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Characterization of drought and adaptation of cool season food legumes to water-limiting environments

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Abstract

Non-irrigated (rainfed) agriculture is the major crop production system worldwide. It occupies large proportion of total land areas in Asia (88 %) and Africa (99 %). In some important food legume growing countries in South Asia, rainfed lands range from 33 to 75% of total agricultural land area. Drought of varying intensities and duration, and associated economic crop yield losses, are a recurrent phenomenon in food legumes crops that are grown generally on rainfed lands.

A large variation in climate and soil physical conditions results in an equally large spatial and temporal variation in soil moisture availability in rainfed cropping systems. Characterization of drought-prone conditions in a target region, for probability of occurrence of various intensities and types of drought, is essential to relate rainfed Cool Season Food Legumes (CSFL) production with drought. It is also required for development of targeted genetic and agronomic management strategies and technologies. A useful application of information technology in agriculture has been in relating soil physical conditions and climate with food legume production in South Asia.

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Substantial knowledge on genetic and agronomic management to mitigate drought effects in food crops has been accumulated. Focus in this paper is on genetic improvement of drought tolerance in food legumes, with emphasis on chickpea, the most important CSFL crop. Both conventional (traditional) and trait-based breeding (including molecular markers) approaches have been used in improving adaptation of legumes to water limiting conditions. An important contribution is the development of short- to extra-short duration varieties of food legumes that escape terminal drought. Drought tolerant chickpea germplasm with a yield advantage of 10-30%, and others with putative drought tolerant traits, have been identified. Rigorous evaluation of drought tolerant varieties in multi-location trials and release of the same as cultivars remains to be done.

Drought tolerant cultivars, combined with tolerance/resistance to other important biotic and abiotic stresses are an effective, easy to disseminate, and cost-effective technology, that would be affordable by resource-poor, small landholding, rainfed farmers. Efforts on quantitative characterization of global, regional, and national food legume growing areas (using tools of GIS and modeling) to classify the diverse and complex drought-prone environments into conditions with similar limiting-soil-moisture conditions and severity of evapo-transpiration demand of the atmosphere would be very rewarding. It would facilitate development of varieties with specific adaptation to target drought conditions, and dissemination of effective technologies Existing multidisciplinary Drought Research Networks need to be strengthened with Electronically Net-Working Groups (ENG) and, if necessary, establish new groups for a systematic and rapid progress.

Introduction

A holistic perspective of food security (including CSFL), sustainability, and availability encompasses the economics of sustainable crop production, imports to meet the demand, and above all the impact on income and well being of the people depending on agriculture for livelihood. Adoption of technologies depends not only on potential positive impact on increasing crop production but its relevance to prevailing socio-economic, soil and climate conditions.

A large population (world: >52%, Africa and Asia: >60%) depends on agriculture for livelihood. Also, a sizeable fraction of the economically active population (world: 44%, Africa and Asia >55%) is engaged in agriculture (FAO 2003). However, a sizeable proportion of the global agricultural land area (>95%) is rainfed, and rainfed crop production is uncertain because of insufficient rainfall and its non-uniform distribution. This uncertainty in rainfall not only affects food security but also has a very adverse impact on the household economy of the resource-poor and small land-holding farmers that generally dominate rainfed agriculture.

On a global scale, food legumes occupy nearly 10% of total cereals and legumes (0.74 billion ha) cropped area but contribute only 2.5% to the total (2.2 billion Mt) of cereals and legumes production (FAO 2003). Despite the small area and production, legumes are important crops in the sustainability of crop production systems and economy of the countries, particularly in the rainfed production systems in Asia and Africa. For example, India spent more than 50% of the total food imports on pulses in 1994, and in 1997 more than $162 million were spent on import of pulse crops. Since pulse crops are grown mostly rainfed, technologies that focus on improving adaptation of these crops to water limiting conditions would have a significant and positive impact on increased CSFL availability, security, national economy, and most important of all on the well being of farmers.

A Multidisciplinary team of scientists made a critical review of various aspects of rainfed legumes production, ranging from socio-economic aspects, climate characterization, and the agronomic and genetic management of drought at a workshop. Outcome of these deliberations were published in a book (Saxena, 2003). In this paper we present an overview of genetic improvement of CSFL crops, with emphasis on chickpea. It is not a comprehensive review on the subject but highlights the progress made and suggests areas of future research for a rapid progress in improvement of drought tolerance and sustainable CSFL production.

Prioritization of CSFL Crops for Research and Development

The two most important CSFL crops worldwide are chickpea and dry peas on the basis of relative contribution to total crop area and production of pulse crops (Table 1). Grasspea (*Lathyrus sativus*), one of the five CSFL crops, does not seem to be important as food legume because crop statistics on it is not available in global crop databases (FAO 2003). Relative importance of CSF crops, based on area vary as: chickpea>peas>lentil>faba bean, and for production as: peas>chickpea>faba bean>lentil (Tables 2a and 2b).

Importance of chickpea and dry peas among CSFL crops is also obvious from the large number of scientific publications on these two crops. These publications also establish the significance of chickpea in improving soil health and fertility and sustainability of rainfed crop production systems. Considering these facts, two international agricultural research centers, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) located at Patancheru in India and International Center for Agriculture Research in Dry Areas (ICARDA) located at Alleppo in Syria, were established to focus research and development efforts on chickpea in semi-arid, dry, and arid agroecologies.

Relative importance of various CSFL crops, however, varies from regions and countries. For example, while chickpea and lentil are important crops in Asia, faba beans are a dominant crop in Africa (Table 1). It is interesting to note that *Lathyrus*, which is not an important CSF crop on a global basis, is as important as peas in India, whereas faba bean does not feature as a CSFL crop (Table 2c).

