ASCERTAINING THE EXTENT OF CONTRIBUTION OF VARIOUS TRAITS TO TERMINAL DROUGHT TOLERANCE IN CHICKPEA (*Cicer arietinum* L.)

A THESIS

Submitted

in the partial fulfillment of the requirements for

the award of the degree of

DOCTOR OF PHILOSOPHY

in

FACULTY OF BIOTECHNOLOGY

By

R. PURUSHOTHAMAN
[Reg. No. 1003PH0249]

RESEARCH AND DEVELOPMENT CELL
JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY HYDERABAD
KUKATPALLY, HYDERABAD-500 085
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DECLARATION

I hereby declare that the work described in this thesis, entitled **"ASCERTAINING THE EXTENT OF CONTRIBUTION OF VARIOUS TRAITS TO TERMINAL DROUGHT TOLERANCE IN CHICKPEA (*Cicer arietinum* L.)"** which is being submitted by me in partial fulfillment for the award of Doctor of Philosophy (Ph.D.) in the Dept. of BIOTECHNOLOGY to the Jawaharlal Nehru Technological University Hyderabad, Kukatpally, Hyderabad -500 085, is the result of investigations carried out by me under the guidance of **Dr. L. KRISHNAMURTHY.**

The work is original and has not been submitted for any Degree/Diploma of this or any other university.

Place: Hyderabad R. Purushothaman

Date: 1003PH0249

CERTIFICATE

This is to certify that the thesis / dissertation entitled **"ASCERTAINING THE EXTENT OF CONTRIBUTION OF VARIOUS TRAITS TO TERMINAL DROUGHT TOLERANCE IN CHICKPEA (*Cicer arietinum* L.)"** that is being submitted by **Sri. R. PURUSHOTHAMAN** in partial fulfillment for the award of Ph.D. in BIOTECHNOLOGY to the Jawaharlal Nehru Technological University Hyderabad is a record of bonafide work carried out by him under my guidance and supervision.

The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Dr. L. Krishnamurthy
Scientist
Grain Legumes

CERTIFICATE

This is to certify that the thesis entitled **"ASCERTAINING THE EXTENT OF CONTRIBUTION OF VARIOUS TRAITS TO TERMINAL DROUGHT TOLERANCE IN CHICKPEA (*Cicer arietinum* L.)"** that is being submitted by **Sri. R. PURUSHOTHAMAN** in partial fulfillment for the award of Ph.D. in BIOTECHNOLOGY to the Jawaharlal Nehru Technological University Hyderabad is a record of bonafide work carried out by him under the supervision of **Dr. L. KRISHNAMURTHY**, Scientist at our organization/institution.

Dr. G. Dileepkumar
Global Leader
Knowledge Sharing and Innovation

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(R. Purushothaman)

ABSTRACT

Chickpea cropping system is largely rainfed and terminal drought is a major constraint to its productivity. Breeding for drought tolerance requires knowledge of the type and intensity of drought and the various traits and mechanisms employed by the plant to overcome the drought effects. The number of traits that are associated with terminal drought tolerance is overwhelmingly large and needs to be prioritized and ranked for their strength of contribution to drought adaptation and to incorporate in breeding programs. Therefore, the objectives of this study were to understand the relative value of various putative traits that confer yield advantages under terminal drought stress in chickpea, and the traits that are amenable for high throughput and their association with molecular markers. Twelve chickpea genotypes, selected for contrast in root and shoot strength, field-based drought tolerance and canopy temperature differences were grown in terminal drought stressed and optimally irrigated environments. Root, shoot, soil water, physiological and analytical yield components were measured at periodical intervals and these related traits were associated with grain yield through correlations, regressions and path analysis. Path coefficient analysis revealed that root traits, RLD and RDW, were associated with grain yield and these relations were explained well if the active soil water mining zone roots were considered against yield. Roots of all the depths were associated closely with the total soil water uptake of the plants except at the surface and ultimate depths at any given stage. This close relationship

permits use of one expression, either the root or the soil water uptake, to explain the grain yield under drought. Among the shoot traits LAI and SLA and among the yield traits HI, pod number m^{-2}, p and CTD explained the yield closely. CTD, a trait that is amenable to high throughput phenotyping, was measured using an infrared camera on 59, 62, 69, 73, 76 and 82 days after sowing (DAS). CTD recorded at 62 DAS was positively associated with the grain yield by 40% and shoot biomass by 27% and such association diminished gradually to minimum after 76 DAS. Moreover, CTD at 62 DAS also showed similar positive association with the grain yield recorded in two previous years (r= 0.45***, 0.42***). The association analysis of CTD with the existing molecular marker data was performed to understand the marker trait association. Genome-wide and candidate gene based association analysis had revealed the presence of nine SSR, 11 DArT and three gene-based markers that varied across the six stages of observation. Two SSR markers were associated with CTD through crop phenology or grain yield while the rest were associated only with CTD. Exploration of anatomical traits provided clear indications of presence of useful variation between the two chickpea types and among other grain legumes. Xylem vessels in *desis* were fewer in number and narrower in diameter compared to the kabulis. In addition, traits such as total number of xylem vessels, xylem vessel diameter, average xylem vessel size and root cortex and stele ratio of chickpea varied among grain legumes providing a clue to their drought adaptation.

CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

t	:	Tons
ha	:	Hectare
$^{-1}$	:	Per
%	:	Per cent
et al.	:	Et alia (and others)
ODAP	:	Oxalyl-diamino-propionic acid
Mb	:	Megabase
SPAD	:	Soil plant analytical development
>	:	Greater than
<	:	Less than
CIMMYT	:	International Maize and Wheat Improvement Center
n	:	Numbers
QTL	:	Quantitative trait loci
US	:	United states
i.e.	:	That is
ICCV	:	ICRISAT chickpea variety
e.g.	:	Example
/	:	Division

CO_2	:	Carbon dioxide
cm	:	Centimeter
mm	:	Millimeter
g	:	Gram
±	:	Plus or minus
~	:	Approximately
RIL	:	Recombinant inbred line
M	:	Meter
$^{\circ}C$	:	Degree celsius
Mm	:	Micro meter
N	:	North
E	:	East
N	:	Nitrogen
P	:	Phosphorous
Kg	:	Kilogram
KPa	:	Kilopascal
H	:	hours
SNP	:	Single nucleotide polymorphism
DArT	:	Diversity array technology

SSR	:	Simple sequence repeat
S.Ed	:	Standard error of difference
S.E.	:	Standard error
Eds	:	Editors
Fig.	:	Figure
Pp	:	Pages
etc.	:	Etcetera
Viz.,	:	Videlicet (namely)

1. INTRODUCTION

Chickpea (*Cicer arietinum* L.) is the second most widely grown legume crop in the world, with a total production of 13.1 million tons from an area of 13.5 million ha and a productivity of 0.97 t ha^{-1} (FAOSTAT, 2013). The major chickpea producing countries include India, Australia, Pakistan, Turkey, Myanmar, Ethiopia, Iran, Mexico, Canada, and the United States. India is the largest chickpea producing country producing about 68% of the global production. Its seeds are protein-rich alternatives of animal protein in human diet. Chickpea is a good source of protein (20 to 22%), and is rich in carbohydrates (around 60%), dietary fiber, minerals and vitamins (Williams and Singh, 1987; Jukanti *et al.*, 2012). Chickpea does not contain any specific major antinutritional factors such as ODAP in grasspea (*Lathyrus sativus* L.), vicin in faba bean (*Vicia faba*), and trypsin inhibitors in soybean (*Glycin max*), although it has oligosaccharides which cause flatulence (Williams and Singh, 1987). There is a growing international demand for chickpea and the number of chickpea importing countries has increased from about 60 in 1989 to over 140 in 2009. This is partially due to increased awareness about the health benefits of pulses, including chickpea. Chickpea has several potential health benefits, including beneficial effects on some of the important human diseases such as cardiovascular diseases, type 2 diabetes, digestive diseases, and some forms of cancer (Jukanti *et al.,* 2012).

Like other legumes, chickpea fixes atmospheric nitrogen through symbiotic nitrogen fixation and this reduces the need for chemical fertilizer, thereby lowering the cost of production and associated green house gas emissions. The residual nitrogen in the soil after chickpea cultivation benefits the subsequent crop. This is particularly important when the subsequent crop is a cereal. Crop diversification with legumes is highly desired in cereal-dominated cropping systems for improving and sustaining the overall productivity of the cropping system. Further benefits include disruption of disease cycles affecting non-legumes and an enhanced water use efficiency (WUE) by breaking the cereal–cereal rotations. A major rationale for including chickpea in the cropping systems of the semi-arid environments is its demonstrated potential to contribute to enhancement of the natural resource base used for the production of the other crops that are staple foods of the poor communities who rely on marginal rainfed lands. The crop's natural drought resistance makes it eminently suitable for such lands. Its benefits to traditional cropping systems in the Indian subcontinent are well documented (Ryan, 1997).

Chickpea is a self pollinated crop, with 2n=2x=16 chromosomes genome size of 738.09 Mb (Varshney *et al.,* 2013a). The two distinct forms of cultivated chickpeas are "*desi*" and "kabuli". *Desi* or "indigenous" type is usually of small size, angular shape, and variously colors with a high percentage of fibre. The kabuli type is characterized by its large seed size, ram-head shape, and beige

colored seeds with low percentage of fibre. A third type, designated as pea shaped, is characterized by medium to small size, and cream colored seeds (Singh *et al.,* 1985; Upadhyaya *et al.,* 2008). The *desi* types are primarily grown in South Asia, while kabuli types mainly in the Mediterranean region.

Chickpea is largely grown as a rainfed crop in the arid and semi-arid environments in Asia and Africa where more than 80% of the annual rainfall is received during rainy season (June-September). The rainfall variability within the region is usually high, leading to varying intensities of drought stress (DS). Terminal drought is one of the major stresses limiting crop yield in chickpea. Chickpea is usually sown under stored soil moisture condition, with very little rainfall during the cropping season, leading to a constantly receding soil water condition. Such a growing condition imposes increasing intensities of water deficit as the crop cycle advances leading to a severe water deficit at crop maturity. This type of receding soil water conditions imposes a ceiling on the cropping duration demanding selection for a matching duration of varieties for the best adaptability and productivity (Saxena, 1987; Ludlow and Muchow, 1990).

Genetic improvement for better drought adaptation can be a long-lasting and less-expensive solution for drought management than the agronomic options. However, understanding yield maintenance under DS becomes increasingly difficult (Tuberosa and Salvi, 2006), due to the numerous mechanisms that plants can use to maintain growth in conditions of low water supply. As a result, a trait-based

breeding approach is being increasingly emphasized over yield-based breeding for realizing better stability as grain yields are heavily influenced by high genotype × environment (G×E) interactions and exhibit low heritability (h^2) (Ludlow and Muchow, 1990). Also, a trait-based breeding increases the probability of crosses resulting in additive gene action (Reynolds and Trethowan, 2007; Wasson *et al.*, 2012). Breeding for drought tolerance requires knowledge of the type and intensity of DS and the various traits and mechanisms employed by the plant to overcome the drought effects. Moreover it is also important to rank and prioritize the traits/mechanisms on the basis of their strength of contribution to drought adaptation. For better success in drought tolerance breeding, the traits of choice need to be causal rather than the effect (Kashiwagi *et al.*, 2006a) and an integrator of the responses to events across the whole life cycle e.g., transpiration efficiency (TE), partitioning coefficient or rate of partitioning (p) and carbon isotope discrimination ($\Delta^{13}C$) (Krishnamurthy *et al.*, 2013a, b). There is a general agreement on the fact that many traits simultaneously contribute to drought tolerance at a given crop and environment with this combination varying across crops and environment (Passioura, 1983; Blum 2009; Reynolds *et al.,* 2011). For instance, in broader functional perspectives, attributes like matching phenology to soil water, photoperiod sensitivity, developmental plasticity, mobilization of preanthesis dry matter, rooting depth (RDp) and density, low root hydraulic conductivity, early vigor, leaf area maintenance, osmotic adjustment (OA), low lethal

water status, reduced stomatal conductance, leaf movements, leaf reflectance, seedling heat tolerance, low epidermal conductance and TE have been suggested to be involved in drought tolerance (Ludlow and Muchow, 1990) with each such attribute offering large number of traits that can be either measurable directly or indirectly. For example the functional attribute TE based on dry matter production per unit of water used can also be measured with surrogate traits such as $\Delta^{13}C$, specific leaf area (SLA), SPAD chlorophyll meter readings (SCMR) etc. In summary, a large number of drought-adaptive responses exist and it can be overwhelming for researchers to know which traits to study first given a lack of quantitative information (Reynolds *et al.,* 2007). Therefore, it is not only important to look for new traits that can explain drought tolerance but it is much more important to rank the known DS response traits on the merits of quantitative importance, relevance and high throughput in measurement for any specific location.

The inability to measure the traits high throughput has been a major limitation with majority of the drought tolerance traits. Breeding for quantitative traits controlled plant components, particularly the molecular one, require high throughput measurements involving either breeding lines or germplasm. Plant water balance is a direct measure of drought response but most of the related measurements such as shoot water potential, OA or stomatal conductance do not support a high-throughput phenotyping required for characterizing a larger population. Under water-limited conditions,

transpiration (T) is known to directly proportional to the plant biomass production (Blum, 2009). T is the major cause of changes in leaf temperature, and also a direct association was found between leaf temperature, transpiration rate (TR), leaf porosity and stomatal conductance (Jackson *et al.*, 1981; Jones *et al.*, 2002, 2009; Rebetzke *et al.*, 2013). As long as the plants continue to transpire through open stomata the canopy temperature (CT) could be maintained at metabolically comfortable range otherwise higher temperature would destroy the vital enzyme activities. Stomatal closures for a considerable period of time are known to increase the leaf temperature (Kashiwagi *et al.*, 2008a) and maintenance of a cool canopy during grain filling period in wheat is an important physiological response for high temperature stress tolerance (Munjal and Rana, 2003). CT differences have been shown to correlate well with the T status in rice, potatoes, wheat and sugar beet (Fukuoka, 2005).

Thermal infrared imaging through an infrared camera provides numerous benefits compared with temperature sensors, majorly the facility for spatial resolution and the ability to sample larger area. Most infrared cameras currently have arrays of 320×240 sensor elements, which mean that >75000 individual temperature readings are recorded in a single image. This allows more accurate measurements in a very less time needed to perform many replicate readings per plot, which is also susceptible to error due to varying environmental conditions between the measurements. CT is one such integrative trait that reflects the plant water status or the resultant

equilibrium between root water uptake and shoot T (Jones, 2007; Berger *et al.*, 2010). CT has been used successfully as selection criteria in breeding for drought-prone environments (Blum *et al.*, 1989; Fischer *et al.*, 1998; Balota *et al.*, 2008a; Jones *et al.*, 2009).

Deviation of temperature of plant canopies from the ambient temperature, also known as canopy temperature depression (CTD) (= air temperature (T_a) - canopy temperature(T_c)), has been recognized as an indicator of overall plant water status (Ehler, 1973; Jackson *et al.*, 1981; Blum *et al.*, 1982; Idso, 1982; Penuelas *et al.*, 1992; Balota *et al.*, 2008a) and facilitate in evaluation of plant response to environmental stress like tolerance to heat (Amani *et al.*, 1996; Reynolds *et al.*, 1998) and drought (Blum *et al.*, 1989; Rashid *et al.*, 1999; Royo *et al.*, 2002). CTD is positive when the canopy is cooler than the air and this value has been associated with yield increase among wheat cultivars at CIMMYT (Fischer *et al.*, 1998). The thermal imagery system is a powerful tool as it can capture the temperature difference of plant canopies quite rapidly. Developmental patterns of terminal DS in peninsular India is more predictable across years as the growing season is devoid of major rains (Johansen *et al.*, 1994) and the homogeneity of the DS crop was often better than the irrigated crop (Krishnamurthy *et al.,* 2010, 2013b). To test any given assumption, it is important to select a population that is elaborately characterized and well known to be diverse not only for DS but also for cross stress reactions. The mini-core collection of chickpea germplasm is assembled based on morphological and agronomic

diversity (Upadhyaya and Ortiz, 2001) and also been characterized for most biotic and abiotic stress reactions (Upadhyaya *et al.*, 2013). A subset of extremely contrasting accessions (n=84) were chosen for checking the reaction in CT. Molecular markers and QTLs have been chosen to help in a rapid introgression of specific traits such as the root traits and the TE in chickpea and to accelerate the progress of stress tolerance breeding (Varshney *et al.*, 2013b; Gaur *et al.*, 2013). Also molecular markers and genomic regions identified for higher CTD had helped for a targeted transfer of this trait in wheat (Rebetzke *et al.*, 2013) highlighting the importance of molecular genes in breeding programs.

