties with both stress tolerance and yield)

Screening for drought tolerance

Many plant traits (listed below) conferring adaptation to water-limited environment have been identified for screening for drought tolerance.

Anatomical	Thicker cuticle, large epidermal cells, larger sub stomatal cavity, low stomatal frequency
Physiological	High stomatal resistance (low conductance) High leaf water potential, High relative water content, High membrane integrity
Biochemical	High wax contentHigh proline content, Low lipid peroxidation, High SOD, PO, CAT Stable NRA, High photosynthetic rate, High chlorophyll fluorescence

My association with drought research – Reminiscence

I was initiated to drought research during 1966 at S.V. University, Tirupathi under the able guidance of Prof. I. M. Rao, a renowned Plant Physiologist. My earlier work, investigations on drought resistance an ICAR scheme in Jowar and ground nut, helped in identifying TMV 2 ground nut var. as relatively resistant to moisture stress and also to understand dry matter partitioning in Jowar varieties under moisture stress conditions. Later at the Water Technology Centre, IARI, New Delhi: (1972 -1977) studies were conducted in screening for stress tolerance in *Sorghum*, wheat and cowpea. The threshold leaf water potential for various physiological and biochemical process in stressed sorghum, wheat and cowpea was understood. Development of rapid screening methods, identification of C-306 and Kalyansona in wheat and CSH-3 and M 35-1 in sorghum as the drought tolerant varieties and understanding the mechanism of stress tolerance in some of the annual crops were the major achievement during this period. I had the previlege of working under Prof. S.K. Sinha, National Professor.

At the Department of Plant Physiology and Anatomy, Royal Veterinary and Agricultural University, Copenhagen, Denmark (1977-1979), my contributions to stress physiology were on root formation and the root regeneration ability of pea plants grown in the controlled environment chambers at two levels of irradiance and subjected to different degrees and duration of stress. Similarly the effect of moisture stress and ABA on proline accumulation in barley seedlings grown under two levels of irradiance in the controlled growth chambers was investigated. The biphasic pattern of proline accumulation was evident. ABA – induced increase in the conversion of glutamate to proline was shown. In addition to this, the relationship between proline - stomatal resistance in *Vicia faba* also was delineated. I was holding the DANIDA, Post Doctoral Fellowship and associated with Prof. A. Skytt Andersen.

During the fellowship, I had the good opportunity to visit the leading laboratories in different Universities like Arhus (Denmark), Gotenburg, Stockholm, Lund and Uppasala (Sweden), Wageingen, Leiden (Netherlands), Hamburg (Germany) Reading University, Rothamsted Exp. Station (U.K.) and Edinburg and interacted with diitinguished professors.

Genesis of drought research in coconut

Consequent upon the unprecedented drought that occurred in 1982-83 in Kerala with devastating effect on crops like coconut, arecanut, pepper etc., the work on drought tolerance screening in coconut was started to unravel the impact of drought.

Coconut, a perennial tree crop, grows well in tropical climate with temperature around 27°C with a diurnal variation of 5 to 10°C and sunshine about 120 hours per month under rainfed conditions (Child, 1974; Murray, 1977). Rainfall is one of the important parameter that influence the growth and productivity of the palms. Although Kerala receives more than 3000mm rainfall per year due to early cessation of south- west monsoon or failure of north- east monsoon and non- seasonal rains, prolonged droughts have been common, resulting in considerable crop losses. It has been observed that productivity of palms are affected if the adverse climate occurs during the three critical stages of fruit development i.e., initiation of inflorescence primordium, ovary development and button size nuts (Rajagopal *et al.* 1996). The nut production during these periods can be sustained by giving life saving irrigation during summer months. Palms withstand both soil as well as atmospheric drought for five to six months starting from January to May by various adaptive mechanisms.