Characterization of Drought-Prone Environments

Soil and climate under which CSFL are cultivated differ very widely across eco-regions and also within a country. These two factors of environment have a strong impact on the occurrence of important abiotic stresses, in particular drought. Drought is ubiquitous in its occurrence in rainfed production systems, irrespective of crops on global, eco-regional or national scales. In comparison, the biotic stresses of diseases and insect pests, in general,

Table 1. Ranking of various pulse crops in terms of area and production (FAO, 2003)

Pulses area			Pulses production		
Crop	% of total pulse area	Rank	Crop	% of total pulse area	Rank
Dry bean	37.1	1	Beans, Dry	30.6	1
Chickpea	15.4	2	Peas, Dry	19.8	2
Cowpea, dry	14.2	3	Chickpea	14.1	3
Peas, dry	8.7	4	Broad beans, dry	7.0	4
Pulses nes	6.7	5	Pulses nes	6.7	5
Pigeonpea	6.4	6	Cowpeas, dry	6.5	6
Lentil	5.6	7	Lentil	6.3	7
Broad beans	3.3	8	Pigeonpea	5.5	8
Vetches	1.3	9	Vetches	1.9	9
Lupins	1.1	10	Lupins	1.5	10
Bambara bean	0.1	11	Bambara bean	0.1	11
Pulses area (ha)	**71136776**		**Pulses prod. Mt**	60259943	

Table 2. Ranking of CSFL among the pulse crops grown in the world. A. Area (millions of ha) and B. Production (millions of tonnes) (FAO 2003)

	a. Area			b. Production		
Crop	Area	% of total (m/ha)	Rank pulse area	Production (m/t)	% of total pulses production	Rank
Chickpea	10.98	15.4	2	8.48	14.1	3
Peas	6.20	8.7	4	11.91	19.8	2
Lentil	3.96	5.6	7	3.82	6.3	7
Broad beans	2.34	3.3	8	4.24	7.0	4

c. Ranking of area, production and yield of cool season food legumes in India (Source: India, 2000)

Crop	Area (m/ha)	Production (million t)	Yield (kg/ha)
Chickpea	6.82	5.13	750
Lentil	1.20	0.79	657
Lathyrus	0.93	0.50	531
Peas and beans	0.64	0.60	933

are crop specific. Solutions to efficient management of adverse drought effects in crop plants, therefore, would have a vast potential positive and significant impact on food production and sustainability. A quantitative characterization of rainfed or drought-prone conditions is an essential prerequisite for developing targeted agronomic or genetic management technologies suitable for water limiting situations.

Drought Events

Occurrence of drought of varying severity is common in one or the other region in the world. In parts of Asia and Africa, drought events are more frequent in occurrence than others. For example, in India 36 drought events occurred between the years 1876-1987, that varied in intensity from mild (<20% area affected), moderate (up to 40%) and calamitous (>40% area affected due to drought) (Katyal and Vittal 2003).

Yield Losses in CSFL due to Drought

Drought events are known to cause huge losses in food, fodder and feed production, and also occasional famines. Loss in grain and shoot mass (fodder) yield due to varying intensities of drought in CSFL was studies in field experiments at ICARDA, Syria (Table 3). A gradient of drought was created by line-source method of irrigation in these experiments (Hanks *et al.* 1976). The average seed yield loss in CSFL was around 56% at the drier site, Breda (275 mm rainfall) compared to 36% at Tel Hadya (348 mm rainfall). Reduction in shoot mass, and therefore fodder yield, was larger (61% at Breda and 50% at Tel Hadya) compared to percent losses in seed yield (Table 3). Lathyrus was better adapted to water limiting conditions compared to all other CSFL, and faba bean was most sensitive to drought. Relative losses in seed yield due to drought at Breda varied as: lathryus<chickpea<peas = lentil<faba bean.

Table 3. Differences in yield loss due to drought among CSFL crops at two locations in Syria (Source: Saxena, N.P. and Saxena, M.C. 1993)

a. Loss (%) in seed yield and shoot mass in CSFL

	Seed yield loss (%)		Shoot mass loss (%)	
Crop	Breda	Tel Hadya	Breda	Tel Hadya
Chickpea	43.6	28.7	47.9	43.0
Lentil	60.2	54.6	65.0	51.6
Faba bean	79.7	52.5	69.8	54.9
Peas	59.3	35.5	59.3	31.2
Lathyrus	21.5	9.5	53.8	56.6
LSD (<.05)	21.02	21.06	12.73	15.74

b. Mean loss (%) across CSFL crops

Location	Seed yield (%)	Shoot mass (%)
Breda	56	61
Tel Hadya	36	50

Impact of Variation Environments on Drought

Climate: Rainfall, the primary source of moisture in soil profile for crop growth in rainfed conditions, has a dominant effect on intensity of drought, duration and associated crop losses when compared to other factors of soil or climate. The unpredictability of occurrence of drought arises from the fact that there is a large annual and spatial variation in the amount and distribution of rainfall.

For example, in west Asia (e.g., Syria), where chickpea is grown as a traditional spring season crop, nearly 70-73% of the annual rainfall occurs during preceding winter crop season and around 30-35% in the spring season (Table 4). ICARDA introduced winter chickpea technology to take advantage of predominant rainfall in winter and early spring seasons to nearly double chickpea yields over the yield of spring chickpea. Statistical analysis of long-term rainfall data (1974-2005) also reveal the high standard deviations (SD) values associated with the mean, maximum and minimum rainfall across the two locations (Table 4). The dry location of Breda, receives 20% less rainfall compared to Tel Hadya. Evaporation and maximum and minimum temperatures, the other two important components of atmospheric drought, are more severe at Breda (3-4 mm/week higher evaporation and 7° C higher maximum and 3° C higher minimum temperatures), compared to Tel Hadya. The SD of means for these three parameters are smaller (SD ±0.5-2.0) as compared to large SD of means associated with rainfall.