Physiological traits for drought environments are dubious to be universal and some will be significant in one region but detrimental in another. There are different types of DS. The traits that may be significant while the crop is growing almost solely on stored soil water are expected to be different from while the crop is growing exclusively dependent on current rainfall. For chickpea, the exploration need to continue for new traits that are relevant exclusively for the use of stored soil water, better heritable than the drought yield, and that would enhance diversity among traits for introgression. Breeding for increased axial resistance in wheat, pursued to a moderate success, through narrow xylem vessels in the seminal roots of bread wheat is one good example (Richards *et al.,* 2002) that suggests that conservative use of water could be important under stored soil water use. A prerequisite to pursue before mapping such a trait within

species is to look for variation of this trait across other leguminous crops and to understand the likely contribution of this trait in chickpea.

Thus the objectives of this study are under three major areas as follows.

1. Understand the relative value of various putative traits that confer yield advantages under terminal drought stress in chickpea and estimate the diversity of molecular markers.
2. Evaluate the suitability of canopy temperature depression as a trait to measure the grain yield under drought, evaluate the crop stage at which this relationship is close and identify associated molecular markers.
3. Compare the root anatomy of chickpea with other grain legumes and among types of chickpea for understanding the axial resistance to soil water uptake.

2. REVIEW OF LITERATURE

World-wide, water deficit had remained responsible for the greatest crop losses and are expected to be worsened, generating international interest in crop drought tolerance. Globally, drought is the most common abiotic stress that constrains the chickpea production (Boyer, 1982; Araus *et al.,* 2002). Arid and semi-arid zones accomodate most chickpea producing areas, and approximately 90% of world's chickpea is grown under rainfed conditions (Kumar and Abbo, 2001). Terminal DS is typical of the postrainy season in the semi-arid tropical regions, and determined by the rainfall and the evaporative demand before and during the crop season, and also the soil characteristics. Terminal DS is the consequence of the crop growing and maturing in a progressively receding soil water environment (Ludlow and Muchow, 1990; Krishnamurthy *et al.,* 1999). It is estimated that if the soil water stress is alleviated, chickpea production could be improved up to 50% that is equivalent to approximately 900 million US dollars (Ryan, 1997). Therefore, chickpea productivity is largely dependant on efficient use of available soil water (Kumar and van Rheenen, 2000). Although chickpea is considered to be well adapted to grow on conserved soil moisture in drought prone environments, still terminal DS remains to be a major yield reducer (ICRISAT, 1996; Sabaghpour *et al.,* 2006).

Genetic improvement in chickpea under DS mainly relies on the identification of traits that have a major impact on yield. Such trait identification leads to the understanding of the physiological

mechanism of drought tolerance with an output of many vital traits that are associated with yield under DS. Such traits have been found useful in successful enhancement of yields in crop improvement programs (Blum, 1978; Richards *et al.,* 2002; Richards, 2006). In early generations, most of the plant breeding programs used plant type and later they had used yield as a selection criterion to evaluate genotypes under DS conditions. Moreover, they almost had no direct selection of genotypes on the basis of physiological traits, except flowering time and plant height (Richards, 2006). Across environments, the performance of genotypes could not be constant to discriminate it in terms of yield due to the variability in DS pattern from year to year. That makes the economic yield as an inferior selection criterion (Blum, 1978). Moreover, chickpea yields are highly prone to large G×E interactions (Saxena, 1987; Krishnamurthy *et al.,* 1999, 2004; Berger *et al.,* 2004, 2006; Kashiwagi *et al.,* 2008b). Several traits are expected to play a collective role in adaptation to terminal DS (Ludlow and Muchow, 1990; Saxena and Johansen, 1990a; Johansen *et al.,* 1997; Soltani *et al.,* 2000) and these traits are less likely to be influenced by G×E. Under such circumstances, a better strategy of breeding for drought tolerance is to select for traits, which can be more readily related to crop performance under particular environment, rather than yield (Krishnamurthy *et al.,* 2010).

Analytical or physiological models of grain yield provide an indication of the traits that might confer yield advantages under any given environments. Two such models are of particular importance

under DS as these are sensitive to water related components of yield formation.

An analytical model had explained grain yield under DS environments through the following equation (Passioura, 1977; Fischer, 1981):

Grain yield = T × TE × HI

where, T =Amount of water transpired per unit area

TE =Amount of biomass produced per unit of water transpired

HI = Ratio of grain yield to total above-ground biomass

This proposal was widely accepted and improvement in any one or the combinations of the above components is expected to improve grain yield under DS (Passioura, 1977; Fischer, 1981). Also the existence of substantial genetic variation has been demonstrated for each of these functional components in various crops (Hubick *et al.,* 1986; Donatelli *et al.,* 1992; Nageswara Rao *et al.,* 1993, 2001; Hebbar *et al.,* 1994; Wright *et al.,* 1994; Hammer *et al.,* 1997; Udayakumar *et al.,* 1998; Krishnamurthy *et al.,* 2007; Balota *et al.,* 2008b; Ratnakumar *et al.,* 2009; Xin *et al.,* 2009; Vadez *et al.,* 2011) as well as in chickpea (Kashiwagi *et al.,* 2005, 2006a). Although those components were considered as highly useful, these traits could not be used as selection criteria in a large-scale breeding program. Further studies led to the identification of surrogate traits that can be measured non-destructively with less labor and time in efforts for

improved TE such as $\Delta^{13}C$ (Farquhar *et al.,* 1982; Hubick *et al.,* 1986; Wright *et al.,* 1994; Clay *et al.,* 2003; Kashiwagi *et al.,* 2006b; Krishnamurthy *et al.,* 2013b), SLA (Wright *et al.,* 1994; Nageswara Rao *et al.,* 2001; Bindu Madhava *et al.,* 2003; Vadez *et al.,* 2014), SCMR (Bindu Madhava *et al.,* 2003; Kashiwagi *et al.,* 2006c, 2010) and specific leaf nitrogen (SLN) (Nageswara Rao *et al.,* 2001; Bindu Madhava *et al.,* 2003) and for T such as canopy-chamber method (Tahiri, 2011), sap-flow method (Kostner *et al.,* 1992; Dye and Olbrich, 1993; Cermak *et al.,* 1995), steady–state porometer (Easter and Sosebee, 1975; Nilsen *et al.,* 1983; Schulze *et al.,* 1985; Munro, 1989; Ansley et al., 1990, 1992), leaf temperature differences (Fuchs and Tanner, 1966; Jackson *et al.,* 1981; Fuchs, 1990; Reynolds *et al.,* 1992), which are relatively easy to measure and support high throughput measurements. Moreover, improvement of HI (see formula), is considered to be relatively less cumbersome and very often deferred to be dealt at the last stages of breeding and selection. These developments towards understanding the underlying mechanisms of drought tolerance, and in efficient ways of measuring genotype differences in trait expression of chickpea, encouraged breeders to attempt a physiological trait-based selection approach in drought tolerance breeding with a hope that it would result in greater and rapid progress (Edmeades *et al.,* 1999; Bruce *et al.,* 2002; Richards *et al.,* 2002; Nigam *et al.,* 2005; Gaur *et al.,* 2014; Varshney *et al.,* 2014). Simultaneously, it was also thought appropriate to compare the efficiency of selection between trait-based and empirical

approaches so that an effective strategy could be devised for drought tolerant breeding (Nigam *et al.,* 2005).

There is yet another physiological model of yield analysis that is applicable under DS. A model for analyzing the processes leading to seed yield determination in groundnuts was proposed by Duncan *et al.* (1978). Among others, this was adopted by Williams and Saxena (1991) to explain the yield differences among chickpea genotypes grown in Hisar, a northern Indian location. This model explains grain yield as:

$$\mathbf{Y = C \times Dr \times p}$$

Where, Y = grain yield

C = mean crop growth rate

Dr = duration of reproductive growth

p = mean fraction of C partitioned to Y

This model varies from the previous one in combining both T and TE into C and splitting HI into Dr and p. Thus this model analyzes the contribution of partitioning more elaborately than the plant biomass accumulation.

High h^2 and a weak response to environmental variation of HI (Hay, 1995) makes it suitable as a major trait for improving yield stability under stress. However, HI alone had not been considered as a yield determining trait for selection as high yields under DS were the product of interaction of C and HI. Therefore, success in selecting for high yield under DS requires a simultaneous selection for both C and

HI. An independent selection for HI alone poses the danger of selecting entries with a poor biomass potential (Wallace *et al.,* 1993). HI is a product of two components; i.e. the reproductive duration (Dr) and the p to grains (Duncan *et al.,* 1978; Williams and Saxena, 1991; Gallagher *et al.,* 1976; Scully and Wallace, 1990; Krishnamurthy *et al.,* 1999). Terminal DS in chickpea, as in many other crops, is known to reduce the growth duration, especially the reproductive phase (Krishnamurthy *et al.,* 2013a). Chickpea growing environments experience a ceiling to the reproductive growth duration due to progressively increasing terminal DS and heat stress at the final stages of reproductive growth, requiring an increased p, thereby providing the plants to escape the later stress stages with less compromise on the yield formation (Krishnamurthy *et al.,* 2013a). Several plant functions such as increased radiation use efficiency (RUE), non-lodging crop stands, increased sink size (twin pods in each node or smaller leaf size), more terminal branches, synchrony in flowering and greater flower production per unit area can be envisaged as contributing to increased p.

Also there were other physiological models that were used to describe the development, growth and yield of chickpea (Sinclair, 1994; Soltani *et al.,* 1999). The components required for this model were relatively few and the major processes simulated are crop phenology, leaf development as a function of DS and temperature, crop biomass accumulation as a function of intercepted radiation and RUE modified for temperature and water deficit stresses, dry-matter accumulation in

grains as a function of time, temperature and water, and soil water balance (Sinclair, 1994).

2.1 Physiological adaptations of plant to drought stress

Plants are known to have different mechanisms to adjust to water stress condition. Classically, it was categorized in to three strategies as (i) drought escape, (ii) drought avoidance, and (iii) drought tolerance (Levitt, 1972). However, some physiologist suggests that those strategies should be categorized as (i) drought escape, (ii) dehydration postponement, and (iii) dehydration tolerance because water deficit affects the hydration of the plants (Kramer, 1980; Turner, 1986a; Blum, 1988). Nevertheless, these strategies are not mutually exclusive and, in practice, plant may combine a range of response types (Ludlow, 1989; Gaff, 1980). Therefore, when water in the plant environment becomes deficient, plant T cannot fully meet the atmospheric demand, and plant water deficit evolves. In such case, plant may escape from DS through their early maturity (Kumar and Abbo, 2001) or the water deficit creates strain on the plant that causes damage and drives a network of gene responses. These are proportional to the rate of deficit. The plant can cope with this strain by avoiding or by tolerating the strain (Blum, 2014).

2.1.1 Drought escape

The ability of plants to complete their life cycle before getting exposed to constant water deficit condition, by maintaining a high degree of developmental plasticity, is termed as drought escape. As seen in the case of chickpea in the last decade, the main breeding

strategy used to cope with the terminal DS was selecting for drought escape by reducing the crop duration and securing the grain yield before soil water was depleted (Kumar *et al.,* 2001a; Kashiwagi *et al.,* 2008c). Reducing the crop duration may not be beneficial unless the phenological development of the crop is matched with the period of soil moisture availability to minimize the impact of DS on crop production in environments where the growing season is short and terminal DS predominates (Turner, 1986a, b). It has resulted in release of early maturing chickpea varieties such as ICCV 2 with increased yield stability and good adoption by farmers (Kumar *et al.,* 2001a). Therefore, drought escape had been considered as the most important success for breeders so far in comparison with other mechanisms (Sabaghpour *et al.,* 2006). On the other hand, the early maturing varieties had relatively lower biomass and grain yield mainly due to a shortened total photosynthetic duration. Thus, as a long-term strategy, there is a need to develop drought-tolerant genotypes that could optimally utilize the available season for an enhanced yield and its stability under terminal DS. Such breeding strategy for direct yield has been successful in some crops such as rice (Fukai and Cooper, 1995), common bean (Schneider *et al.,* 1997; Frahm *et al.,* 2004) and maize (Banziger *et al.,* 1999).

2.1.2 Drought avoidance (dehydration postponement)

Dehydration avoidance is one of the major physiological components of drought resistance mechanism, defined as the capacity to avoid or reduce plant water deficit (Blum *et al.,* 1982; Blum, 2014)

through a relatively higher level of water potential maintenance (Levitt, 1972). Dehydration avoidance is common to both annual and perennial and associated with a variety of adaptive traits. These involve (i) minimizing water loss and (ii) maximizing water uptake (Chaves *et al.,* 2003). Minimizing water loss is the first response of a plant to stress by limiting water loss mainly through stomatal conductance or by reduction in leaf area (LA) (e.g. small and thick leaves), shedding of older leaves and variations in stomatal conductance of leaf in response to water potential as have been reported in chickpea (Lawn, 1982; Muchow, 1985).

However, a frequent stomatal closure in response to DS is highly linked with reduction in carbon assimilation by the plant (Porporato *et al.,* 2001) that leads to a reduced shoot growth. Water uptake is maximized by adjusting the allocation pattern, namely increasing investment in roots (Jackson *et al.,* 2000) which helps the plant to keep its water potential high in the tissues by maintaining water uptake through a deep root system and an increased hydraulic conductance (Mooney *et al.,* 1977). Therefore, selection of larger and deep root systems can sustain better productivity (Saxena *et al.,* 1995; Singh *et al.,* 1995; Kashiwagi *et al.,* 2005) and those root morphological traits were considered as one of the most important components of drought tolerance in crop to extract the water from the lower soil layers as the upper layers become dry (Gregory, 1988; Lawn, 1988; Ludlow and Muchow, 1988).

2.1.3 Drought tolerance (dehydration tolerance)

Dehydration tolerance is the survival mechanism when DS is more severe. The ability of tissue to maintain turgor pressure during acute DS is an important mechanism of dehydration tolerance (Hsiao *et al.,* 1976). When the plant is exposed to low water potential, it will prepare protective proteins like heat shock proteins, late embryogenesis abundant proteins and accumulation of abscisic acid (Creelman and Zeevaart, 1985). In a practical sense, relative ability of the crop to sustain adequate biomass production and maximize crop yield under increasing water deficit throughout the growing season were essential, rather than the physiological aptitude for plant survival under extreme drought shock (Serraj and Sinclair, 2002), which has a limited economic interest for the farmers. The consideration of tolerance mechanisms depends upon the objectives of the researcher and the pattern of DS or host organism. Plant breeders and agronomists may be interested in drought escape and dehydration avoidance mechanisms that related to productivity while ecologists may be interested in dehydration tolerance mechanisms that related to survival. Therefore, in agricultural context, drought resistance mechanisms related to productivity (drought escape and dehydration avoidance) are very important.

2.2 Incorporation of physiological traits in plant breeding

Plant breeders considered the flowering time and plant height as important physiological traits for yield improvement and they regularly select for desirable expression of these traits to maintain

adaptation and optimal yield. Consequently, these traits had a major role for yield improvement in water-limited environments like Australia (Siddique *et al.,* 1990; Richards, 1991) where, flowering needs to be early enough to avoid the adverse effects of rapidly depleting soil water and temperatures increase, but late enough to avoid frost. Optimal plant height has been an important selection criterion to avoid lodging and also to maximize HI particularly in temperate crops under favorable environments, and genes responsible for reduced plant height have associated to increased yields as they have enhanced the assimilates allocation to grain and the reproductive organs rather than to the stem (Richards, 1992).

Except the above mentioned traits, other physiological traits increasing crop production in DS environment were considered as more elusive (Richards *et al.,* 2007). However, the more understanding plant breeders have on the physiological processes that underlie plant performance, the more efficiently they can exploit relevant physiological mechanisms to improve crop performance. For example, wheat breeders have become increasingly able to use physiological traits directly as selection criteria, as their knowledge of physiological processes has expanded and as traits have been identified that can be used as selection criteria to achieve results more quickly and efficiently than selecting for yield performance alone (Condon *et al.,* 2002, 2004; Ramirez-Vallejo and Kelly*,* 1998; Reynolds *et al.,* 2009, 2011; Ribaut *et al.,* 1997).