Morphological adaptations

Palms combat both soil and atmospheric droughts by drooping and breaking of the leaves, poor spathe development and shedding of buttons. The critical level of atmospheric parameters above which the palms show stress symptoms are radiation around 265 $W.m^{-2}$, temperature 34°C and vapour pressure deficit around 27 mbar. Genotypic variations are found to exist in the morphological adaptations (Kasturi Bai *et al.*, 1988). Even under irrigation with 20 mm of water at IW/CPE ratio of 0.5, dry matter production was affected (Table 3; Rajagopal *et al.,* 1989).

Table 3. Soil water plant relationship in coconut

Irrigation levels	ASW, mm (0-120 cm) depth	rs $Sec.cm^{-1}$	LWP -MPa	Nut yield $Palm^{-1}Year^{-1}$
1.00	51.0	3.07	-0.90	144
6.75	43.7	5.10	-1.20	125
0.50	14.2	7.60	-1.30	110
0.00	9.5	14.9	-1.45	87

Geographical location also reflects on the growth and productivity of the palms. In Kerala, wide variation was observed in the performance of the palms, in terms of growth, yield and copra production between the Southern and the Northern part (Table 4) Even the time taken for the opening of the leaf and spathe varied significantly between the two places. The performance of palms growing in Southern Kerala are found to be better than Northern Kerala due to the even distribution of the rain fall in the former than the latter. Although coconut experience severe soil water deficits during March to May, 40-60% of the yield is realized during these periods.

Table 4. Response of coconut palms to different intensities of drought

Genotypes	Nut Yield $Palm^{-1}$		Copra Weight ($g\ nut^{-1}$)	
	North Kerala	South Kerala	North Kerala	South Kerala
WCT	78.0	93.3	133.0	167.0
COD x WCT	106.0	116.0	135.0	169.0

Physiological adaptation

For any plant to with stand the adverse effects of moisture stress, it must regulate the water balance in the tissues. This is achieved through effective stomatal regulation to check the transpirational loss of water from the leaf surfaces. Once the transpirational loss of water is minimized under stress conditions, the internal tissue water (leaf water potential) remains high leading to maintenance of turgidity in the leaves. In coconut some of the cultivars/hybrids were found to transpire less and maintained turgidity, thus qualifying to be designated as drought tolerant types (Rajagopal *et al.,* 1990). The turgor of the cell can also be maintained through osmotic adjustment. In this process, an active accumulation of organic solutes occurs in tissues subjected to stress thus leading to decrease in osmotic potential of the cells. In coconut also higher accumulation of organic solutes such as sugars and free amino acids was observed in the drought tolerant palms than the susceptible types thus maintaining turgidity during stress period (Kasturi Bai and Rajagopal, 2000).

Water holding capacity of the soil influence the physiology of palms differentially in terms of stomatal regulation, leaf water status and turgor maintenance. Between the three coconut cultivars, viz., WCT, Kerasankara and Chandra sankara, WCT did not show much variation in the maintenance of turgor between the two soil types where as the hybrids exhibited higher adaptability in the laterite soil than the sandy loam soil. These hybrids maintained higher turgor by closing the stomata thus regulating the transpirational rates in the laterite soil than the sandy loam soil. This implies that during summer months under rainfed condition the hybrids suffer more in the sandy loam than laterite soil (Voleti *et al.*, 1993).

Another mechanism by which the plant adapts to drought is through deposition of wax on the leaf surface called epicuticular wax. Besides checking the water loss from leaf surface, wax also plays a key role in reflecting back the heat load on the leaf, thus protecting the tissues from thermal damage. In coconut although cuticular wax did not show much variation during non-stress period, with the advent of stress period the drought tolerant types accumulated more wax than the others. Almost three to four fold increase in ECW has been observed between wet and dry seasons (Rajagopal *et al.*, 1990). This implies that those palms which show high stomatal resistance, low transpiration rate, high leaf water potential, low osmotic potential, high turgor potential and high wax content, when subjected to moisture stress are qualified to be considered as drought tolerant.