Table 4. Variation in long-term rainfall (mm) at two locations in Syria (Breda, 35° 55' N, 37° 10' E, Alt. 350 m; and Tel Hadya, 35° 55' N, 36° 55' E, Alt. 362 m)

Season	Location	Mean annual (1974-2005)	Mean of 1996-2005			
			Mean	Minimum	Maximum	±SD
Winter chickpea	Tel Hadya	348	254	189	356	53.0
	Breda	275	197	112	281	63.0
Spring chickpea	Tel Hadya	348	124	42	203	56.8
	Breda	275	90	31	157	38.0

In the warmer subtropics of South Asia (e.g., India), rainfall occurs predominantly in the monsoon season (>80% of the total annual rainfall). Chickpea is planted in autumn or winter season after cessation of monsoon rainfall (Table 5). There is a great similarity in climate and soil moisture conditions in spring cultivation of chickpea in W. Asia and autumn/ winter cultivation of chickpea in S. Asia.

Table 5. Variation in long-term rainfall (mm), and evaporation (mm/week) at two locations in India (ICRISAT 17° 32' N, 78° 16' E, Alt. 542 m; and Hisar, Haryana, 29° 10' N, 75° 44' E, Alt. 221 m)

Basic statistics	ICRISAT Center, Patancheru Chickpea crop duration 90-95 days			Haryana Agric. Univ., Hisar Chickpea crop duration >140 days		
	Rainfall		Evaporation	Rainfall		Evaporation
	Annual	Crop (winter)	Crop (winter)	Annual	Crop (winter)	Crop (winter)
Mean	889	136	34	448	74	25
±SD	220.0	98.5	2.5	164.9	54.5	5.3
Minimum	558	9	29	140	15	18.9
Maximum	1473	414	40	770	230	28.9

The characteristic high inherent variation in rainfall is also evident in the large SD of means for annual and winter rainfall, as well as minimum and maximum rainfall at the two locations in India, ICRISAT center, Patancheru (18° N) and Haryana Agricultural University

(HAU), Hisar (29° N) (Table 5). Despite a higher rainfall (890 mm) at ICRISAT, Patancheru, which is almost twice compared to Hisar (450 mm), the length of chickpea crop duration at ICRISAT is only 90 days compared to 150 days, and yield 50% of HISAR. The high mean evaporation (31.7 mm/week) and maximum (30.3°C) and minimum (14.3°C) temperatures at ICRISAT during crop season causes rapid loss of soil moisture and induces severe terminal drought compared to Hisar (evaporation 27.3 mm/week; maximum, 27.3°C and minimum 9.7°C) (Saxena, 2003). The high intrinsic variation in spatial and annual distribution in rainfall is also noticeable in the long-term data for India as well as the states or provinces in India (Figs. 1A and 1B).