2.3 Constitutive and adaptive traits

The performance of genotypes across environment may or may not be consistent. Based on the genotype response to environment interaction, traits are majorly considered as constitutive and adaptive. This concept is usually defined as the existence or non-existence of a G×E interaction on the measured trait with a positive effect on grain yield (Blum, 1996). An alteration in plant function or structure which enhances the performance under DS of a particular genotype is defined as adaptive trait (e.g. reduction in TR, allowing the plants to conserve water through to the end of the crop cycle). Conversely, a constitutive trait is either unaltered by environmental conditions, or is altered by similar amounts in all considered genotypes (no G × E interaction) (Reeves and Baker, 1984). Although it does not respond to DS, constitutive trait can bring a relative advantage under DS (e.g. TE under irrigated conditions, early vigour, or deep root system; Richards *et al.,* 2002; Blum, 2009).

Breeding for constitutive traits has brought much improvement in drought tolerance (Blum, 2011). QTLs responsible for deep rooting colocalize with QTLs of grain yield under DS (Tuberosa *et al.,* 2002a), improving WUE of OI plants increases wheat yield under acute DS (Condon *et al.,* 2002). By contrast, plant breeders are often reluctant to consider adaptive traits associated largely with G× E interaction which lowers its h^2 level. However, Reymond *et al.* (2003) has been recently proposed an alternative approach based on the fact that although an adaptive trait alters with environmental conditions, it

often follows a consistent reproducible behaviour. As an example, leaf elongation rate changes with the meristem temperature, and follows a close relationship with it when the plants were grown under no sign of water or nutrient stress and not under high evaporative demand. Under these situations, this relationship pertains to different experimental conditions for maize (Ben Haj Salah and Tardieu, 1995) and *Arabidopsis thaliana* (Granier *et al.,* 2002). Likewise, the leaf elongation rate of maize in response to evaporative demand and to soil moisture status are firm characteristics of a genotype, which apply to both field and controlled conditions (Tardieu *et al.,* 2000). An adaptive trait, with a G × E interaction, can therefore be linked to stable underlying characteristics of genotypes, independent of experimental conditions (Reymond *et al.,* 2003).

2.4 Availability of physiological traits and their current identity in agricultural research

There were ample number of physiological, morphological and phenological traits or responses that were identified to be associated with DS adaptation but all the traits may not appear to be of potential benefit to yield under DS. It had also been realized that several traits collectively contribute to grain yield and yield components under DS and the beneficial trait's combination remains environment-specific. Presence of a trait can be of advantage in some specific location but not in others. But negative contributions of traits to productivity under DS can be rare. The traits that have been listed to be contributory under DS are yield, yield components, grain fill duration

and p, grain number maintenance, staygreen / delayed senescence, CT, OA / relative water content, hormonal regulation, deep root development, root prolificacy, root to shoot ratio, $\Delta^{13}C$, photosynthesis, RUE, WUE, nutrient acquisition / uptake efficiency, phenology / elasticity of development, growth vigor and functional attributes (total T, TE, HI, C, D_v and D_r) were considered as a important putative drought resistance traits (Subbarao *et al.,* 1995; Ludlow and muchow, 1990; Serraj *et al.,* 2004a; Krishnamurthy *et al.,* 1999, 2013a, b). However, the robustness of few above mentioned traits for yield selection was still inconclusive such as OA and $\Delta^{13}C$.

2.4.1 Grain yield and yield components

Grain yield of chickpea is a quantitative trait which is influenced by many genetic factors as well as environmental factors (Muehlbauer and Singh, 1987). Grain yield per plant was considered as a major determinant of plot yield (Reddy and Rao, 1988; Arora, 1991; Sandhu *et al.,* 1991; Singh and Rao, 1991; Dasgupta *et al.,* 1992; Bhatia *et al.,* 1993; Maynez *et al.,* 1993; Jirali *et al.,* 1994; Rao *et al.,* 1994; Srivastava and Jain, 1994; Wanjari *et al.,* 1996; Rao and Kumar, 2000; Kumar *et al.,* 2001b; Burli *et al.,* 2004; Dubey and Srivastava, 2007). Although direct selection for grain yield could be misleading, indirect selection through yield related trait with a high level of h^2 might be more effective (Toker, 1998). Grain yield was highly associated with the plant height, biological yield per plant, number of secondary branches, pods per plant, 100-seed weight and HI in chickpea (Ali *et al.,* 1999; Bakhsh *et al.,* 1998; Renukadevi and

Subbalakshmi, 2006) and were also reported in other legume species such as mungbean (Ghafoor *et al.,* 1990; Khattak *et al.,* 1995, 1997, 1999).

The expected genetic gain was reported to be low (Agarwal, 1986; Panchbhai *et al.,* 1992) for number of seeds per plant and pods per plant, but reported to be high for pods per plant (Jivani and Yadavendra, 1988; Kumar *et al.,* 1991; Chavan *et al.,* 1994; Jahagirdar *et al.,* 1994; Rao *et al.,* 1994; Patil, 1996; Kumar and Krishna, 1998; Kumar *et al.,* 2001b; Dubey and Srivastava, 2007). Therefore, those traits with high genetic variability could be focused for genetic improvement in chickpea (Ali *et al.,* 2002a; Kaur *et al.,* 2004; Qureshi *et al.,* 2004; Sharma *et al.,* 2005; Sidramappa *et al.,* 2008). Normally single flowers are borne on pedicels suspended by single peduncles in the axils of the leaves that contribute to more stable yield (Smithson *et al.,* 1985). However some of the genotypes in chickpea produce two pedicels/flowers/pods per node. Double podded plants produce 6 to13% higher grain yield under terminal DS compared to single podded plants (Sheldrake *et al.,* 1978) suggesting that the trait can contribute positively to higher productivity in chickpea (Singh and van Rheenen, 1994).

The h^2 level for number of pods per plant varied from low (Sandhu *et al.,* 1991; Rao *et al.,* 1994; Arora and Jeena, 2000) to high (Joshi, 1972; Kumar *et al.,* 1991; Singh and Rao, 1991; Mathur and Mathur, 1996; Sial *et al.,* 2003; Dubey and Srivastava, 2007; Gowda

et al., 2011a). The h^2 level for number of seeds per pod varied from low to moderately high (Iqbal *et al.,* 1994; Pandey and Tiwari, 1989).

The mean plot yield of *desi*, kabuli, and intermediate types were significantly different from each other and kabuli types have the lowest plot yield than *desi* and intermediate types under tropical DS conditions (Upadhyaya *et al.,* 2001; Krishnamurthy *et al.,* 2013a).

2.4.2 Osmotic adjustment (OA)

For OA, solutes are known to accumulate in the cell in response to water deficit. This accumulation of solutes in the cell reduces its water in the cell leading to greater extraction of water from the soil, as observed in wheat (Morgan, 1983), sorghum (Basnayake *et al.,* 1996) and barley (Gonzalez *et al.,* 1999). OA has been suggested to be an important trait for drought tolerance in cereals, through maintaining its cell turgor and physiological processes when water deficits develop (Turner and Jones, 1980; Morgan, 1984), and empirically validated their positive association with yield in cereals, e.g. wheat (Morgan *et al.,* 1986), sorghum (Tangpremsri *et al.,* 1995). However, later a series of experiments on OA were arrived with incompatible results (Serraj and Sinclair, 2002), which confirmed the inconsistency of the trait, in many cereals such as wheat (Morgan, 1983, 1995; Morgan and Condon, 1986; Blum *et al.,* 1999), barley (Grumet *et al.,* 1987), sorghum (Ludlow *et al.,* 1990; Santamaria *et al.,* 1990), maize (Bolanos and Edmeades, 1991; Guei and Wassom, 1993) and rice (Fukai and Cooper, 1995), and legume species such as cotton (Quisenberry *et al.,* 1984), soybean (Cortes and Sinclair, 1986), pea

(Rodriguez-Maribona *et al.,* 1992), chickpea (Morgan *et al.,* 1991) and pigeonpea (Subbarao *et al.,* 2000).

In case of chickpea, Morgan *et al.* (1991) indicated that the degree of OA observed under controlled environment was positively correlated with the grain yield of the cultivar under rainfed conditions. Variation in OA among chickpea cultivars has also been observed in several studies (Singh *et al.,* 1990; Lecoeur *et al.,* 1992; Leport *et al.,* 1999; Moinuddin and Khanna-Chopra, 2004). However, the association between OA and grain yield of chickpea under DS condition is inconsistent as already stated. Moinuddin and Khanna-Chopra (2004) found that the degree of OA had a good association with grain yield of chickpea grown under a line source irrigation system in the field. However, Leport *et al.* (1999), did not observe any relationship between OA and yield in chickpea, and Singh *et al.* (1990) found that OA did not always result in a grain yield increase, particularly in genotypes that had the greatest degree of OA and partitioned a large fraction of assimilates to the plant root. A recent study conducted at multiple locations in India and Australia concluded that phenotypic expression of OA is not stable and it cannot considered as a selectable drought tolerance trait in chickpea breeding programs (Turner *et al.,* 2006). However, OA has a beneficial response to yield, is in the maintenance of root growth in order to attain soil water that may be available in the deeper soil profile (Serraj and Sinclair, 2002).

2.4.3 Surrogate traits for measuring TE in field condition

Under field condition, TE is difficult to measure. Therefore, evaluation of TE relied mostly on surrogate traits, although this has most likely resulted in over-dependence on the surrogates. The reason for using surrogate measures of TE is the difficulty of measuring TE gravimetrically, by assessing biomass increases and plant water use on a long-term basis (Vadez *et al.,* 2014). Because of the cost of measuring $\Delta^{13}C$ and the fact that such measurements are not immediate, other surrogates were subsequently identified, such as SLA or SCMRs, as proxies of $\Delta^{13}C$ (Nageswara Rao *et al.,* 2001). However, these surrogates were found to explain TE poorly in groundnut mapping populations (Krishnamurthy *et al.,* 2007; Devi *et al.,* 2011).

2.4.3.1 Carbon isotope discrimination ($\Delta^{13}C$)

The method proposed by Farquhar *et al.* (1982) for estimating TE through measuring the $\Delta^{13}C$ in leaves and it should be correlated with TE through independent links with the ratio of internal CO_2 pressure to ambient CO_2 pressure (*pi/pa*). Although, alternate protocol are available for direct TE measurement, $\Delta^{13}C$ is used as a surrogate for TE as it allows the storage of test tissue and limits the tissue requirement to a small sample (Krishnamurthy *et al.,* 2013b), and this integrated measure possibly used as a rapid and nondestructive selection trait in large-scale breeding programs (Farquhar and Richards, 1984). Plants are known to vary in their discrimination against heavy isotopes of carbon during photosynthesis

under low intercellular CO_2 concentration, leading to a higher ^{13}C concentration in low transpiration efficient genotypes (Farquhar *et al.,* 1989). Relatively early stomatal closure is thus shown to prevent further water loss and improve TE. It has been claimed that $\Delta^{13}C$ being a good surrogate for WUE is well established (Sheshshayee *et al.,* 2003).

The extent of genotypic variation in TE and its correlation with $\Delta^{13}C$ has been reported in many grain legume crops, including chickpea (Uday Kumar *et al.,* 1996; Kashiwagi *et al.,* 2006b; Krishnamurthy *et al.,* 2013b), bean (Wright and Redden, 1995), cowpea (Ismail *et al.,* 1994), peanut (Hubick *et al.,* 1986; Wright *et al.,* 1994), lentil (Matus *et al.,* 1995), and soybean (White *et al.,* 1995; Uday Kumar *et al.,* 1996; Tobita *et al.,* 2007). But the lack of such relationship between $\Delta^{13}C$ and TE was also shown in three other legume species (lentil, chickpea and lupin) grown well watered (Turner *et al.,* 2007). Further studies indicated that there can be direct as well as indirect effect of $\Delta^{13}C$ on yield performance, and special attention is required to understand such effects (Khazaie *et al.,* 2011; Mohankumar *et al.,* 2011), and the expression of significant relationship between $\Delta^{13}C$ and TE is seems to be linked to specific weather and soil moisture conditions. Thus, $\Delta^{13}C$ cannot act as a standalone trait for the selection of drought tolerance in chickpea without the consideration of shoot biomass parameter (Krishnamurthy *et al.,* 2013b). Moreover, it is considered as a less efficient trait in C_4 plants, where CO_2 leakage occurs between the mesophyll and the

bundle sheath, resulting in reduced discrimination (Henderson *et al.,* 1998). The $\Delta^{13}C$ analytical facilities are a few and the utilization remains very limited because it is expensive to analyze large numbers of germplasm particularly in developing countries. Measurements of $\Delta^{13}C$ are not immediate, and they are quite expensive, which has triggered a search for alternative surrogates that are cheaper and faster to measure (Vadez *et al.,* 2014). SLA, which is a crude but easily measurable parameter, is suggested as a rapid and inexpensive selection criterion for high WUE (Wright *et al.,* 1994; Nageswara Rao and Wright, 1994). Further, a handheld portable SPAD chlorophyll meter have been used effectively by following necessary protocols for rapid assessment of SLA and SLN, the surrogate measures of WUE (Nageswara Rao *et al.,* 2001).

2.4.3.2 Specific leaf area

The ratio of LA (cm^2) to leaf dry weight (g) was considered as SLA. SLA is easy to measure, is highly correlated with TE and has a considerable genetic variation in groundnut (Serraj *et al.,* 2004a; Upadhyaya, 2005). The existence of a strong and negative association between SLA and TE (Wright *et al.,* 1994; Nageswara Rao *et al.,* 2001; Bindu Madhava *et al.,* 2003) and a low G × E interaction for the relationship between them have led to the suggestion of SLA as an economical surrogate tool to select for TE (Wright *et al.,* 1994). Thicker leaves (low SLA) usually have higher chlorophyll per unit LA and hence have a greater photosynthetic capacity compared with thinner leaves. The subsequent findings of low SLA genotypes also having

greater photosynthetic capacity for unit LA in groundnut further fortified the suggestion of using leaf thickness (low SLA) as a criterion for selection in improving TE (Nageswara Rao *et al.,* 1995). SLA has been shown to be related to TE in a number of studies (Comstock and Ehleringer, 1993; Sheshshayee *et al.,* 2006; Thompson *et al.,* 2007). However, other studies have found poor relationships between the surrogate and gravimetric TE measurements (Krishnamurthy *et al.,* 2007; Devi *et al.,* 2011).

In cereals, high SLA has appeared to be associated with early growth vigour (Lopez-Castaneda *et al.,* 1995; Rebetzke *et al.,* 2004) and to the extent of the high SLA was reflected in low photosynthetic capacity. As a consequence, it was suggested that the high SLA may also reflect in high $\Delta^{13}C$. Therefore, a tendency to higher SLA will need to be avoided during selection, if high vigour and low- $\Delta^{13}C$ are to be successfully combined. This may be desirable for other reasons (Condon *et al.,* 2004). SLA has relatively low h^2 in cereals (Rebetzke *et al.,* 2004), so its value as a selection trait for high early vigour may be limited. However, as seen in groundnut, there have been high levels of correlations between SLA and SLN (Nageswara Rao and Wright, 1994) and SLA and ribulose 1-5 bisphosphate carboxylase (Rubisco) (Nageswara Rao *et al.,* 1995) in various studies suggesting that photosynthetic capacity per unit LA is the key factor that contributes to variation in WUE. SLA measurements are favored more for the ease in measurement and cost effectiveness. It has been shown to act as a surrogate for WUE but has been shown to be significantly influenced

by factors such as leaf age and time of sampling (Wright and Hammer, 1994; Nageswara Rao *et al.,* 1995). However, Nigam and Aruna (2008) had reported that SLA can be measured at any time after 60 days of crop growth to reduce extraneous variability, particularly under DS. This provides peanut breeders a large flexibility to measure this trait in a large number of segregating populations and breeding lines in the field condition.

2.4.3.3 SPAD chlorophyll meter reading (SCMR)

SCMR is an indicator of leaf chlorophyll content and it was found to be associated directly with TE in legumes (Nageswara Rao *et al.,* 2001; Bindu Madhava *et al.,* 2003; Kashiwagi *et al.,* 2006c). It was also shown to be linearly associated with the extracted leaf chlorophyll content (Yadava, 1986) and linked to leaf nitrogen concentration (Kantety *et al.,* 1996; Bullock and Anderson, 1998). SCMR is a nondestructive method of quantifying the relative nitrogen status of leaves. Significant and positive correlations between SCMR and chlorophyll content, and chlorophyll densities have been reported (Akkasaeng *et al.,* 2003; Arunyanark *et al.,* 2008, 2009). The capacity to maintain high chlorophyll density under DS conditions has been proposed as an advantage under drought in barley (This *et al.,* 2000) and potato (van der Mescht *et al.,* 1999). It has also been demonstrated that the variation in TE was well associated with the genotypic variation in chlorophyll density and therefore with photosynthetic capacity (Arunyanark *et al.* 2008). Thus chlorophyll density has been suggested for use as a possible indicator of TE in

groundnut. In addition, Nageswara Rao *et al.* (2001) and Bindu Madhava *et al.* (2003) proposed that SCMR could be considered as a reliable and rapid measure to recognize genotypes with low SLA or high SLN (and hence high WUE) in groundnut.