Leaf anatomy

Leaf cuticular thickness, responsive stomata, stomatal frequency and size are the factors which control the water loss of plants. In coconut differences in the anatomical features have been observed among the drought tolerant and susceptible cultivars. The drought tolerant types have larger epidermal cells and thick cuticle on the upper and lower epidermis (FMS) and large substomatal cavity (WCT). While the drought susceptible types have thinner leaf and thinner cuticle on the upper epidermis, smaller sub stomatal cavity (Gangabondam) and smaller epidermal cells (COD x WCT). The size of guard cells also varied among the genotypes with largest size in COD x WCT and smallest in FMS. The size of the hypodermal cells which store water was higher in drought tolerant types. These anatomical features have strong hold on the photosynthetic characteristics as well as water relation of coconut (Table 5; Naresh Kumar *et al.,* 2000).

Table 5. Correlation between anatomical features and physiological parameters

Parameters		R value
Leaflets	Stomatal frequency	-0.67
	Photosynthetic rate	-0.41
	Transpiration rate	-0.12
Sub-stomatal cavity (size)	Stomatal frequency	-0.54
	ECW	0.61
	Transpiration rate	-0.15
	Photosynthetic rate	-0.11
Cuticle thickness	Cuticular wax	0.79
	Transpiration rate	-0.74
	Leaf water potential	0.57
Mesophyll cell size	Photosynthetic rate (Pn)	-0.72
	Transpiration rate	-0.17
	Leaf water potential	0.11

Biochemical adaptation

The high temperature occurring during the stress period will denature some of the important enzymes which scavenge the toxic materials such as hydrogen peroxide and oxygen radicals produced during the incomplete oxidation of the metabolite inside the cells. These are toxic to the cell membrane, which lead to the higher peroxidation of cell wall lipids leading to cell membrane damage. In the drought tolerant palms the enzymes are activated more leading to the scavenging of all these toxic substances produced during the high temperature stress thus reducing the peroxidation of cell wall lipids. This helps in maintaining the membrane integrity and survival of the palms during drought (Chempakam *et al.*, 1993). Loss of cell membrane integrity will affect the production potential of the palms due to impaired metabolism.

Screening for drought tolerance

Based on these criteria coconut cultivars/hybrids were screened for drought tolerance. The studies revealed that WCT, FMS, Fiji, Java Giant, Laccadive Ordinary (LCT) among the talls and Lakshaganga (LCTxGB), Chandra Laksha (LCTxCOD), WCTxWCT and WCT x COD among the hybrids are tolerant to moisture stress by virtue of possessing the above mentioned desirable traits. Out of these, Laksha Ganga and Chandralaksha proved to be good yielders under severe drought condition. Conversely the dwarfs do not posses the above desirable traits during stress conditions and are grouped as drought susceptible types (Rajagopal,1990).

Mechanism for drought tolerance

These findings have helped in deciphering the mechanism of drought tolerance and stability in yield under water stress conditions. Thus the mechanism of drought tolerance, in it's totality is highlighted for the first time in coconut (Rajagopal and Kasturi Bai,2002). The relation between stress sensitive parameters and nut yield has been observed there by validating the usefulness of the screening methods for drought tolerance in coconut. This has helped the breeders in the breeding strategies to produce crosses suitable for cultivation under water limited situations.. Having elucidated the factors that impart drought tolerance and identified the drought tolerant types, seedlings have been produced by crossing selected parents and screened them for tolerance to drought at the nursery stage.

Selection for drought tolerance

The crop improvement in areas with limited water supply or high frequency of soil water deficits should aim at identifying the varieties, which can withstand the adverse condition of soil and atmospheric droughts. So far tolerance with desirable traits is a positive step towards selection for breeding strategies. However, success in breeding for drought tolerance has been achieved only with a few traits. The mechanism and strategies to be adopted in breeding and selection program will depend not only on their effect on productivity, but also on the type of drought likely to be encountered.

Germplasm should be screened for targeted traits under the targeted environments varying in time and space. In perennials, the stability of such tolerance over a period of time is the key factor for realizing stable yields even during stress years. Special emphasis should be given for field tolerance and *in situ* tolerant plants. High water use efficiency types with high dry matter production efficiency and good harvest index are the ones, which should perform better under stress conditions. Early vigor and high revival capacity are very significant factors that should take pivotal place.