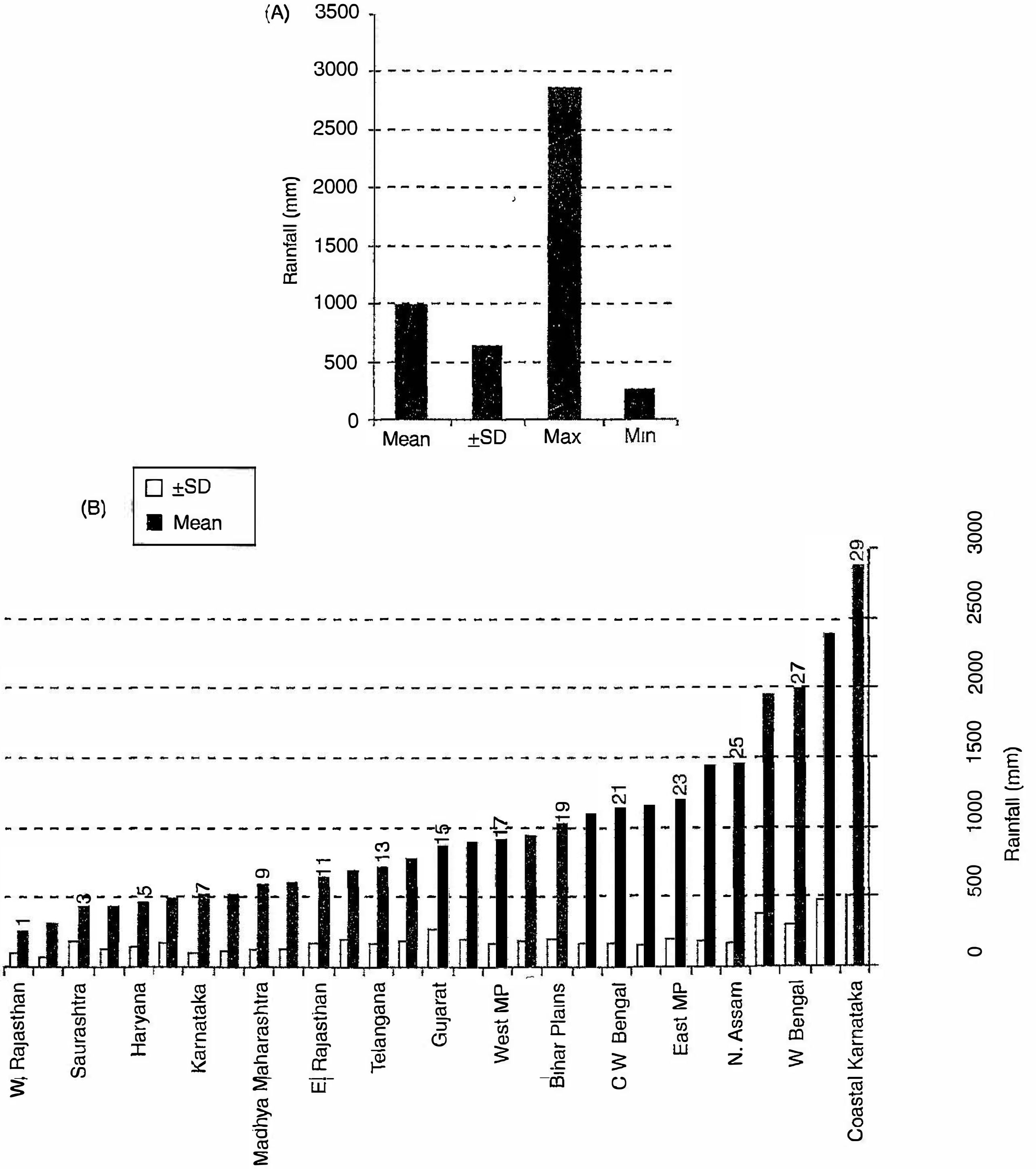

Fig. 1. Variation in rainfall (A) India and (B) within the states or provinces in India (Source: Parthasarathy *et al.*, 1995)

Variation in Soil Types

The soil types are known to vary widely across agricultural lands. Each soil type has its typical characteristic soil depth and other physico-chemical constants that determine the maximum water holding capacity and profile soil moisture available for crop growth. In India, there are at least 24 distinct soil groups. Around 15-20% of the total land area in India is under major types of alluvium, sandy, loams, and black soils. In addition there are varying land area under problem soils (saline, acid, alkaline, calcareous, etc). (India, 2000).

Soil Moisture

Interaction between climate factors, in particular rainfall and evaporation, together with the soil types determines the maximum soil moisture available for crop growth and yield. Quantification of soil moisture profiles during crop season is an essential first step for developing targeted drought management technologies.

Soil moisture, modeled using the inputs of rainfall and maximum water holding capacity of the soil (Keig and McAlpine 1976), are presented for two locations in Mediterranean climate of Syria (Fig. 2) and at two locations in warm subtropics of India in south Asia (Figs. 3). Winter chickpea in Syria grows on an increasing soil moisture availability regime, while the spring chickpea grows on rapidly declining soil moisture conditions, subjecting the spring season crop to severe terminal drought effects. Year to year variation in soil moisture availability, associated with variation in rainfall, and departure from the long-term average can also be seen (Fig. 3).

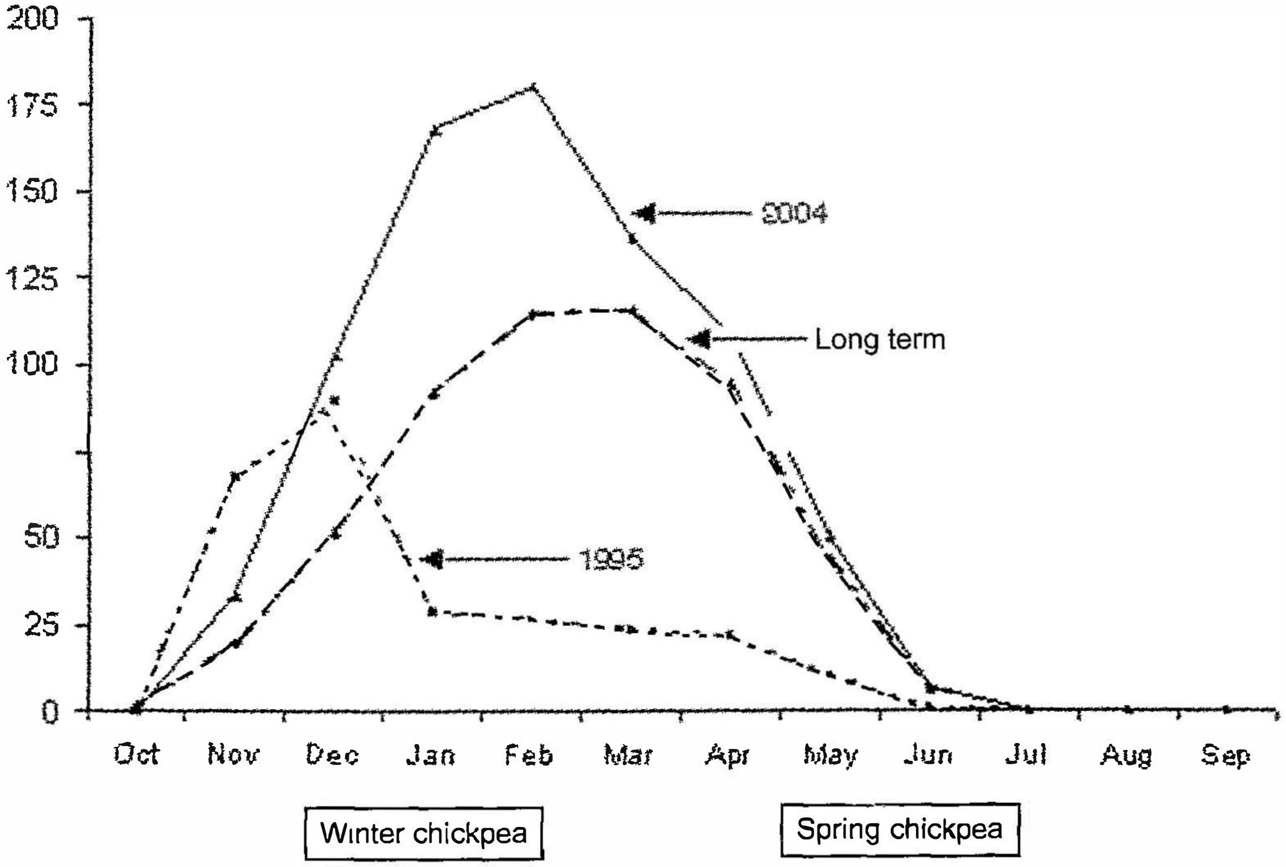

Fig. 2. Departure of year-to-year variation in simulated soil moisture from the long-term simulated soil moisture (1979-2004) on a red Vertisol at Tel Hadya, Syria

The pattern of rapidly declining soil moisture availability, and the year to year variation at ICRISAT, in the warm subtropics of S. Asia, during chickpea growing season are shown in Fig. 3a. These are similar to spring chickpea crop season at Tel Hadya, Syria (Fig. 2). In the cooler winter cropping conditions, such as Hisar in India or the in the western parts of Pakistan, the pattern of soil moisture depletion is modified because of relatively low temperatures and low evaporation conditions that prevail during crop season. This demonstrates the influence of atmospheric components of drought on progressive development of soil drought, and has been reported earlier (Saxena, 2003).