As a noninvasive surrogate of TE, SCMR is easy to measure, reliable, fairly stable and low cost. The SCMR is reported to be more stable than SLA. A significant positive relationship was observed between seed yield and SCMR in many legumes (Argenta *et al.,* 2001; Costa *et al.,* 2001; Nageswara Rao *et al.,* 2001; Sudhakar *et al.,* 2006; Kashiwagi *et al.,* 2010) and cereals (Talwar *et al.,* 2010; Seetharam, 2011). Ease, rapidity and noninvasiveness in measurement have been recognized as the advantages of this measurement while the light weight of SPAD meters have been considered to rate it as the best choice for use in the trait-based drought tolerance breeding programs of groundnut and chickpea at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (Serraj *et al.,* 2004a; Kashiwagi *et al.,* 2006c). However, they stated that it is difficult to complete SCMR observations in a large-scale breeding program within a specified time and crop stage.

2.4.4 Surrogate traits for measuring transpiration (T) in field condition

Many studies had shown that Twas closely correlated with crop yield (Stanhill, 1986; Hanks, 1983). The relationship, also, has been incorporated into many simulation models (Tanner and Sinclair, 1983). Direct assessment of T under field condition is difficult. In the

past, efforts were made to identify techniques to measure T in agronomic species (Granier, 1987). Thas been measured on surfaces differing in area from a leaf portion to entire fields or forests, and the methods followed by researchers have also differed equally widely. Initially, most measurements were carried out on individual plants, but interest of forestry and agriculture has turned that toward study of the water balance of large stands of plants (Kramer, 1983). Many techniques such as, gravimetric method, cut-shoot method, water vapor loss measurement, canopy-chamber method, sap-flow method, steady–state porometer, soil-evaporation measurement, micro-lysimeter and energy balanced method, were identified to measure the T (Tahiri, 2011).

Under field condition, only a few of these techniques had been known to support the requirements such as relatively direct, non-destructive and rapid in assessing T (e.g., canopy-chamber method, sap-flow method and steady–state porometer).

2.4.4.1 Canopy-chamber method

Canopy-chamber method has been considered as a suitable approach for plot-sized experiments in the field (Steduto *et al.,* 2002). Two major kinds of systems were adopted for the application of canopy-chamber, i.e., (i) steady-state open-systems and (ii) transient-state closed-systems.

Steady-state open-systems comprise the open-top chambers, used extensively for the long-term studies of field-grown plants which exposed largely to elevated CO_2 (Leadley and Drake, 1993). This

system allows to observing the plant response continuously throughout the crop growth period. But regular alteration of microclimate depend on the crop requirement was considered as a limitation. Moreover, they often require flow measurements and climate control (Steduto *et al.,* 2002). The canopy-chambers working as transient-state closed-systems, instead, do not require any flow measurement or climate conditioning and are chiefly used for ambient-level CO_2 and water vapor gas-exchange measurements. These chambers are placed over the crop for a while (approximately two minutes) and then removed for a subsequent measurement, permitting many number of replicates and less interruption of the plant growing environment. Nevertheless, during the measuring time, the natural gradients of temperature, CO_2 and water vapor are reduced due to forced ventilation (Held *et al.,* 1990), and the leaves orientation pattern at the chamber borders can be altered during the placement (Reicosky *et al.,* 1990).

2.4.4.2 Sap-flow or stem-flow measurement

Steady-state heat balance method developed by Sakuratani (1981, 1984) to measure the sap-flow or stem-flow was considered to be a promising method to measure the T (Baker and Van Bavel, 1987). This method does not change any of the environmental and physiological factors affecting the T process. Using a thin flexible heater that encircles the stem and is itself encircled by foam insulation, a steady, known amount of heat is applied to a small stem segment of the plant. In the steady state, this heat input to the

segment have to be balanced by four heat fluxes out of the segment: conduction up the stem, conduction down the stem, conduction outward through the foam sheath and convection in the moving T stream. Subtraction of the conductive fluxes from the known heat input yields the heat transported by the moving sap flow (Baker and Nieber, 1989). It is a direct method to assess the T with an accuracy of ±10% (Sakuratani, 1981; Baker and Van Bavel, 1987) and requires no calibration process. Moreover, much work has been done using a continuous supply of heat as a tracer (Dugas, 1990; Dugas *et al.,* 1992). However, some authors have reported that high sap flow rates may cause some systematic errors in measuring the heat balance components (Baker and Nieber, 1989). Moreover, Ishida *et al.* (1991) reported that the gauge accuracy may be influenced by stem vascular anatomy, with potentially greater accuracy in dicotyledons than in monocotyledons.

2.4.4.3 Steady-state porometer

Many plant-water relations studies had used the porometer to measure T of individual or group of leaves, plants and trees (Schulze and Hall, 1982; Dugas *et al.,* 1993). Thad been calculated from the stomatal conductance, using the leaf temperature, air temperature and humidity that were measured. Porometry had a greater advantage such as relative ease of use and capacity for measuring many individuals of the population, especially in remote locations. This method had been used widely for desert plants and mesquite (Easter and Sosebee, 1975; Nilsen *et al.,* 1983; Ansley *et al.,* 1990, 1992).

Leaf responses, including those measured with a porometer, are often used to make assumptions regarding whole plant or community responses (Jarvis and Leverenz, 1983; Meinzer *et al.,* 1988; Givnish, 1988; Norman, 1993). In addition, measurement of stomatal conductance on a sample of leaves can then be scaled up using total LA and other climatic variables to calculate whole plant T. However, leaf responses may not parallel to whole plant response under all conditions because of variation within the canopy (Jarvis and Catsky, 1971; Schulze *et al.,* 1985; Gold and Caldwell, 1989; Hinckley and Ceulemans, 1989) and the accuracy of this whole-plant T calculation depends upon leaf size, canopy aerodynamic conductance, and within-plant gradient of LA and vapor pressure (Pearcy *et al.,* 1989). An additional concern is that porometers may not estimate T accurately because micro-environmental conditions in the porometer leaf chamber modify wind speed and humidity (Fichtner and Schulze, 1990; McDermitt, 1990). The assumption is made if the chamber is applied to the leaf for a short time before stomatal aperture changes, stomatal conductance can be accurately measured and T calculated from the conductance.

Schulze *et al.* (1985) and Munro, (1989) reported that, porometer measurement has been widely used to estimate T of plants because there is often no alternative for this method. Later, the remote estimation of leaf TR monitored through infrared thermometry was considered as more useful and realistic than the porometer method (Inoue *et al.,* 1990).

2.4.4.4 Canopy temperature

The advantage of CT as a measure of 'crop water stress' was recognized in the 1960s (Tanner, 1963; Gates, 1964). The differences in photosynthetic and TR and stomatal resistances of plants could easily be detected by means of infrared image analysis, while the micro-meteorological conditions were exactly the same. Inoue (1986) and Inoue *et al.* (1990) suggested that a thermal image of a crop canopy could provide the spatial differences in canopy surface temperatures which significantly reflected the differences in physiological activity of individual leaves. Moreover, their experimental fact implies that a large number of leaves could be monitored simultaneously if infrared leaf temperatures were interrelated quantitatively with TR and stomatal resistances. From energy balance considerations, it can be shown that leaf temperature has a direct relationship with TR, leaf porosity and stomatal conductance (Fuchs and Tanner, 1966; Jackson *et al.,* 1981; Fuchs, 1990; Jones, 1992; Jones *et al.,* 2002, 2009; Rebetzke *et al.,* 2013). An important consequence of the stomatal closure that occurs when plants are subject to water stress is that energy dissipation is decreased so leaf temperature tends to rise. Since a major role of T is leaf cooling, CT and its reduction relative to ambient temperature is an indication of the role of Tin cooling the leaves. The relationship among CT, air temperature and T is considered when CT is used to develop the crop water stress index, which is gaining importance in irrigation

scheduling in crops (Idso *et al.,* 1977; Jackson *et al.,* 1977, 1981; Inoue and Moran, 1997).

Infrared thermography has been used successfully for many years for genetic screening in controlled environments (Raskin and Ladyman, 1988; Merlot *et al.,* 2002) but it has been felt complicated to scale up the technology to the field condition (Jones *et al.,* 2009) mainly due to the difficulty in separating the soil reflection from that the plant canopy (Munns *et al.,* 2010). There has been substantial recent progress in those area, with success in separation of reflection of the leaf from that of the background soil with the help of thermal thresholds (Giuliani and Flore, 2000; Jones *et al.,* 2002) and image analysis techniques (Leinonen and Jones, 2004). There is also good level of progress in using linear un-mixing in separating the temperatures of canopy and soil components where there is a predominance of mixed pixels, as has been seen in cereal canopies in the field (McCabe *et al.,* 2008). The temperature variation from leaf-to-leaf, far from necessarily being a problem, provides the basis of one approach to the detection of stomatal closure (Fuchs, 1990), with stressed canopies theoretically showing a greater temperature variance than OI canopies (Bryant and Moran, 1999; Jones *et al.,* 2002).

Interest is also increasing in using CT in plant breeding for drought tolerance. The goal is to select genotypes that maintain lower CT in relation to other genotypes under the same field conditions. Relatively lower CT of crop plants under DS is largely due to better soil

water uptake and sustenance of a relatively better plant water status. CT was considered to be effective in screening wheat (Blum *et al.,* 1982; Pinter Jr*et al.,* 1990; Amani *et al.,* 1996; Reynolds *et al.,* 1998; Ayeneh *et al.,* 2002) and pearl millet (Singh and Kanemasu, 1983) genotypes for resistance to DS. Chaudhuri and Kanemasu (1982) found that yields of sorghum hybrids were negatively correlated with the seasonal average CT and canopy – air temperature differences. Similar results have also been reported for potato (Stark and Pavek, 1987). Maintenance of a cooler canopy during grain filling period in wheat is an important physiological response for high temperature stress tolerance (Munjal and Rana, 2003) with the ability to maintain T through access of roots to water deep in the soil profile. This is supported by the fact that ~60% of yield variation under DS in a wheat RILs population was explained by CT (Olivares-Villegas *et al.,* 2007), as well as the observation that ~50% of variation in soil drying to a depth of 1.2m was explained by CT in a set of wheat genetic resources (Reynolds *et al.,* 2007). Therefore, thermal imaging is becoming a high-throughput tool for screening plants for differences in stomatal conductance (Merlot *et al.,* 2002) and recent advances in infrared thermography have increased the probability of recording drought tolerant responses more accurately (Krishnamurthy *et al.,* 2011a).

2.4.5 Crop growth rate, reproductive duration and partitioning coefficient

All the three components of yield C, Dr and p has been shown to be interrelated. Dr has been shown to reduce more than Dv under terminal DS (Krishnamurthy *et al.,* 2013a). This work has suggested that these durations have been vulnerable to soil moisture changes. In all soil moisture environments the variations in C and p were shown to be associated with grain yield as seen in common bean (Scully and Wallace, 1990; Scully *et al.,* 1991), groundnut (Jogloy *et al.,* 2011) and winter wheat (White and Wilson, 2006). However, this association was found to improve under DS both in germplasm or in advanced breeding lines of chickpea (Krishnamurthy *et al.,* 1999, 2013a), emphasizing the need for a selection for both these traits. Breeding programs have been aware of the need to breed for C or greater plant biomass at maturity (Singh *et al.,* 1983; White and Wilson, 2006) aiming for higher crop yields through larger plant size. But this is not the case with better p. The greatest challenge to using HI directly in breeding programs is its often observed negative linkage with shoot biomass (Scully and Wallace, 1990) and maturity duration (Krishnamurthy *et al.,* 2010). Usually, HI explains yields poorly as highest yields can result through either increased shoot biomass or increased harvest indices (Austin, 1980; Duncan *et al.,* 1978; Scully and Wallace, 1990; Scully *et al.,* 1991). Direct selection for HI is rightly deterred as poor harvest indices are often linked to larger plants (as seen under OI or well-fed or longer duration ones). But this

linkage is a result of extended vegetative duration leading to an excessive vegetative growth or conversely reduced Dr. To explain it further, HI is an integration of two negatively linked individual components, i.e., the Dr and the p (Jogloy *et al.,* 2011; Krishnamurthy *et al.,* 1999). One apparent effect of DS is the large reduction in Dr. Therefore, any effort to keep a higher HI needs to aim for a greater p to compensate for the loss in duration and to keep the yield gap reduced. The importance of and selection for p or HI is not new (Adams, 1982; Duncan *et al.,* 1978; Scully and Wallace, 1990; Jogloy *et al.,* 2011). On the basis of a much earlier hypothesis (Searle, 1965), Scully and Wallace (1990) proposed an equation called Relative Sink Strength (equivalent to p here), the ratio of seed growth rate upon biomass growth rate, and suggested 1.0 as the highest sink strength for common beans.

Terminal DS reduced Dr more than Dv is an indication that these durations are vulnerable to soil moisture changes. When water is not a limitation for T, canopy and plant temperatures are known to be cooler and close to 25°C deviating heavily from the ambient temperatures. Cooler temperatures and shorter photoperiods are known to encourage suppression of reproductive growth (Roberts *et al.,* 1985). As individual or collective effects of soil moisture, temperature and photoperiod are expected to alter both Dv and Dr, making them unstable, genotypes capable of adjusting themselves to such variation and maintain their yield stability are desirable. Selective reduction in reproductive growth phase is commonly

observed not only in response to DS but also in response to salinity or heat (Krishnamurthy *et al.,* 2010, 2011b, c). And if the efforts to compensate the stress induced yield gaps are to be successful, increased p has to be sought after (Anbessa *et al.,* 2007).

2.4.6 Root traits - the hidden half

Root systems are generally complex three-dimensional structures that offers functions central to plant fitness, such as water and nutrient acquisition. Crop plants respond to variations in water and oxygen status of the soil through morphological, anatomical and physiological adjustments that help them cope with such variations and the associated stress (Krishnamurthy *et al.,* 1998, 1999; Chandler and Bartels, 2008). Crop health and survival are reliant on root system architecture, the spatial configuration of different types and ages of roots emerging from a single plant (Lynch, 1995). RSA differs dramatically within and across species, permitting for soil exploration in diverse conditions (Fitter, 2002). Crop age is also an important factor in RSA; young plants have relatively less complex root systems, however as plants mature their root systems become correspondingly more complicated. Variation of RSA could contribute to enhancements of desirable traits such as yield and drought tolerance (Tuberosa *et al.,* 2002b). Moreover, several studies have shown that root traits are important drought adaptive attributes (Jordan *et al.,* 1983; Jones and Zur, 1984; O'Toole and Bland, 1987; Sponchiado *et al.,* 1989; Serraj *et al.,* 2004b; Kashiwagi *et al.,* 2005, 2008c; Krishnamurthy *et al.,* 1998, 2012; Sinclair and Muchow, 2001; Manschadi *et al.,* 2006, 2008;

Reynolds and Trethowan, 2007; Christopher *et al.,* 2008). However, root traits are notoriously difficult to measure in realistic field situations (Mohammadi *et al.,* 2012).

Root traits at different level such as organism, organ system, organ, and tissue and cellular, were found to be related to crop productivity under water deficit and genetic screening of traits to identify their markers (Comas *et al.,* 2013).

2.4.6.1 Organism level traits

The size of a plant's root system was considered as a key trait of interest related to acquisition of soil resources, only when considered in relation to the size of the remaining parts such as LA, shoot, or the whole plant size (Maseda and Fernandez, 2006). Allometry (metrics of root to shoot relationships) was generally measured as root/shoot ratio of dry mass. When determined from biomass, root biomass per total plant biomass (root mass fraction) was considered as more strong quantification of the relative size of root systems for statistical reasons but has been less oftenly used (Reich, 2002). Chickpea mini-core accession had been shown to have a large range of genetic variation in ratio of root to total biomass in comparison with cultivated and wild chickpea (Krishnamurthy *et al.,* 2003; Kashiwagi *et al.,* 2005). Moreover, the root to shoot dry weight had been known to reduce with the increase in plant age as a consequence of relatively higher dry matter allocation to the shoots (Gregory, 1988; Brown *et al.,* 1989; Krishnamurthy *et al.,* 1996).