Drought characterization and its management

In nature, intensity of drought varies with the place and time. It is important that drought prone areas may be characterized for the nature, intensity, frequency, length of dry spell, onset and off set of critical dry spell. Since the sensitivity of plant to dry spell varies with the crop type, a close coordination between these two areas is essential for furthering the yields in drought prone areas. Any specific recommendation to improve the yield should include resource characterization. Based on the resources available, production zones can be made so as to enable to achieve maximum yield in a given situation. The water balance and regional hydraulic cycle plays an important role apart from the soil characteristics. By employing screening techniques for desirable traits for drought tolerance, varieties have been selected and released for planting in drought prone areas. Exhaustive lists of drought tolerant crop varieties are available in India (Rajagopal, 1997).

Characterization of Drought in coconut growing areas

The nature and length of drought in different coconut growing areas in India was worked out based on the weather data for last 15 to 20 years from different agro-climatic zones viz., Western coastal area – hot sub-humid-per-humid (Kasaragod – Kerala; Ratnagiri – Maharastra), hot semi arid (Arisikere – Karnataka) and Eastern coastal plains- hot sub-humid (Veppankulum-Tamil Nadu; Ambajipeta- Andhra Pradesh). The study revealed that the dry spell during the critical stages of nut development ultimately determine nut production in coconut

Drought management

Studies revealed drought occurs once in three to four years with different intensities in major plantation areas. In order to have sustained yields it is important to have strategies to manage drought, which includes the soil as well as atmospheric droughts.

Drought management strategies mainly include the conservation of available soil moisture and efficient use of available water resources for high production. As the plantation crops are grown under different soil types having variation in hydro physical characteristics different methods have to be adopted to conserve soil moisture. The agronomic practices such as adoption of organic farming technologies and tillage practices like summer ploughing, soil mulching and addition of soil stabilizers can be used for soil management for conservation of water during drought periods.

Crop management also offers scope to reduce drought impact on crop mainly by the removal of old leaves to reduce transpiration loss. If late rains occur, pulses or fodder crops can be sown in between coconut rows. After harvest, these plant residues can be used as mulches. So also green manure crops can be raised in the plantations. Application of higher doses of fertilizers (eg. for each coconut palm 1 kg urea, 2 kg Super phosphate, 1.2 kg muriate of potash, 0.5 kg $MgSO_4$, 50 kg green leaf or FYM) will also help in alleviating the impact of water stress on production, by increasing the soil water holding capacity. Ploughing back tender *Glyricidia* has given encouraging results.

***In situ* tolerant plants**

The plants which can with stand the natural occurrence of drought and other stresses and still produce good yield are of premium in nature for their possessing desirable gene pool. During the survey in drought areas, we observed some of the palms yielding very high compared to others in their vicinity. Such palms are having desirable canopy shape, leaf number apart from being better yielder. The physiological water use efficiency of these palms is also high. This type of *in situ* tolerant plants with desirable traits should be used in breeding programmes (Naresh Kumar *et al.*, 2000)

Conclusion

In nature, the degree and duration of abiotic stresses are complex, because they coincides generally with high light intensities and high temperature regimes. The exploitation of the already identified varieties for drought tolerance involves meticulous planning of breeding strategies. The work on developing cross combinations involving parents with not only drought tolerance but also the potential for high yield under limited water availability would be an important step for the overall improvement of crops under drought. Thus, the linking of water relations of crops to yield potential assumes significance in the overall crop improvement scenario. In future, the biotechnological/molecular approaches may accentuate on accumulating as many desirable genes as possible in one genotype in order to get a much dreamt "Ideotype".

Future thrust:

- Exploitation of natural tolerance (*in situ* tolerant palms)
- Emphasis on water conservation and management in plantation crops
- Molecular basis of drought tolerance
- QTL for drought tolerant traits

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