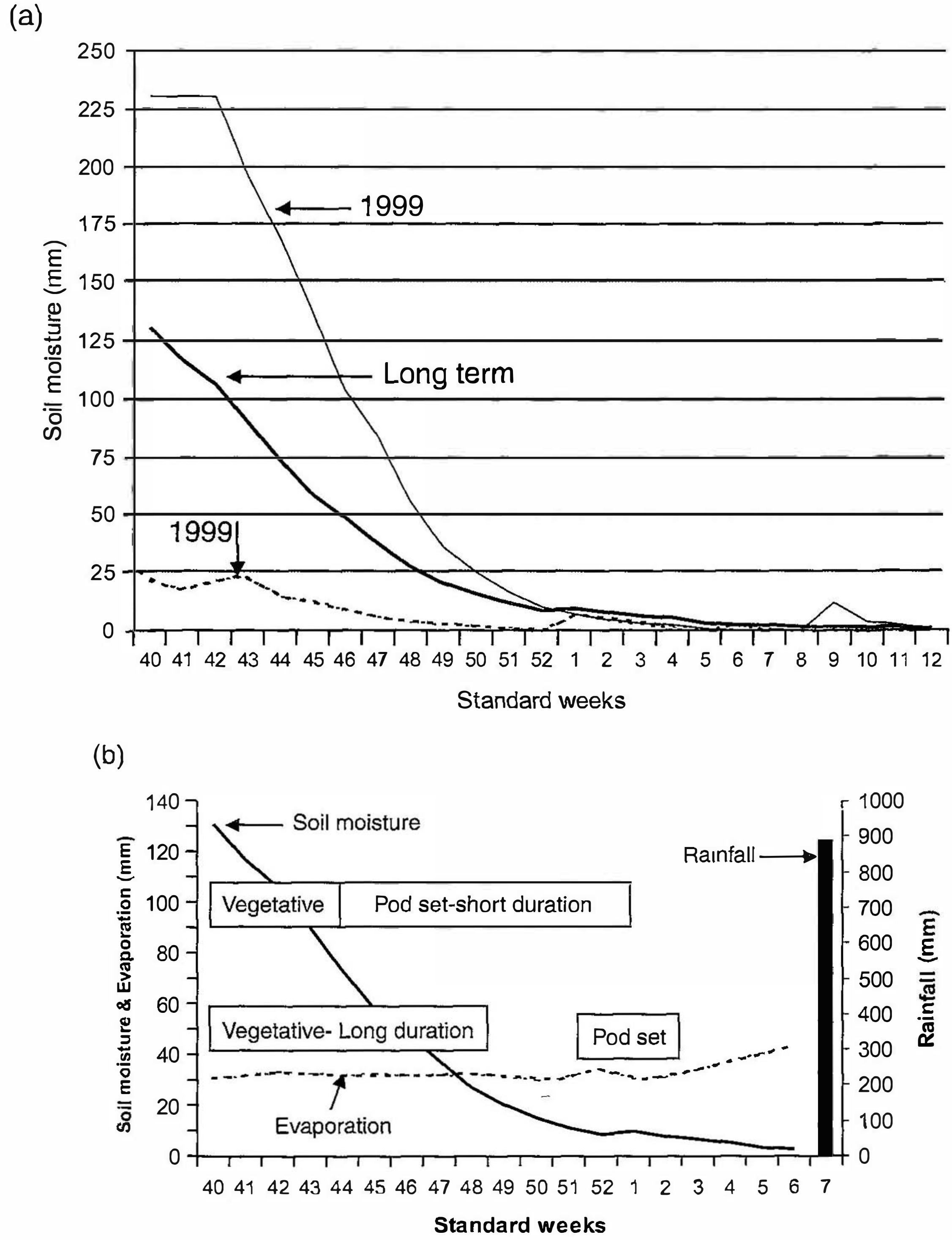

Fig. 3. Simulated variation in soil moisture (a) between years and the long term mean (1974-2004) and (b) escape of short duration varieties of chickpea from severe terminal drought on a Vertisol at ICRISAT, Patancheru, A.P., India

These results also point out to the limited utility of long-term averages of rainfall or soil moisture data. These data may be good for making gross comparisons between locations, but has no practical value in planning strategies for management of drought in a given target area. Detailed analysis of soil moisture profiles, for probability of occurrence of various intensities of drought and identification of most frequently occurring (modal) pattern of drought are required for developing meaningful technology to minimize drought effects.

Soil Moisture Simulation Models and GIS Technology in Management of Drought

A significant development in agricultural research and development in the last decade is the progress made in the application of powerful tools of simulation models, statistical methods, and information technology (GIS and GPS, combined with remote sensing). Quantitative descriptions of target environment at national and eco-regional scales have been done using these methods. For example, lands that remain fallow after harvest of paddy in south Asia were identified using satellite imagery for introducing legumes and thereby increasing cropping intensity to increase CSFL production and to render sustainability to the production system through improved soil health (Subbarao *et al.* 2001). This opens opportunities for increasing CSFL production through area expansion, in particular for chickpea that has been consistently on decline. A large impact on chickpea production through area expansion by introducing chickpea in wheat fallow has been demonstrated in Turkey and in Australia (Saxena *et al.* 2000).