2.4.6.2 Organ system and organ level traits

Considering the organ system and organ level altogether, for both fine and coarse portions of root systems (Comas *et al.,* 2013), several morphological and physiological root traits such as RDp, root length density (RLD), length to weight ratio, root dry weight (RDW), root length (RL), root volume (RV), root surface area (RSA), average root diameter and root angle have been shown to be related with increased productivity under terminal DS environments (Ludlow and Muchow, 1990; Saxena *et al.,* 1993; Krishnamurthy *et al.,* 2003; Kashiwagi *et al.,* 2005; Subbarao *et al.,* 1995; Turner *et al.,* 2001). Depending on the growing environment, the level of contribution of those root traits to drought tolerance may vary. The ability of plants to grow their roots according to distribution of available soil moisture profoundly enhances plant productivity under DS and the methods of root trait assessment for water uptake from deep in the soil profile was illustrated recently (Wasson *et al.,* 2012).

The development of deep roots is one common example of both the adaptation and avoidance mechanisms of DS (Chandler and Bartels, 2008). Under DS condition, surface level soil moisture stay for a short period compared to the subsequent layers due to the evaporation demand. Crops that have shallow root system grow comfortably at the vegetative stage and later suffer if there is an acute terminal DS, due to inaccessibility of available soil water in the deeper soil profile with an output of poor yield. Genotypes capable of supporting greater root biomass would be better able to develop the

extensive, deep root systems required to utilize soil water resources fully (Sponchiado *et al.,* 1989; White and Castillo, 1989). Field studies in various crops had shown that both profuse root systems that extract more of the water in upper soil layers and longer root systems that extract soil moisture from deeper soil layers were important for maintaining yield under terminal DS (Ludlow and Muchow, 1990; Saxena and Johansen, 1990b; Turner *et al.,* 2001; Krishnamurthy *et al.,* 2003; Zaman-Allah *et al.,* 2011a). Therefore, breeding for plants with lower RLD (root length per soil volume) in shallow soil layers and higher RLD in medium and deeper soil layers has been suggested as an efficient growth strategy in environments where deep soil water could be available to crops later in the growing season (Wasson *et al.,* 2012; Lynch, 2013). Twenty years of major effort was invested at ICRISAT for improving a better adaptation of plants to terminal DS through deeper rooting and higher RLD in the deep layers (Saxena, 1984; Johansen *et al.,* 1997; Krishnamurthy *et al.,* 1999) and also a large range of genetic variation were found in chickpea germplasm (Kashiwagi *et al.,* 2006a, 2008c), that are being useful in enhancing the drought productivity in integrated chickpea breeding program (Varshney *et al.,* 2014).

Deep root system seems to contribute more to RL than to root weight (Follett *et al.,* 1974; Krishnamurthy *et al.,* 1996) as they tend to be finer compared to the whole root system. A high ratio of deep root weight to shoot weight was also found to maintain higher plant water potentials and have a positive effect on yield under DS (Mambani and

Lal, 1983). In addition to the deep-rooting capability, traits like rapid in root growth and soil water extraction under receding soil moisture conditions were also considered as beneficial in yield improvement in chickpea (Krishnamurthy *et al.,* 1996). In rice, traits such as deep root morphology and root diameter have been associated with increased water extraction during progressive water stress (Fukai and Cooper, 1995; Kamoshita *et al.,* 2002). Deep roots for water uptake deep in the soil profile found to be essential for smaller statured crops, such as wheat, rice, and common bean and have generally conferred benificial for crops growing under limited soil moisture in agricultural and natural systems (Ho *et al.,* 2005; Schenk and Jackson, 2005; Hund *et al.,* 2009; Lopes and Reynolds, 2010; Henry *et al.,* 2011).

2.4.6.3 Tissue and cellular level traits

Plant responds to environmental changes through short-term physiological regulation and long-term anatomical adjustment (Mencuccini, 2003). Traditionally, root conductivity has been considered as one of the main controlling factors of water flow in the plants (Jones, 1983). Variation in root anatomical traits were found to be associated with drought adaptation and tolerance mechanism in many crops (Passioura, 1972; Richards and Passioura, 1981a, b; Zhu *et al.,* 2010; Burton *et al.,* 2013; Jaramillo *et al.,* 2013; Comas *et al.,* 2013; Lynch *et al.,* 2014). As a consequence, there are number of anatomical traits were proposed by researcher for reducing the metabolic cost of soil exploration, water transport and penetration in hard soils such as living cortical area, root cortical aerenchyma, root

cortical senescence, cortical cell file number, cortex and stele ratio, xylem vessel diameter, xylem vessel number, cell wall suberization and lignification, rhizosheaths, root thickness, root hairs, etc (Richards and Passioura, 1981a, b; Passioura, 1983; Drew *et al.,* 1989; Przywara and Stepniewski, 2000; Bouranis *et al.,* 2003; Evans, 2003; Lynch and Brown, 2008; Zhu *et al.,* 2010; Comas *et al.,* 2013; Gea-Izquierdo et al., 2013; Lynch *et al.,* 2014). However, traits such as xylem vessel number and diameter were focused largely in comparison with other anatomical traits under drought prone conditions.

Developmental pattern of xylem vessel has been reported to be highly influenced by the growing environment (Gea-Izquierdo *et al.,* 2013). Decrease in xylem vessel diameter and hydraulic conductivity was induced by the DS (Lovisolo and Schubert, 1998). On the other hand, a negative effect of DS on xylem vessel size was hypothesized by Zimmermann and Milburn (1982). But there is no direct evidence of such negative effect had been published. The efficiency of the xylem vessels water transport system can significantly affect the water movement by imposing conductivity constraints (Tyree and Ewers, 1991) and possibly by the regulation of delivery to the leaves of root chemical signals (Davies and Zhang, 1991; Davies *et al.,* 1994; Jackson, 1997). Moreover, xylem conductivity is determined by the structure and size of the vessels (Schultz and Matthews, 1993; Tyree and Ewers, 1991). Variation in seminal root xylem vessel diameter was considered as an indicator for improving WUE of spring wheat and to increase the production level in Australia (Passioura, 1983;

Richards and Passioura, 1989). As a result, the breeding program narrowed the xylem vessel diameter of two Australian commercial wheat varieties from 65 µm to less than 55 µm. Therefore, reduction in root xylem vessel diameter and numbers can be a surrogate trait for enhanced WUE and were found to be useful in conserving soil water so that a crop may complete its life cycle under terminal DS condition (Passioura, 1983; Lovisolo and Schubert, 1998; Richards and Passioura, 1989; Lynch *et al.,* 2014).

3. MATERIALS AND METHODS

3.1 Experiment-1: Assesment of various traits in chickpea for terminal drought tolerance

3.1.1 Experimental site, design and soil type

The experiment was carried out in a Vertisol field (fine montmorillonitic isohyperthermic typic pallustert) during the postrainy season, in 2009-10 and 2010-11, at ICRISAT, Patancheru (17^{o} 30' N; 78^{o} 16' E; altitude 549 m) in peninsular India. The experiment was conducted in a randomized complete block design (RCBD) with three replications.

The water holding capacity of this field in lower limit: upper limit was 0.26:0.40 cm cm^{-1} for the 0-15 cm soil layer, and 0.30:0.47 cm cm^{-1} for the 105-120 cm soil layer. The available soil water up to 120 cm depth was 165 mm, and the bulk density was 1.35 g cm^{-3} for the 0-15 cm soil layer and 1.42 g cm^{-3} for the 105-120 cm soil layer (El-Swaify *et al.,* 1985).

3.1.2 Field preparation

At the start of summer (beginning of April) previous to the cropping season, the experimental field was ploughed and furrow irrigated. The whole field was covered with transparent polythene sheets of 400 gauge (94 g nr^{2} and 100 /urn thick) 2-3 days after irrigation with their edges tucked under soil all around to prevent air passage (Plate 1). This soil mulch was kept on the soil surface for 4 months (end of July) for effective soil solarization a process through which the *Fusarium* wilt causing pathogens are kept under control.

This also helps in weed control (Chauhan *et al.,* 1988). Later, the polythene sheets were removed from the field and the field was prepared in to broad bed and furrows with 1.2 m wide beds flanked by 0.3 m furrows. Surface application and incorporation of 18 kg *N* ha^{-1} and 20 kg *P* ha^{-1} as di-ammonium phosphate were carried out.

3.1.3 Plant material and crop management

Twelve chickpea genotypes viz., ICC 4958, ICC 8261, ICC 867, ICC 3325, ICC 14778, ICC 14799, ICC 1882, ICC 283, ICC 3776, ICC 7184, Annigeri, and ICCV 10 with close phenology but good contrasts for root development, drought response and CT were chosen for this study (Table 3.1). Seeds were treated with 0.5% Benlate® (E.I. DuPont India Ltd., Gurgaon, India) + Thiram® (Sudhama Chemicals Pvt. Ltd. Gujarat, India) mixture for both 2009-10 and 2010-11 seasons. The seeds were hand-sown manually at a depth of 2-3 cm maintaining a row to row distance of 30 cm and a plant to plant distance of 10 cm with in rows with a row length of 4 m on 31 October, 2009 and 20 November, 2010 (Plate 2). About 82 seeds were used for each 4 m row and at 10 days after sowing (DAS) the plants were thinned maintaining a plant-to-plant spacing of 10 cm. A 20 mm irrigation through sprinklers was applied immediately after sowing to ensure uniform seedling emergence. Subsequently, plants were grown under rainfed condition to impose terminal DS and irrigated once in 15 to 20 days under optimally irrigated (OI) condition. The plots were kept weed free by hand weeding and intensive protection were taken against pod borer (*Helicoverpa armigera*).

Plate 1: Experimental field covered with polythene mulch for soil solarization

Plate 2: Row and plant spacing of the chickpea field experiments

Table 3.1: The root, drought and canopy temperature reactions of the germplasm accessions and the checks (best adapted varieties) used in this study

S. No	Germplasm accession	Root strength at 35 days age	Drought reaction [4]	Canopy temperature [3]
1	ICC 4958	Large [2]	Moderately tolerant	Cool
2	ICC 8261	Large [2]	Moderately tolerant	
3	ICC 867		Highly tolerant	Cool
4	ICC 3325		Tolerant	Cool
5	ICC 14778		Highly tolerant	Cool
6	ICC 14799		Tolerant	Cool
7	ICC 1882	Small [2]	Tolerant	
8	ICC 283	Small [2]	Tolerant	
9	ICC 3776		Highly sensitive	Warm
10	ICC 7184		Highly sensitive	Warm
11	Annigeri		Tolerant, adapted variety	
12	ICCV 10	Large [1]	Wider adapted variety	

[1] Ali *et al.*, 2002b; [2] Kashiwagi *et al.,* 2005; [3] Kashiwagi *et al.,* 2008a; [4] Krishnamurthy *et al.,* 2010.

The plant material included in this study has consisted both germplasm accessions and released varieties. To make it simple to read, it will be hereafter mentioned as genotypes.

3.1.4 Weather conditions

The meteorological data recorded during the crop growing seasons such as rainfall, vapour pressure deficit (VPD), evaporation, temperature and relative humidity for 2009-10 and 2010-11 are presented in Table 3.2.

Table 3.2: Weather during the crop growing seasons (November to March) of 2009-10 and 2010-11

Year/ Standard week	Rainfall (mm)	Mean maximum VPD (kPa)	Evaporation (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Minimum relative humidity (%)	Maximum relative humidity (%)
2009-10							
44	0.0	2.9	40.1	30.9	16.7	83.0	32.4
45	0.8	1.6	28.7	28.8	21.4	87.1	58.0
46	25.4	1.7	28.5	30.1	21.9	93.6	59.3
47	18.0	1.7	20.2	28.7	17.1	93.6	55.9
48	0.0	2.3	26.3	28.2	12.6	92.1	38.0
49	0.0	2.4	23.4	28.7	13.5	97.7	38.4
50	0.0	2.3	26.2	28.5	14.1	97.1	40.1
51	0.0	1.9	26.7	28.0	15.1	91.7	47.7
52	7.4	2.0	29.2	26.9	13.5	90.8	41.5
1	0.0	2.2	26.0	28.3	12.7	84.6	40.1
2	39.0	1.6	20.8	27.3	17.5	92.0	54.7
3	0.0	2.0	23.5	27.6	13.7	91.3	45.9
4	0.0	2.4	28.4	27.5	13.0	86.1	33.1
5	0.0	2.6	35.1	28.8	14.0	82.7	32.4
6	0.0	2.9	39.4	30.3	15.1	86.1	29.6
7	1.6	3.6	45.6	32.9	17.4	89.9	26.3
8	1.4	3.4	39.0	33.9	19.1	88.1	34.4
9	0.0	4.2	47.9	35.3	18.3	74.9	25.1
10	0.0	4.2	55.5	36.2	20.2	74.7	28.3
2010-11							
44	44.1	1.3	14.7	27.0	19.7	94.7	65.4
45	12.3	1.2	17.4	28.0	19.8	95.1	68.4
46	3.3	1.6	20.8	29.3	20.7	95.6	60.6
47	0.0	1.7	21.6	29.6	19.4	95.4	58.1
48	0.0	2.1	27.0	29.3	16.5	96.9	47.4
49	9.0	1.5	24.8	26.5	17.7	89.3	57.7
50	3.5	1.6	20.9	27.6	15.2	93.0	55.0
51	0.0	2.5	24.8	27.0	7.5	95.9	29.1
52	0.0	2.2	24.3	27.4	11.6	95.8	37.6
1	0.0	1.8	22.5	27.0	11.7	94.6	48.6
2	0.0	2.6	26.9	27.8	7.4	96.0	27.1
3	0.0	2.9	30.0	29.9	11.4	93.1	30.7
4	0.0	2.5	34.0	29.6	11.6	96.7	38.9
5	0.0	2.8	37.7	30.3	13.5	92.3	32.1
6	0.0	3.3	38.6	31.0	12.4	87.7	25.3
7	0.0	3.2	41.8	31.1	14.4	85.1	28.9
8	0.4	2.6	32.5	31.2	18.9	88.4	42.1
9	0.0	2.7	40.3	31.2	19.1	84.7	40.0
10	0.2	4.2	54.9	35.5	17.8	74.6	26.3

VPD= Vapour pressure deficit

3.1.5 Periodical crop growth measurement

One meter long, two rows of chickpea plants were harvested from each plot periodically to comprehend the shoot biomass variation in each genotype. The plants components leaf, stem and reproductive parts were separated and dried in a hot-air oven at 70°C till there were no weight change and the leaf dry weight (LDW), stem dry weight (StDW) and the reproductive parts dry weight were recorded.

3.1.5.1 Specific leaf area (SLA)

The separated compound leaves were placed between two plastic transparent sheets and scanned and the scanned image was used to measure LA by using an image analysis system (WinRhizo, Regent Instruments INC., Quebec, Canada). The leaf samples were then oven-dried to measure leaf dry weight. The SLA was calculated using the following equation:

$$\text{Specific leaf area} = \frac{\text{Leaf area } (\text{cm}^2)}{\text{Leaf dry weight (g)}}$$

3.1.5.2 Leaf area index (LAI)

Total LA per square meter ground area was estimated using the leaf harvested from the sampled ground area (0.6 m^2). WinRhizo software was used to estimate the LA of the sample harvested. LAI was calculated using the following formula.

$$\text{Leaf area index} = \frac{\text{Leaf area } (\text{m}^2)}{\text{Ground area } (\text{m}^2)}$$

3.1.6 Root sample extraction and processing

Steel soil core tubes (50 mm in diameter) were used to collect soil sample up to 120 cm at regular time intervals. Each sample

comprised of two or three cores and all these cores were pooled depth-wise to increase the sample size. The extracted soil core was separated in to sub-cores of 15 cm each having 8 sub-cores out of 120 cm. The soil sample containing roots were soaked in water overnight, soil was mixed with tap water to form a suspension, and the roots were recovered by passing the soil-water suspension through a 2 mm wire mesh sieve. Chickpea roots were then separated from the organic debris and weed roots manually by floating the sample material on water in trays. Recovered roots were suspended in a transparent tray with 2-3 mm film of water for easy dispersion of roots and scanned using a scanner. Total RL of each sample was measured using the image analysis system (WinRhizo, Regent Instruments INC., Quebec, Canada) (Plate 3). The roots were kept for oven drying at 70°C for 72 h (to constant weight). RDW (g m^{-3}) was estimated for each depth or for total depth separately. RLD was as cm cm^{-3} of soil was estimated from the RL of the sub-core.

3.1.6.1 Root length density (RLD)

The total RL of extracted roots was obtained from WinRhizo software. The RLD was calculated by using the following formula.

$$\text{Root length density (cm cm}^{-3}) = \frac{\text{Length of roots (cm)}}{\text{Volume of soil core (cm}^3)}$$

The soil volume is calculated by following the mathematical expression:

Soil volume= $\pi.r^2.h$

π = 3.14; r = Soil core inner radius; h = Sub-core height

3.1.6.2 Root dry weight (RDW)

The weight of roots is measured after drying the roots in hot air oven at 70°C for 72 h.

3.1.7 Soil moisture measurement

The TRIME-tube system was used to measure the available soil moisture content in the field. TRIME access tube of a depth of 150 cm and inner diameter of 4.2 cm (0.1 cm wall-thickness) was installed in each plot. TRIME-FM (IMKO, Germany) (Plate 4) instrument connected with a cylindrical 18 cm long probe that can access the entire depth of access tube measures and directly converts measured transit-times in terms of soil water-contents displayed on its front-panel. These measurements were taken in both the irrigated and non-irrigated conditions. The amount of soil moisture (in volumetric terms) at each 15 cm depth interval was recorded up to 120 cm. There were six access tubes each under DS and OI conditions in which both TRIME TDR and the manual gravimetic soil moisture measurements were carried out separately for establishing soil depth wise calibration curves. The TDR soil moisture observations were corrected using the correction factor specific to soil depth and season. Moisture content of the surface soil (0-15 cm) was measured only through gravimetry. When required the soil water held in each soil horizon of 15 cm depth was summed up to 1.2 m.

Crop utilized soil water, from the root inhabited soil layers, was calculated as follows:

ASWS = (AWSS D_1 – LL) + (AWSS D_2 – LL) +... (AWSS D_n – LL) ---------- (1)

ASWS = Available soil water at sowing

ASWS D_1= Available soil water at sowing in soil depth 1 (0-15 cm)

ASWS D_2= Available soil water at sowing in soil depth 2 (15-30 cm)

ASWS D_n= Available soil water at sowing in soil depth n

LL = Lower limit for plant uptake

CUSW = (ASWS – $ASWBI_1$) + ($ASWAI_1$ – $ASWBI_2$) +... ($ASWAI_n$ – ASW_m) ---- (2)

CUSW = Crop utilized soil water (mm)

ASWS = Available soil water at sowing (mm)

$ASWBI_1$ = Available soil water before the first irrigation or rain

$ASWAI_1$ = Available soil water immediately after the first irrigation or rain

$ASWBI_2$ = Available soil water before the second irrigation or rain

$ASWAI_n$ = Available soil water before the n_{th} irrigation or rain

ASW_m = Available soil water at crop maturity

3.1.8 Canopy temperature measurement

The thermal images of plant canopies were captured at 63 DAS onwards, when all the genotypes reached the early to mid-podding stage under DS condition, by an infrared camera, IR FLEXCAM (Infrared Solutions, Inc, USA) (Plate 5) with a sensitivity of 0.09°C and an accuracy of ±2% between 1400 and 1445 h from a height of 1.0 m above the canopy. The target area of the image obtained was about 30 × 20 cm at the center of each plot, and the images were captured from north to avoid shading of the target area (Kashiwagi *et al.,* 2008a). The software SmartView 2.1.0.10 (Fluke Thermography Everett, WA, USA) was used for eliminating the ground area reflection and for analyzing the images and the estimation of CT (Plate 6) and canopy proportions

Plate 3: Scanned image of chickpea roots saved as .tif files used for image analysis. The root sample used here is harvested from cylinder culture

Plate 4: Soil moisture measurement using TRIME-FM TDR (Time-Domain Reflectometry) meter under field condition

Plate 5: Infrared camera, IR FLEXCAM, used for measuring the crop canopy temperature

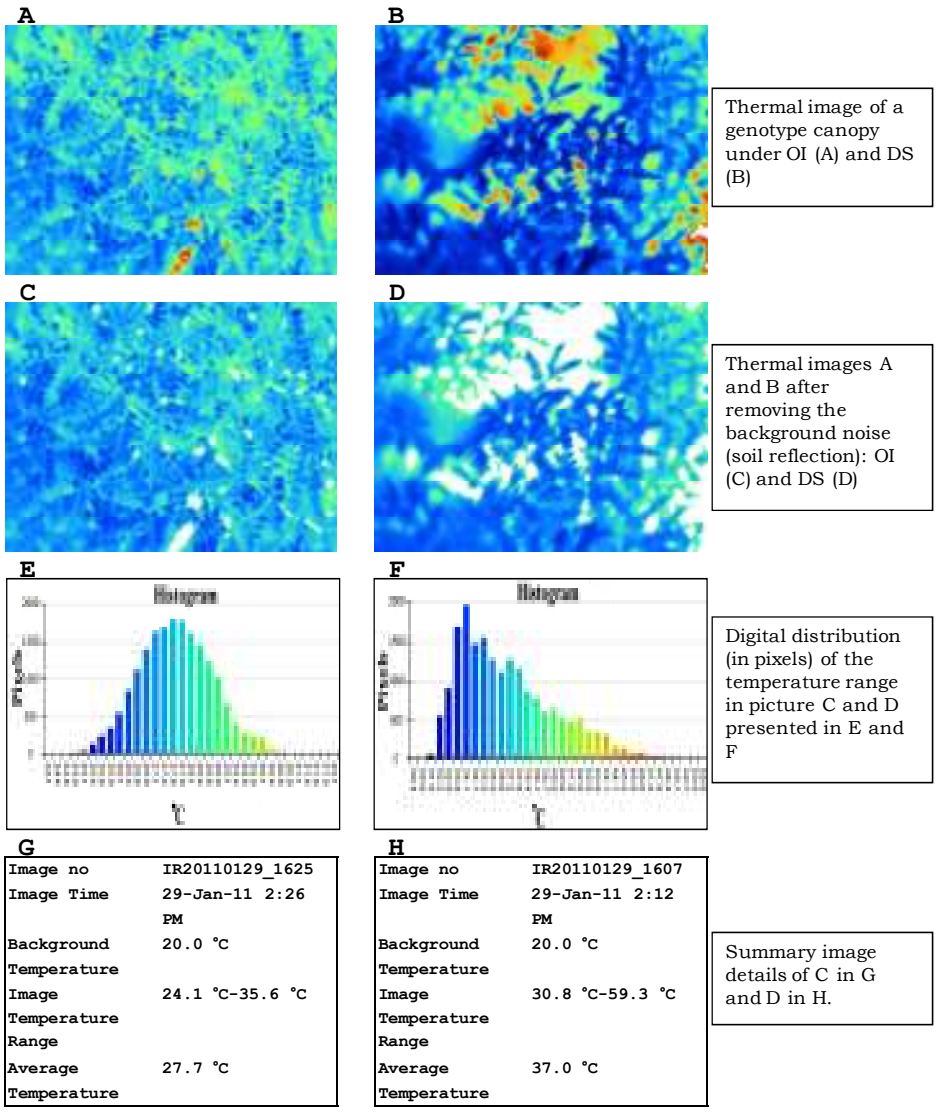

Plate 6: Thermal image of chickpea canopy and the soil background using SmartView 2.1.0.10 software (Fluke Thermography Everett, WA. USA).

following the previous report by Zaman-Allah *et al.* (2011b). Based on the mean CT recorded in any one frame the canopy temperature depression (CTD) was calculated.

3.1.8.1 Canopy temperature depression

CTD was calculated by the following formula.

$$CTD = T_a - T_c$$

T_a = air temperature (°C); T_c = canopy temperature (°C).

Under high ambient temperatures (often beyond 30°C) the CTD values can be increasingly negative under DS to indicate the inability of the canopy to maintain the required evaporative cooling.

3.1.9 Final harvest

After the physiological maturity, plant aerial parts (shoot – fallen pinnules) were harvested from an area of 3.6 m × 8 rows in each plot in both the year. Total shoot dry weights of the harvested sample were recorded after oven drying till constant weight at 45°C in draught air driers and the dry weights were recorded. This shoot weight was adjusted for an estimated 20% loss of dry matter as pinnule fall (Saxena, 1984; Williams and Saxena, 1991). Grain weights were recorded after threshing.

3.1.9.1 Days to 50% flowering

Number of days from sowing to the date when 50% of the plants in the plot had at least one open flower was recorded as days to 50% flowering.

3.1.9.2 Days to maturity

Number of days taken from sowing to the time when more than 80% of pods on the chickpea plant had turned from green to light yellow or brown (dry pod) were recorded as days to maturity.

3.1.9.3 Shoot biomass (kg ha^{-1})

The total weight of all the plant shoots harvested at ground level from the ear-marked net plot area and converted in to kg per ha.

3.1.9.4 Grain yield (kg ha^{-1})

The weight of total seed from all the plants harvested of the net plot area and converted in to kg per ha.

3.1.9.5 Harvest index (%)

The ratio in percent of the grain yield to shoot biomass yield was presented as HI.

3.1.9.6 Pod number m^{-2}

Total number of pods (both filled and unfilled) from one meter of two rows plants was counted and pod number m^{-2} was calculated as:

$$\text{Pod number m}^{-2} = \frac{\text{Total number of pods}}{\text{Harvested area (m}^2\text{)}}$$

3.1.9.7 Seed number m^{-2}

Total number of seeds from one meter of two rows plants was counted and seed number m^{-2} was calculated as:

$$\text{Seed number m}^{-2} = \frac{\text{Total number of seeds}}{\text{Harvested area (m}^2\text{)}}$$

3.1.9.8 Seed number pod^{-1}

Number of seeds per pod was calculated as:

$$\text{Seed number pod}^{-1} = \frac{\text{Total number of seeds per plant}}{\text{Total number of pods per plant}}$$

3.1.9.9 100-seed weight

The weight of 100-seed in gram was obtained by the following formula.

$$100 - \text{seed weight} = \frac{\text{Seed yield per plant (g)}}{\text{Total number of seeds per plant}} \times 100$$

3.1.9.10 Crop growth rate, reproductive duration and partitioning coefficient

The time taken for the crop pre-flowering and post-flowering periods was converted to thermal time using temperature observations in the meteorological observatory of ICRISAT Asia center. Base temperature (t_b) was taken to be 0°C (Williams and Saxena, 1991; Singh and Virmani, 1996) and the equation used for calculating thermal time (°Cd) was:

$$°\text{Cd} = \sum_{t=0}^{n} (\ldots - t_b) \frac{t_{max} + t_{min}}{2}$$

The crop growth rate (C) in kg ha^{-1}°Cd and p of each genotype were estimated using the equations:

$$C = (V + Y) / (Dv + Dr)$$

and $p = (Y / Dr) / C$

where: V = Vegetative shoot mass kg ha^{-1} (adjusted for pinnule fall)

Y = Grain weight kg ha^{-1}

Dr = Duration of growth after the start of 50% flowering °Cd

Dv = Duration of growth before the start of 50% flowering °Cd

3.1.10 Phenotypic data analyses

The data observed for all the traits at different stages in 2009-10and 2010-11 were subjected to statistical analysis.

3.1.10.1 Analysis of variance (ANOVA)

Simple one-way ANOVA, considering genotypes as treatments and replications as the blocking structures, was conducted using

GENSTAT (12th edition, Version–12.1.0.3278) to assess the differences among the genotypes. Significance of means was estimated through F value for each trait.

3.1.10.2 Correlation coefficient (r) and path coefficient analysis

The means derived from the ANOVA were used for correlations, regressions using GenStat software (12th edition) and path coefficient analysis using MINITAB® Release 14.1 software.

3.1.10.3 Heritability (h^2)

Heritability in broad sense was calculated as the ratio of genetic variance to the total phenotypic variance as suggested by Hanson *et al.* (1956) and expressed as percentage.

$$\text{Heritability in broad sense } (h^2) = \frac{\sigma^2_g}{\sigma^2_p} \times 100$$

Where,

σ^2_g = Genotypic variance

σ^2_p= Phenotypic variance

The qualitative descriptions of these ranges were made following Johnson *et al.* (1955) as follows:

Low - 0–30 percent

Medium - 31–60 percent

High - >61 percent

3.1.11 Genotypic data analyses

3.1.11.1 Assembling genotypic data

The molecular markers data were available only for 10 genotypes out of the 12 chickpea genotypes (ICC 4958, ICC 8261, ICC

867, ICC 3325, ICC 14778, ICC 14799, ICC 1882, ICC 283, ICC 3776 and ICC 7184) used in this study. This marker data was provided by Dr Rajeev Kumar Varshney and the detailed marker information is mentioned in Thudi *et al.* (2014). A total of 1926 markers which consist of 819 SNP, 1072 DArT and 35 SSR markers were used to understand the genetic diversity pattern across the 10 chickpea genotypes. Incase of SSR markers, the genotype ICC 4958 had the maximum per cent of missing data and this genotype was excluded from the marker diversity analysis.

3.1.11.2 Genetic diversity analysis

All the SNP, DArT and SSR markers were used to run basic statistics using PowerMarker version 3.25 (Liu and Muse, 2005) that included the number of alleles per locus, gene diversity, heterozygosity (%), polymorphic information content (PIC) and major allele frequency.

A UPGMA dendrogram was constructed based on the simple matching dissimilarity matrix of SNP markers implemented in DARwin 5.0.156 (Perrier and Jacquemoud-Collet, 2006) and MEGA 6.06 (Tamura *et al.,* 2013). A neighbour-joining tree was constructed based on the simple matching similarity matrix of DArT and SSR markers as implemented in NTSYSpc 2.02i (Rohlf, 1988).

3.2 Experiment-2: Assessing the relationship of canopy temperature depression with grain yield and its associated molecular markers in chickpea under terminal drought stress

3.2.1 Assembling genotyping data

The chickpea germplasm used in this study is a subset of the minicore collection (Upadhyaya *et al.,* 2008). The complete set of accessions of the minicore appears also in the reference collection. The reference collection is a marker-based subset. For establishing marker trait associations (MTAs), the available genotyping data on this set was taken and used from Varshney *et al.* (2013b) and that totaled 1849 marker data (35 SSRs, 1157 DArT loci, 657 SNPs and 113 gene-based SNPs).

3.2.1.1 Association analysis

Mixed linear model (MLM) with optimum compression and P3D in TASSEL 4.0 version was used for computing MTAs. Both population structure and kinship relationships among the germplasm lines were taken into consideration to avoid false positive MTAs. MTAs were considered to be significant when p=<0.001.

3.2.2 Plant material, experimental design and crop management

A subset of the minicore collection of chickpea germplasm (n= 84), consisting of all the highly tolerant (n=5), several tolerant (53 out of 78), none of the moderately tolerant (0 out of 74), a few of moderately sensitive (14 out of 39) and about half of the highly sensitive (12 out of 20) genotypes that were previously categorized based on their drought tolerance index (DTI) (Krishnamurthy *et al.,*

2010), were field-evaluated during the postrainy seasons of 2008-09, 2009-10 and 2010-11 on a Vertisol at ICRISAT-Patancheru in peninsular India.

The field preparation, fertilizers application and other crop management practices were the same as adopted for experiment-1. The trials were sown in an alpha lattice design with three replications on 31 October 2008, 31 October 2009, and 20 November 2010. About 61 seeds were used for each 4 m row and at 12 DAS the plants were thinned maintaining a plant-to-plant spacing of 10 cm. A 20 mm irrigation through sprinklers was applied immediately after sowing to ensure uniform seedling emergence. Subsequently, plants were grown under rainfed condition. Intensive protection against pod borer (*Helicoverpa armigera*) and weeds was provided.

3.2.3 Canopy temperature measurement

The thermal images of plant canopies were recorded using an infrared camera, IR FLEXCAM (Infrared Solutions, Inc, USA) with a sensor size of 160 × 120 pixels, sensitivity of 0.09°C and an accuracy of ±2%. The target area of the image obtained was about 30 × 20 cm at one of the central row of each plot, and the images were captured from north to avoid shading of the target area (Kashiwagi *et al.,* 2008a). The software SmartView 2.1.0.10 (Fluke Thermography), was used for the image analysis and the estimation of CT after removing the soil (background) emissions (Zaman-Allah *et al.,* 2011b). The camera was strapped on shoulder at a height of 1.0 m and the observations were recorded between 1400 and 1530 h. Based on the mean CT recorded

in any one frame the canopy temperature depression (CTD) was calculated using the formula mentioned in 3.1.8.1.

3.2.4 Soil moisture measurements

In all the years, neutron moisture meter access tubes were installed in four spots planted with two drought tolerant (ICC 867 and ICC 14778) and two drought sensitive genotypes (ICC 6263 and ICC 8058) (Krishnamurthy *et al.,* 2010) in an adjacent broad bed in each replication and treatment. Neutron moisture meter (Depth Moisture Gauge, Model 3332, Troxler Electronic Laboratories Inc., NC., USA) readings at soil depths of 15 cm increments up to a depth of 120 cm were made before and after each irrigation as well as matching it at about 10 day intervals. The troxler soil moisture observations were corrected with a calibration curve developed for each depth separately using the data collected gravimetrically across the season. Moisture content of the surface soil (0-15 cm) was measured only gravimetrically. The water held in each soil horizon of 15 cm depth was summed up to 1.2 m.