A significant development in practical use of combined application of simulation models and GIS has been in mapping soil moisture profiles on spatial and temporal scales for a few countries in South Asia (Nepal, Bangladesh, and Indo-gangetic plains of India and Pakistan). (Chauhan *et al.*, 2000). This in particular is very significant as it has relevance to CSFL crops because quantification of a relatively large proportion of available soil moisture (nearly 70% or more of the crop season) can be determined at the time of planting in the Central and West Asia and North Africa (CWANA) or the monsoon rainfall regions in South Asia. It leaves relatively a small proportion of unpredictable soil moisture (20-30%) associated with rainfall that occurs during CSFL crop growing season. Using this technology it is relatively simple to compute soil moisture on farmers' scale, irrespective of the size of landholding, as it requires simple and a few inputs of rainfall, temperature or evaporation and maximum soil moisture holding capacity of the soil (Keig and McAlpine, 1976). Appropriate choice of a CSFL crop, or a variety within a CSFL crop, and deployment of effective agronomic management technology can then be based on informed judgment.

Management of Drought

Both agronomic and genetic management options are available for alleviating or minimizing the drought effects. Although the focus in this paper is on the genetic management options with reference to chickpea, a few agronomic management practices that have demonstrated large and significant impact on increasing rainfed CSFL crop production are highlighted.

Agronomic Management Options

A linear relationship between evapotranspiration (ET) with yield as well as above ground shoot mass has been reported in many crops, and CSFL are no exception (Figs. 4a & 4b) This relationship shows that complete alleviation of drought is feasible with irrigation. However, irrigation is not a practical option in most of the rainfed production systems.

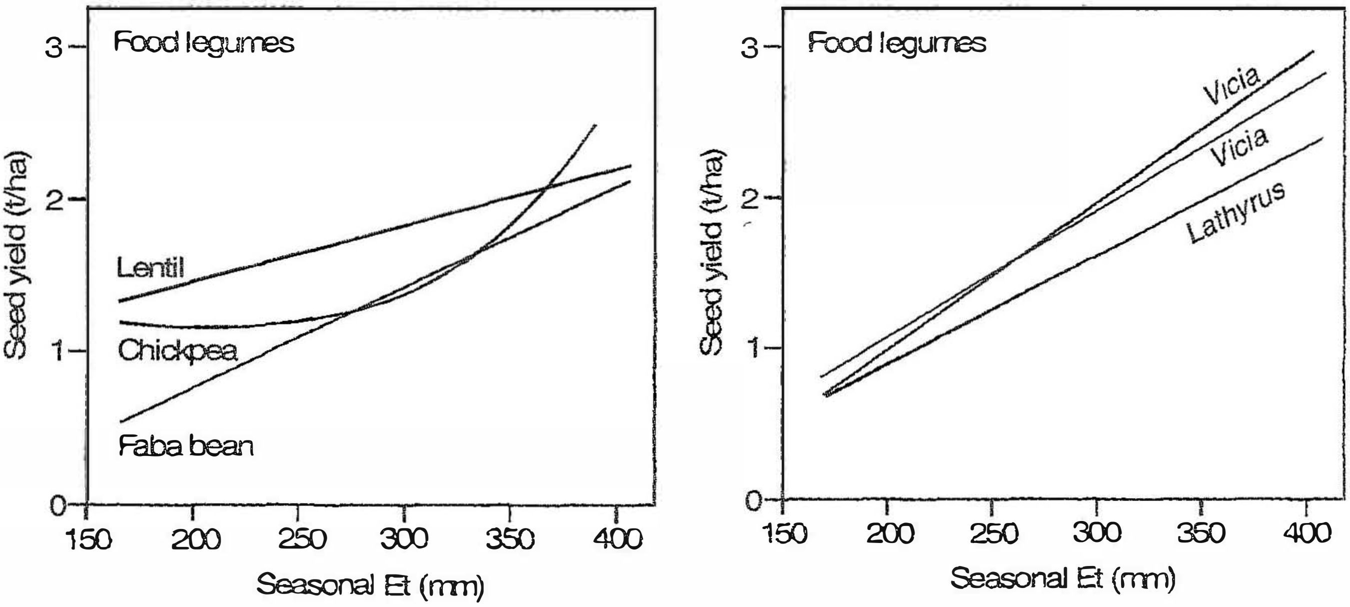

Fig. 4. Relationship between seasonal evapotranspiration (ET mm) and seed yield of some cool season food and feed legumes in Syria. (Saxena and Saxena 1993)

There are other agronomic management options for management of crops under rainfed conditions. For example, water-harvesting technologies, with *ex-situ* conservation of rainfall for supplemental or life-saving irrigations (Saxena, 2003); or increased *in-situ* conservation with methods of land management (tillage, mulches, contour bunds and others) and other related agronomic practices (Katyal and Vittal, 2003).

Poor plant stands, below the optimum required, are known to be a major constraint to production in rainfed conditions. On farmers' field in India, most frequently occurring plant stand range between 13-20 plants m^{-2} compared to the optimum recommended of 30-35 plants m^{-2} (Saxena *et al.*, 2000). Improving plant stands would have a large and significant impact on yields of rainfed crops. Seed soaking in nutrient solutions (0.2-0.5% concentration of salts) showed an yield increase that ranged from 20-40% in chickpea (Saxena and Yadav, 1975) Interest in seed soaking treatments with water, termed as seed priming. was revived in recent years. It has shown a large and significant impact on increasing yield of different crops in rainfed conditions. It proved to be a good non monetary technology in improving plant stands and yield of chickpea in on-arm trails in Bangladesh (Musa *et al.*, 2001). The improvement in plant stands in chickpea ranged from 9-18% and yield from 15-32% (computed from the published data; Musa *et al.*, 2001).