3.2.5 Final harvest

After the physiological maturity, plant aerial parts (shoot – fallen pinnules) were harvested at ground level from an area of (3.6 × 1.5) 5.4 m^2 with care to eliminate border effects in each plot. Total shoot dry weights of the harvested sample were recorded after oven drying till constant weight at 45°C in draught air driers and the dry weights were recorded. This shoot weight was adjusted for an estimated 20%

loss of dry matter as pinnule fall (Saxena, 1984; Williams and Saxena, 1991). Grain weights were recorded after threshing.

3.2.5.1 Days to 50% flowering

Number of days from sowing to the date when 50% of the plants in the plot had at least one open flower was recorded as days to 50% flowering.

3.2.5.2 Days to maturity

Number of days taken from sowing to the time when more than 80% of pods on the chickpea plant had turned from green to light yellow or brown (dry pod) were recorded as days to maturity.

3.2.5.3 Shoot biomass (kg ha^{-1})

The total weight of all the plant shoots harvested at ground level from the ear-marked net plot area and converted in to kg per ha.

3.2.5.4 Grain yield (kg ha^{-1})

The weight of total seed from all the plants harvested of the net plot area and converted in to kg per ha.

3.2.5.5 Harvest index (%)

The ratio in percent of the grain yield to shoot biomass yield was presented as HI.

3.2.6 Phenotypic data analyses

The data observed for all the traits at different stages in 2008-09, 2009-10 and 2010-11 were subjected to statistical analysis.

3.2.6.1 Analysis of variance (ANOVA)

Simple one-way ANOVA, considering genotypes as treatments and replications as the blocking structures, was conducted using

GENSTAT (12th edition, Version–12.1.0.3278) to assess the differences among the genotypes. Significance of means was estimated through F value for each trait. Variance components due to genotypes (σ^2_g) and error (σ^2_e) and their standard errors were determined.

3.2.6.2 Correlation coefficient (r)

The means derived from the ANOVA were used for correlations, regressions using GenStat software (12th edition).

3.2.6.3 Pooled and cluster analysis

For the pooled analysis, homogeneity of variance was tested using Bartlett's test (Bartlett, 1937). Here, the year (environment) was treated as a fixed effect and the genotype (G) × environment (E) interaction as random. The variance due to (G) (σ^2_g) and (G) × (E) interaction (σ^2_{gE}) and their standard error were determined. The significance of the fixed effect of the year was assessed using the Wald statistic that asymptotically follows a x^2 distribution**.** The genotypes were grouped into representative groups using the means of CTDs by a hierarchical cluster analysis (using Ward's incremental sum of squares method) for characterizing them as low or high CTD genotypes.

3.2.6.4 Heritability (h^2)

Heritability in broad sense was calculated using the formula as previously mentioned in this thesis at the materials and methods of experiment-1, paragraph number-3.1.10.3**.**

3.3 Experiment-3: Assessing the root anatomy of chickpea in comparison to other grain legumes and between types of chickpea to understand their drought adaptation

3.3.1 Plant material and experimental design

3.3.1.1 Experiment-3a

Six major legumes and pearl millet, a cereal crop adapted to semi-arid environments, were tested for variation in their root anatomy in relation to their level of drought tolerance. Genotypes Annigeri (chickpea), ICPL 87119 (pigeonpea), TAG 24 (groundnut), Suvita (cowpea), JS 9305 (soybean), Topcrop (common bean) and ICMV 155 (pearl millet), were sown on 1 July, 2010 in a Vertisol field at ICRISAT, Patancheru. Each crop species was planted in a 3 m long row and in 2 such rows in 30 × 20 cm spacing. Four crops (adjacent to one another) on one side and three more on the other with no borders were planted.

3.3.1.2 Experiment-3b

Three genotypes of *desi* type [ICCV 10, ICCC 37 and JG 11] and three genotypes of kabuli type [ICCV 2, JGK 1 and KAK 2] plants were assessed for variation of their root anatomy in relation to their level of drought tolerance. This trial was sown on 29 October, 2010 on a Vertisol at ICRISAT, Patancheru, in peninsular India. The fields were prepared into broad bed and furrows with 1.2 m wide beds flanked by 0.3 m furrows for all the experiments. The experiments were conducted in a RCBD with four replications with the plot size of 4.0 m × 4 rows under rainfed condition.

3.3.2 Crop management

Seeds were treated with fungicide mixture before planting and the plots were kept insect pest and weed free until the roots were harvested.

3.3.3 Root sampling and root sectioning

Roots were harvested at 35 DAS in experiment-3a, and at mid pod filling stage in experiment-3b. A 2 cm long piece of the tap root, 10 ± 2 cm above the root tip and where the secondary thickening is expected to be complete, was collected from each crop species and kept in distilled water after washing them. Free-hand sections of about 50 µm thick were cut and the selected sections were stained with 50% toludine blue, a polychromatic stain that gives different colors with different tissues, and mounted in distilled water. For each genotype, ten uniform sections were selected at random for observation. The root section images were taken using an optical microscope (Olympus BX43F, Tokyo, Japan) connected to a digital camera, and the following measurement were performed using image analysis software (Q-Capture pro-7); (i) thickness of the whole root (ii) thickness of cortex and stele, (iii) diameter of the xylem vessels. It was difficult to identify the metaxylem vessels from the protoxylem, therefore all the xylem vessels were grouped into two groups 1. large metaxylem vessels and 2. small vessels (protoxylem vessels and small metaxylem vessels). The collected data were used to compute the percentage of large metaxylem vessels in roots (ratio between the area occupied by the large metaxylem and total cross sectional area).

4. RESULTS

4.1 Experiment-1: Assessment of various traits in chickpea for terminal drought tolerance

4.1.1 Performance of physiological traits and soil water use across growth stages

4.1.1.1Performance of shoot traits across growth stages both under drought stressed and optimally irrigated conditions

4.1.1.1.1 Shoot growth at 28 days after sowing in 2009-10 and 24 days after sowing in 2010-11

As the first irrigation was given at 38 DAS in 2009-10 and 30 DAS in 2010-11, the irrigation effects were not expected prior to these days. The first sample for shoot growth measurement was carried out on 28 DAS in 2009-10 and 24 DAS on 2010-11. Therefore in this sample existence of any differences in shoot growth between the DS and OI treatments needs to be treated as a sampling error. Growth stage 28 or 24 DAS is a stage when the peak vegetative growth starts. At this stage a shoot biomass productivity of 20.4 to 21.5 g m^{-2} in 2009-10 and 11.0 to 10.3 g m^{-2} was noted in genotype ICC 4958 remaining as the top shoot biomass producing genotype followed by ICC 8261 and Annigeri at this early growth stage (Table 4.1a and 4.1b). Genotypes ICC 867, ICC 3325, ICC 3776 and ICCV 10 in 2009-10, and additionally ICC 14799 and ICC 283 in 2010-11, produced moderate levels of shoot biomass. Genotypes ICC 14778, ICC 14799 and ICC 7184 were consistently poor in biomass production across years. At this stage, the stem and leaf constituted the shoot and

Table 4.1a: Shoot growth of 12 diverse genotypes of chickpea at 28 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Leaf weight ($g\ m^{-2}$)	Stem weight ($g\ m^{-2}$)	Reproductive parts weight ($g\ m^{-2}$)	Total shoot biomass ($g\ m^{-2}$)	SLA ($cm^2\ g^{-1}$)	LAI
Drought stressed						
ICC 4958	14.00	6.39	0.00	20.4	187.0	0.350
ICC 8261	9.37	5.17	0.00	14.5	171.8	0.216
ICC 867	9.21	4.03	0.00	13.2	224.0	0.274
ICC 3325	8.71	4.32	0.00	13.0	209.3	0.246
ICC 14778	5.78	2.49	0.00	8.3	206.7	0.160
ICC 14799	7.44	3.00	0.00	10.4	204.7	0.204
ICC 1882	6.30	2.45	0.00	8.8	194.0	0.163
ICC 283	7.24	3.33	0.00	10.6	191.4	0.189
ICC 3776	7.45	3.65	0.00	11.1	199.3	0.199
ICC 7184	6.29	4.07	0.00	10.4	217.7	0.193
Annigeri	10.07	4.69	0.00	14.8	199.7	0.268
ICCV 10	9.21	3.56	0.00	12.8	180.1	0.222
Mean	8.42	3.93	0.00	12.4	198.8	0.224
S.Ed (±)	1.06	0.511	0.00	1.43	20.1	0.038
Optimally irrigated						
ICC 4958	13.91	7.59	0.00	21.5	207.7	0.389
ICC 8261	12.55	6.87	0.00	19.4	181.0	0.303
ICC 867	8.38	4.00	0.00	12.4	212.2	0.238
ICC 3325	9.53	4.51	0.00	14.0	209.3	0.267
ICC 14778	7.06	3.34	0.00	10.4	195.8	0.185
ICC 14799	8.37	3.27	0.00	11.6	216.3	0.241
ICC 1882	6.23	3.15	0.00	9.4	195.7	0.162
ICC 283	7.87	3.84	0.00	11.7	182.4	0.191
ICC 3776	8.94	5.12	0.00	14.1	187.8	0.224
ICC 7184	7.58	4.63	0.00	12.2	184.2	0.186
Annigeri	10.83	5.55	0.00	16.4	181.6	0.264
ICCV 10	8.56	3.71	0.00	12.3	191.1	0.221
Mean	9.15	4.63	0.00	13.8	195.4	0.239
S.Ed (±)	0.861	0.621	0.00	1.36	15.3	0.037

SLA= Specific leaf area; LAI= Leaf area index

Table 4.1b: Shoot growth of 12 diverse genotypes of chickpea at 24 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})	SLA (cm^2 g^{-1})	LAI
Drought stressed						
ICC 4958	7.00	4.00	0.00	11.00	199.6	0.186
ICC 8261	7.39	4.57	0.00	11.96	196.4	0.193
ICC 867	4.15	2.57	0.00	6.71	236.0	0.131
ICC 3325	3.58	2.05	0.00	5.62	210.4	0.101
ICC 14778	3.67	1.92	0.00	5.59	210.6	0.103
ICC 14799	4.02	2.16	0.00	6.18	210.3	0.112
ICC 1882	4.93	2.60	0.00	7.53	206.4	0.136
ICC 283	4.22	2.28	0.00	6.50	202.8	0.114
ICC 3776	3.79	2.58	0.00	6.38	181.0	0.092
ICC 7184	3.45	2.45	0.00	5.91	198.1	0.091
Annigeri	5.57	3.47	0.00	9.04	190.2	0.141
ICCV 10	4.34	2.44	0.00	6.78	200.1	0.116
Mean	4.68	2.76	0.00	7.43	203.5	0.126
S.Ed (±)	0.477	0.304	0.00	0.670	7.50	0.014
Optimally irrigated						
ICC 4958	6.35	3.97	0.00	10.33	231.4	0.197
ICC 8261	6.51	4.11	0.00	10.61	199.6	0.173
ICC 867	3.63	2.23	0.00	5.87	253.7	0.122
ICC 3325	4.31	2.39	0.00	6.69	239.2	0.138
ICC 14778	3.61	2.08	0.00	5.69	261.4	0.128
ICC 14799	3.28	2.24	0.00	5.52	243.6	0.106
ICC 1882	4.73	2.60	0.00	7.33	214.6	0.136
ICC 283	3.83	2.13	0.00	5.97	232.4	0.118
ICC 3776	3.97	2.29	0.00	6.26	207.6	0.110
ICC 7184	3.39	2.17	0.00	5.57	209.7	0.095
Annigeri	4.56	3.00	0.00	7.56	220.7	0.134
ICCV 10	4.15	2.35	0.00	6.51	202.8	0.112
Mean	4.36	2.63	0.00	6.99	226.4	0.131
S.Ed (±)	0.48	0.23	0.00	0.61	11.52	0.017

SLA= Specific leaf area; LAI= Leaf area index

their biomass very closely and positively related with total shoot. The proportion of leaf ranged from 58 to 72% of the shoot and that of stem from 28 to 42% at this stage across genotypes. The leaf weight was high in genotypes ICC 4958, ICC 8261 and Annigeri across both the environments and years. The leaf weight was low in genotypes ICC 14778, ICC 1882 and ICC 7184 and was moderate in rest of the six genotypes. The leaf area indices ranged from 0.16 to 0.39 in 2009-10 and from 0.10 to 0.20 in 2009-10. The genotype distribution for LAI followed similar pattern as that of the total shoot biomass distribution confirming ICC 4958, ICC 8261 and Annigeri remaining as the top LAI producing genotypes at this early stage. The genotypes varied consistently for the SLA. In both the stress treatments and years, with a few exceptions, the drought tolerant genotypes ICC 867, ICC 3325, ICC 14778 and 14799 produced very high SLA compared to ICC 8261 and ICC 3776. Genotype ICC 7184 under DS environment in 2009-10 and ICC 283 in OI treatment in 2010-11 also showed high SLA. The best adapted genotypes Annigeri and ICCV 10 had an average SLA.

4.1.1.1.2 Shoot growth at 37 days in 2010-11

The sample at this stage was taken only in 2010-11 and the first irrigation was given at 30 DAS, and therefore the irrigation treatment differences were 7 days old. Growth stage 37 DAS is a stage when genotypes ICC 4958 and Annigeri had already flowered and the rest of genotypes yet to flower over a period of 15 more days under DS treatment. At this stage a shoot biomass productivity of ICC 4958, ICC 8261 and Annigeri under DS condition and ICC 4958, ICC 8261 and

ICC 1882 under OI condition were significantly greater than that of the mean (Table 4.1c). Genotypes ICC 3325, ICC 14778 and ICC 14799 under DS condition and ICC 867 and ICC 7184 under OI condition produced poor shoot biomass. Rest of the genotypes produced moderate shoot biomass. Also at this stage, the stem and leaf constituted the shoot and their biomass very closely and positively related with total shoot. The proportion of leaf ranged from 62 to 70% of the shoot and that of stem from 30 to 39% at this stage across genotypes. The leaf weight was high in genotypes ICC 4958, ICC 8261, and Annigeri in the DS treatment and ICC 4958, ICC 8261, and ICC 1882 in the irrigated treatment. The leaf weight was low in genotypes ICC 3325, ICC 14778 and ICC 114799 under DS condition and in ICC 7184 under OI condition. The leaf weight of the rest of the genotypes was moderate. The leaf area indices ranged from 0.32 to 0.76 under DS condition whereas it ranged from 0.28 to 0.66 under OI condition. The genotype distribution for LAI followed similar pattern as that of the total shoot biomass distribution confirming ICC 4958 and ICC 8261 producing significantly greater LAI while ICC 3776 and ICC 7184 producing significantly smaller LAI than the mean under both irrigation environments. The genotypes varied consistently for the SLA. Genotype ICC 867 under DS condition and ICC 14799 under OI condition produced significantly greater SLA than the means. In both the irrigation treatments and years, with one exception the drought tolerant genotypes ICC 867, ICC 3325, ICC 14778 and ICC 14799

Table 4.1c: Shoot growth of 12 diverse genotypes of chickpea at 37 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})	SLA (cm^2 g^{-1})	LAI
Drought stressed						
ICC 4958	32.1	14.4	0.217	46.7	178.3	0.762
ICC 8261	21.9	11.1	0.000	33.0	167.2	0.486
ICC 867	17.1	7.8	0.000	24.9	193.1	0.439
ICC 3325	14.7	7.1	0.000	21.8	172.7	0.340
ICC 14778	14.8	7.6	0.000	22.4	176.5	0.350
ICC 14799	13.7	7.2	0.000	20.9	187.8	0.341
ICC 1882	17.1	7.9	0.000	25.0	163.4	0.370
ICC 283	15.3	7.5	0.010	22.8	177.2	0.362
ICC 3776	15.0	8.4	0.000	23.4	158.3	0.315
ICC 7184	15.1	8.6	0.000	23.8	159.3	0.328
Annigeri	19.4	10.6	0.143	30.1	171.3	0.442
ICCV 10	17.0	7.7	0.000	24.7	164.1	0.373
Mean	17.8	8.82	0.030	26.6	172.4	0.409
S.Ed (±)	1.61	1.00	0.060	2.30	10.8	0.041
Optimally irrigated						
ICC 4958	24.5	15.29	0.00	39.7	202.1	0.661
ICC 8261	23.8	12.62	0.00	36.4	187.2	0.589
ICC 867	15.1	6.81	0.00	21.9	213.4	0.438
ICC 3325	17.4	7.45	0.00	24.8	215.5	0.498
ICC 14778	16.8	8.53	0.00	25.3	214.5	0.481
ICC 14799	16.2	8.06	0.00	24.3	239.6	0.518
ICC 1882	20.6	10.32	0.00	30.9	209.1	0.572
ICC 283	15.5	8.64	0.00	24.1	202.7	0.422
ICC 3776	15.9	8.76	0.00	24.6	172.6	0.363
ICC 7184	10.6	6.45	0.00	17.1	193.6	0.277
Annigeri	18.5	9.28	0.00	27.8	201.6	0.508
ICCV 10	15.8	7.23	0.00	23.0	198.9	0.423
Mean	17.5	9.12	0.00	26.7	204.2	0.479
S.Ed (±)	1.42	0.91	0.00	2.10	15.2	0.061

SLA= Specific leaf area; LAI= Leaf area index

tend to produce larger SLA that was significantly greater than that of the smallest SLA genotype ICC 3776. The best adapted genotypes Annigeri and ICCV 10 had an average SLA comparable to the mean.