Winter chickpea technology is another example of an effective non-monetary agronomic management technology that works in conjunction with varietal improvement for disease and cold tolerance. Advancing time of chickpea planting from traditional spring months into winter/Autumn months takes advantage of the rainfall that occurs concurrent with crop growth and low evapotranspiration that prevail during winter months. It increased yield by 60% in Spain (Calcagno *et al.*, 1987), by 70% in Syria (Singh *et al.*, 1997), and from 23-188% in Greece (Iliadis, 2001).

Genetic Management Options

Relative differences in drought tolerance among CSFL crops are quite significant. Chickpea seems to be most drought tolerant followed by Lentil among food legumes in field experiments in which the response was studied by creating a gradient of drought using line source irrigation method (Saxena and Saxena 1993); (Fig. 5). Differences between CSFL crops were larger at the drier site of Breda compared to Tel Hadya. Greater responsive to increasing availability of irrigation in lentil suggests that this CSFL crop would take better advantage in the years when spring season rainfall is good.

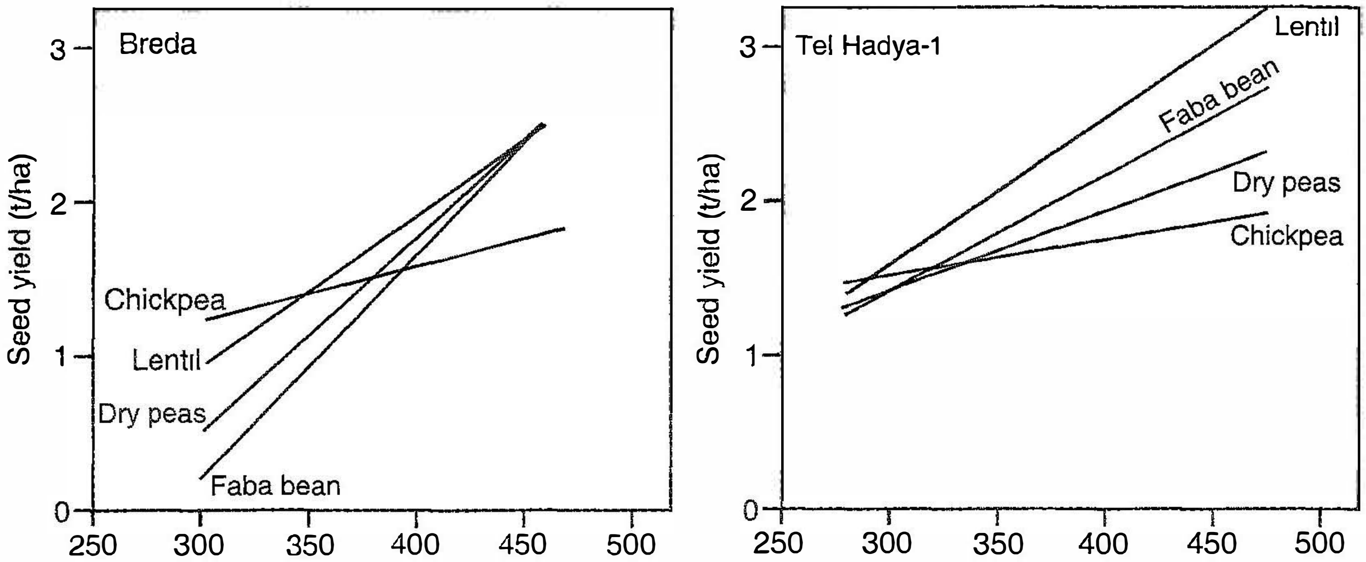

Fig. 5. Response of cool season food legumes to a gradient of soil moisture applied through line-source sprinkler irrigation method on a red Vertisol at two locations in Syria (Saxena and Saxena 1993)

Among feed legumes, *lathyrus* was most drought-tolerant on the criteria of lowest slope combined with high yield at the dry end wi h least available water Yield of rainfed lathyrus was similar to lentil. In *lathyrus* drought has a negative impact on grain quality as well. Percent BOAA content increased with increasing severity of drought (Saxena *et al.* 1993), suggesting thereby an accumulation of neurotoxin under water limiting conditions. These data suggest that appropriate CSFL crop can be made as a first strategy to combat drought.

Breeding Strategies

Both empirical breeding for yield and trait-based or ideotype breeding approaches have been used in improving adaptation of CSFL to drought-prone conditions. Empirical breeding for yield is more widely practiced across national and international CSFL crop improvement programs because it is easy to practice.

The most significant impact of empirical breeding in adapting CSFL to drought-prone conditions has been the identification of short- and extra-short duration varieties of chickpea that escape terminal drought effects. Visual selection for escape in segregating populations is also simple to practice. In addition to short duration varieties, a large number of CSFL varieties with higher yield potential in water limited conditions have been identified with empirical selection for yield in rainfed experiments in international and national CSFL crop improvement programs (http://www.icarda.org/);http://www.icrisat.org/; Saxena *et al.* 2000).

The empirical approach of breeding for high yield though has proved to be effective but is not the most efficient way of breeding for drought tolerance. Trait-based or ideotype breeding is recognized to be a systematic method for improving and enhancing drought tolerance through pyramiding traits or genes However, this strategy is not practiced widely as it is industrious and involves active participation of physiologists with breeders; and physiologists may or may not be available in many breeding programs.

Ideotype or Trait-Based Breeding for Drought Tolerance

Field and laboratory methods of screening chickpea germplasm, and criteria for selection for advancing segregating populations, essential to implement an ideotype breeding program on drought tolerance are available and have been described (Saxena *et al.*, 2002). Genotypic differences in drought tolerance within CSFL crops have been reported (Saxena and Saxena, 1993). Genotypic differences in response to water supply in Kabuli chickpea (Silim and Saxena, 2003) and factors affecting yield of rainfed lentil have also been reported (Silim *et al.*, 2002). More than 2000 accessions of chickpea germplasm have been screened and Sources of drought tolerance have been identified (Saxena, 2003).

Drought tolerant chickpea germplasm were characterized for morphological (large root system, fewer pinnules, narrow pinnules), physiological and functional traits, such as, rapid dry matter partitioning into seed (Saxena 2003, Table 6). Drought tolerant traits have been combined with high yield and fusarium wilt disease resistance through conventional breeding methods by making a three way cross, back-cross and selection for drought tolerant traits, yield, disease resistance and enhancement of drought tolerance (Saxena *et al.* 1995, Saxena, 2003).

Drought tolerance is generally considered synonymous to a large and deep root system to extract maximum soil moisture. Gregory *et al.* (1993) reviewed information on root characteristics in CSFL crops. Root traits are known to be quantitatively inherited. Recent studies on inheritance of root traits in chickpea at ICRISAT showed that additive, and additive x additive components account for nearly 33% of the variation in root length density (Gaur *et al.*, 2008). This is encouraging as it shows that breeding for root traits, which was considered impractical, seems now feasible.

Using conventional methods of breeding, and employing non destructive laboratory methods of selecting for large root system for advancing generations (Saxena *et al.*, 2002), germplasm enhanced for drought tolerance associated with large root system was developed in chickpea (Saxena *et al.*, 1995).

Table 6. Sources and traits of drought tolerance in chickpea/avoidance

Germplasm	Trait	Observations
ICCV 2, ICCV 96029	Early and super early to escape terminal drought	ICRISAT, 2000; Jagdish Kumar *et al.*, 1996
ICC 4958 and ICC 8261	Large root system	Inheritance shows that additive and additive x additive component account nearly 33% of variation in root size (Gaur *et al.*, 2008)
ICC 5680	Small leaf size, fewer pinnules	Reduces leaf area by 30 to 40% (Saxena, 2003)
JG-62 and ICC 4958	Rapid dry partitioning of matter into seed drought	Adds on to high yield in early varieties that escape terminal
None	C^{13} discrimination as a surrogate trait of WUE	Kashiwagi, 2006
None	Osmotic adjustment	Morgan, 1991
None	Thick leaves, high specific leaf weight	Reported in literature
None	Relative water content RWC	Reported in literature

Progress has also been made in identification of molecular markers for larger root system. Recombinant Inbred Lines (RILs, n = 257) were developed in chickpea by crossing ICC 4958, a germplasm accession with large root system as one of the parent, with Annigeri, a cultivar that is well-adapted to short duration, peninsular Indian conditions (Serraj *et al.*, 2004). Using these RILS putative markers linked to root size have been identified (Chandra *et al.*, 2004) This suggests that molecular breeding tool may become a reality for incorporation of root traits in future.

A beginning has been made in identifying surrogate traits for transpiration efficiency (TE). Preliminary studies in chickpea at ICRISAT showed that a positive correlation exists ($r = 0.857$ $p<0.01$) between carbon discrimination ($\delta^{13}C$) and transpiration efficiency (TE) in ten genotypes with contrasting differences in root-trait (Kashiwagi *et al.*, 2006). Carbon discrimination is an indirect measure of TE. Work is now in progress on screening chickpea minicore germplasm accessions (n = 211) for TE and $\delta^{13}C$ to explore opportunity of using $\delta^{13}C$ in improving drought tolerance in chickpea.

There are research reports in literature that drought tolerant genotypes generally maintain higher leaf relative water content (RWC) or have thicker leaves (high specific leaf weight —SLW), but these traits have not been used as selection criteria either in identifying sources of drought tolerance in germplasm or in trait-based breeding programs on drought tolerance. Another physiological traits of drought tolerance that received considerable attention in cereal crops is osmotic adjustment. In chickpea, there is only one report on osmotic adjustment (Morgan *et al.*, 1997) and it is difficult to evaluate the relevance and utility of this trait in breeding programs with the present state of our knowledge.

Achievements and Future Thrust

Progress made in quantitative characterization of drought-prone conditions is indeed significant. It is now feasible to develop targeted drought management strategies and technologies on a sound basis. Future thrust needs to be on clustering diverse drought-prone environments that are similar in intensity, duration, and probability of occurrence of drought, at national, regional, and global scales. This would be useful to upscale effective technologies and to facilitate their widespread adoption.

The task of improving adaptation of crops to drought-prone conditions is challenging, and more so in less researched crops such as CSFL. Progress made in identifying early cultivars to escape terminal drought effects in all CSFL crops is commendable. Empirical breeding for yield has proved to be effective as many varieties of CSFL that either escape or produce high yield under drought-prone conditions were identified and released using this method. The thrust on this approach should continue.

Trait-based or plant type breeding is highly recommended as a targeted approach to breed drought tolerant varieties but is not made use of. However, this method does not attract adequate research attention even in international crop research programs despite the fact that all essential tools to implement such a program are available at least in chickpea. One reason why it is not applied is that it requires a multidisciplinary team effort, though highly desired but is not widely practiced. If development of drought tolerant and high yielding varieties of CSFL is indeed a high priority objective, trait-based breeding programs need to be established for incorporation of drought tolerant traits, using conventional and molecular assisted breeding methods. The current knowledge, information and tools already developed in chickpea should be intensively and extensively used and and applied in other CSFL crops. Greater emphasis on basic research, with clearly established end use of outputs research in applied breeding programs on drought tolerance must be clearly defined. A network of multidisciplinary teams of breeders, physiologists, and pathologists would ensure development of high yielding, drought tolerant CSFL with tolerance to important diseases in short term projects.

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