4.1.1.1.3 Shoot growth at 51 days after sowing in 2009-10 and 48 days after sowing in 2010-11

Growth stage 51 days in 2009-10 and 48 days in 2010-11 under DS environment represents the peak flowering to early pod fill stage of growth. Under DS condition at this stage the shoot biomass produced by ICC 4958 and ICC 8261 continued to be greater than the mean biomass of that year (Table 4.1d and 4.1e). Genotypes ICC 867, Annigeri and ICCV10 produced significantly greater shoot biomass than the lowest genotype at least in one year. Genotypes ICC 14778 and ICC 14799 produced the least biomass in 2009-10 and ICC 3325 and ICC 7184 in 2010-11. Under OI condition, ICC 4958 and ICC 8261 produced greater shoot biomass than the mean in both the years and also genotypes ICC 3776 and ICCV 10 produced significantly greater shoot biomass than the mean only in 2009-10. Genotypes ICC 14778 and ICC 7184 in both the years, ICC 867 and ICC 1882 in 2009-10 and ICCV 10 in 2010-11 produced significantly lower shoot biomass under OI condition. Rest of the genotypes produced moderate levels of shoot biomass. Also at this stage, the stem and leaf constituted the shoot and their biomass very closely and positively was related with total shoot though there were reproductive components weights started appearing in genotypes ICC 4958 and

Table 4.1d: Shoot growth of 12 diverse genotypes of chickpea at 51 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Leaf weight ($g\ m^{-2}$)	Stem weight ($g\ m^{-2}$)	Reproductive parts weight ($g\ m^{-2}$)	Total shoot biomass ($g\ m^{-2}$)	SLA ($cm^2\ g^{-1}$)	LAI
Drought stressed						
ICC 4958	95.5	52.7	12.19	160.4	162.8	2.08
ICC 8261	88.4	52.2	1.00	141.7	143.7	1.71
ICC 867	80.4	48.0	3.80	132.3	194.4	2.10
ICC 3325	81.7	42.0	1.16	124.9	175.2	1.92
ICC 14778	49.4	34.5	0.05	84.0	164.9	1.10
ICC 14799	53.9	34.7	0.78	89.4	180.3	1.29
ICC 1882	66.5	43.6	4.77	114.9	165.8	1.53
ICC 283	74.2	45.7	5.07	125.0	151.3	1.52
ICC 3776	74.7	58.2	1.00	133.9	172.3	1.70
ICC 7184	61.3	65.1	1.32	127.7	180.9	1.50
Annigeri	84.9	54.8	10.76	150.5	170.7	1.94
ICCV 10	78.6	45.8	2.67	127.1	147.5	1.54
Mean	74.1	48.1	3.72	126.0	167.5	1.66
S.Ed (±)	4.81	4.25	1.14	9.18	19.2	0.235
Optimally irrigated						
ICC 4958	126.8	92.8	0.697	220.3	222.1	3.79
ICC 8261	111.7	77.1	0.227	189.0	190.3	2.86
ICC 867	68.9	52.8	1.453	123.2	196.2	1.80
ICC 3325	103.6	70.3	0.443	174.3	228.0	3.14
ICC 14778	82.0	51.9	0.007	134.0	182.6	2.00
ICC 14799	71.7	93.5	0.327	165.5	238.8	2.28
ICC 1882	71.9	57.1	0.220	129.3	210.4	2.06
ICC 283	83.2	70.4	1.260	154.8	170.8	1.91
ICC 3776	109.7	82.5	0.100	192.3	166.8	2.44
ICC 7184	64.6	72.9	0.300	137.8	176.5	1.52
Annigeri	91.8	72.9	0.267	164.9	179.7	2.20
ICCV 10	113.2	79.8	0.833	193.9	214.6	3.20
Mean	91.6	72.8	0.511	164.9	198.1	2.43
S.Ed (±)	5.71	6.07	0.368	11.1	36.2	0.520

SLA= Specific leaf area; LAI= Leaf area index

Table 4.1e: Shoot growth of 12 diverse genotypes of chickpea at 48 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})	SLA (cm^2 g^{-1})	LAI
Drought stressed						
ICC 4958	42.9	24.9	1.72	69.5	173.0	0.988
ICC 8261	42.5	25.3	0.00	67.8	161.9	0.918
ICC 867	35.8	17.2	0.07	53.0	204.2	0.970
ICC 3325	28.5	15.2	0.01	43.6	175.4	0.665
ICC 14778	32.5	17.0	0.00	49.5	168.6	0.734
ICC 14799	33.1	17.1	0.00	50.2	184.0	0.815
ICC 1882	30.4	16.9	0.07	47.3	170.3	0.696
ICC 283	31.2	18.5	0.20	49.9	160.0	0.661
ICC 3776	30.3	18.9	0.00	49.2	155.6	0.628
ICC 7184	26.0	19.2	0.01	45.3	164.6	0.572
Annigeri	31.1	18.8	0.39	50.3	162.4	0.672
ICCV 10	38.5	19.6	0.16	58.3	163.6	0.840
Mean	33.6	19.1	0.22	52.8	170.3	0.763
S.Ed (±)	2.62	1.89	0.22	4.31	11.4	0.075
Optimally irrigated						
ICC 4958	49.8	35.6	0.02	85.4	246.8	1.63
ICC 8261	46.8	28.3	0.00	75.1	209.4	1.31
ICC 867	37.0	21.2	0.00	58.2	233.0	1.14
ICC 3325	32.9	21.6	0.00	54.5	259.3	1.16
ICC 14778	28.0	18.7	0.00	46.7	244.0	0.91
ICC 14799	34.1	22.6	0.00	56.7	268.8	1.22
ICC 1882	34.9	20.1	0.00	55.0	227.3	1.05
ICC 283	36.1	23.0	0.00	59.1	212.1	1.03
ICC 3776	28.2	22.5	0.00	50.6	185.9	0.71
ICC 7184	30.2	18.6	0.00	48.8	201.1	0.81
Annigeri	37.5	25.5	0.03	63.0	217.3	1.10
ICCV 10	29.6	17.8	0.00	47.5	223.2	0.88
Mean	35.4	23.0	0.00	58.4	227.4	1.08
S.Ed (±)	3.13	3.45	0.015	5.71	26.6	0.180

SLA= Specific leaf area; LAI= Leaf area index

Annigeri under DS condition in 2009-10. The proportion of leaf ranged from 48 to 65% in 2009-10 and from 57 to 68% in 2010-11 of the shoot under DS condition and from 43 to 61% in 2009-10 and from 56 to 64% in 2010-11 of the shoot under OI condition. Genotype ICC 7184 recorded lowest leaf proportion under DS condition while the lowest proportion was in ICC 7184 in 2009-10 and ICC 3776 in 2010-11 under OI condition. Overall, with few exceptions, the four drought tolerant genotypes and ICCV 10 maintained a higher leaf proportion under DS environment. Except for ICC 4958 and Annigeri, the stem was in inverse proportion to the leaf. The leaf area indices ranged from 1.10 to 2.08 in 2009-10 and from 0.57 to 1.00 in 2010-11. The genotypes ICC 4958 and ICC 867 produced the higher LAI compared to the mean under DS condition in both the years. Under DS condition, the genotypes that produced significantly higher LAI than the poor genotypes were ICC 8261, ICC 3325, ICC 3776, Annigeri and ICCV 10 in 2009-10 and ICC 14778, ICC 14799 and ICCV 10 in 2010-11. The LAI of ICC 14778 and ICC 14799 in 2009-10 and ICC 3776 and ICC 7184 in 2010-11 were low compared to the mean. Under OI condition, a single genotype that produced the highest LAI was ICC 4958. Genotypes ICC 8261, ICC 3325, ICC 3776 and ICCV 10 in 2009-10 and ICC 8261, ICC 3325 and ICC 14799 in 2010-11 produced LAI close to the mean. The LAI of ICC 7184 in 2009-10 and ICC 3776 in 2010-11 were low compared to the mean. Mean SLA under OI environment was significantly higher than the DS environment indicating that the DS limits leaf expansion. The

genotypes varied for the SLA under both DS and OI environment in both the years. Under DS environment ICC 867 and ICC 7184 in 2009-10 and ICC 867 and ICC 14799 in 2010-11 had larger SLA while ICC 8261 and ICCV 10 in 2009-10 and ICC 867 and ICC 14799 in 2010-11 had smaller SLA. Under OI environment, ICC 3325 and ICC 14799 in both years had larger SLA while ICC 283 and ICC 3776 in 2009-10 and ICC 3776 and ICC 7184 in 2010-11 had smaller SLA. The best adapted genotypes Annigeri and ICCV 10 had an average SLA.

4.1.1.1.4 Shoot growth at 58 days after sowing in 2010-11

Growth stage 58 days in 2010-11 represents the early and mid podfill stages of various genotypes under DS environment. Under DS condition at this stage the shoot biomass produced by ICC 4958, ICC 8261 and ICCV 10 continued to be greater than the mean biomass of that year (Table 4.1f). Genotypes ICC 867, ICC 3325, ICC 14778, ICC 1882, ICC 283, ICC 3776 and Annigeri produced comparable shoot biomass to the mean whereas it was significantly greater shoot biomass than the lowest genotype ICC 7184. Genotypes ICC 14799 and ICC 7184 produced the least biomass. Under OI condition, all the drought tolerant genotypes (ICC 867, ICC 3325, ICC 14778 and ICC 14799) produced greater shoot biomass than the three genotypes ICC 283, ICC 3776 and ICC 7184 that produced lower biomass than the rest of the genotypes tested. Considerable genotypic variation in reproductive parts biomass had appeared at this stage. Though less compact, the stem and leaf components had continued to be in close

Table 4.1f: Shoot growth of 12 diverse genotypes of chickpea at 58 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})	SLA (cm^2 g^{-1})	LAI
Drought stressed						
ICC 4958	65.5	40.5	11.93	118.0	163.4	1.43
ICC 8261	68.8	40.1	0.70	109.6	173.4	1.59
ICC 867	54.5	30.3	2.09	86.9	210.4	1.52
ICC 3325	53.1	30.5	1.07	84.7	187.9	1.33
ICC 14778	52.6	29.1	0.57	82.2	185.8	1.31
ICC 14799	48.4	29.4	0.66	78.5	186.6	1.20
ICC 1882	66.4	36.5	3.65	106.6	176.8	1.56
ICC 283	53.0	34.4	5.52	92.9	173.3	1.23
ICC 3776	51.8	33.8	1.13	86.8	167.0	1.16
ICC 7184	37.0	30.0	0.84	67.8	169.1	0.83
Annigeri	60.0	33.0	9.16	102.2	177.2	1.42
ICCV 10	74.6	37.7	4.90	117.2	165.3	1.64
Mean	57.1	33.8	3.52	94.5	178.0	1.35
S.Ed (±)	4.15	2.88	1.23	7.03	10.8	0.110
Optimally irrigated						
ICC 4958	72.7	56.3	6.35	135.4	236.3	2.27
ICC 8261	81.7	55.2	0.94	137.8	219.4	2.39
ICC 867	62.2	39.8	3.26	105.2	253.4	2.09
ICC 3325	73.0	48.8	1.75	123.6	282.5	2.77
ICC 14778	68.5	46.2	1.12	115.9	257.2	2.35
ICC 14799	66.6	34.7	1.02	102.3	252.3	2.24
ICC 1882	81.1	52.0	3.35	136.5	235.7	2.54
ICC 283	62.0	48.3	3.36	113.6	220.4	1.83
ICC 3776	64.8	53.3	0.86	119.0	212.5	1.82
ICC 7184	56.6	32.1	0.82	89.5	214.3	1.63
Annigeri	73.2	55.5	4.40	133.1	234.0	2.27
ICCV 10	76.6	45.1	3.27	125.0	229.0	2.33
Mean	69.9	47.3	2.54	119.7	237.2	2.21
S.Ed (±)	6.20	6.36	0.473	11.0	17.9	0.245

SLA= Specific leaf area; LAI= Leaf area index

proportion to the shoot biomass even at this stage. Under DS condition, the leaf biomass of ICC 4958, ICC 8261, ICC 1882 and ICCV 10 were greater than that of the mean while that of ICC 14799 and ICC 7184 were smaller than the mean. The leaf weight of remaining six genotypes were close the mean. Similarly under OI condition, the leaf biomass of ICC 8261 and ICC 1882 were greater than that of the mean while that of ICC 7184 were smaller than the mean. The leaf weight of remaining nine genotypes were close the mean. Under DS condition, the stem biomass produced by ICC 4958 and ICC 8261 were greater than that of the mean. None of the genotypes produced significantly lower stem biomass. However the stem biomass of all the drought tolerant genotypes was lower than that of ICC 4958 and ICC 8261 while that of Annigeri and ICCV 10 were moderate in nature. Under OI condition, the stem biomass of genotypes of ICC 14799 and ICC 7184 were smaller than that of the mean while the leaf weight of remaining ten genotypes were close the mean. Though all the genotypes were at podfill stage the reproductive biomass produced by ICC 4958 and Annigeri were the largest and different from the mean. The reproductive biomass of genotypes ICC 867, ICC 1882, ICC 283 and ICCV 10 were closely similar to the meanwhile that of ICC 8261, ICC 3325, ICC 14778, ICC 14799, ICC 3776 and ICC 7184 were smaller than the mean. A similar trend of reproductive biomass was seen under both irrigation treatments.

The leaf area indices ranged from 0.83 to 1.64 under DS condition and 1.63 to 2.77 in irrigated condition. Under DS condition,

the genotypes ICC 8261 and ICCV 10 produced the higher LAI compared to the mean and genotypes ICC 14799 and ICC 3776 produced smaller LAI compared to the mean under DS condition. Under OI condition, the genotype ICC 3325 produced greater LAI and ICC 7184 produced the smaller LAI compared to the mean. The genotypes varied for the SLA under both DS and OI environment in both the years. Under DS environment ICC 867 had larger SLA while ICC 4958, ICC 3776 and ICCV 10 had smaller SLA compared to the mean. Under OI environment, ICC 3325 produced the greatest SLA and genotypes ICC 8261, ICC 283, ICC 3776 and ICC 7184 had smaller SLA.

4.1.1.1.5 Shoot growth at 70 days after sowing in 2010-11

Growth stage 70 days in 2010-11 represents the mid- to late pod fill stage of various genotypes under DS environment. Under DS condition at this stage the shoot biomass produced by ICC 4958, ICC 8261, ICC 3325 and ICC 283 were greater than the mean biomass and that of ICC 3776 and ICC 7184 were smaller than the mean (Table 4.1g). The shoot biomass of rest of the genotypes was similar to the mean. Under OI condition, all the genotypes produced similar shoot biomass as that of the mean except for ICC 1882 that produced greater shoot biomass than the mean. Though occasionally significantly closer, the biomass of the components such as stem, leaf and reproductive components did not correlate very closely as seen in the early growth stages with genotypically variable growth duration,

Table 4.1g: Shoot growth of 12 diverse genotypes of chickpea at 70 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})	SLA (cm^2 g^{-1})	LAI
Drought stressed						
ICC 4958	76.1	52.1	70.3	198.5	157.0	1.59
ICC 8261	98.3	84.1	16.0	198.4	189.0	2.47
ICC 867	73.0	61.9	18.8	153.7	212.9	2.07
ICC 3325	98.4	70.8	24.4	193.6	201.7	2.65
ICC 14778	91.7	50.9	15.0	157.6	203.6	2.49
ICC 14799	82.2	60.9	23.9	167.0	187.4	2.06
ICC 1882	77.6	46.8	35.7	160.2	183.1	1.89
ICC 283	70.6	57.1	58.0	185.7	184.0	1.73
ICC 3776	68.6	58.0	12.4	139.0	186.4	1.73
ICC 7184	51.4	48.1	11.9	111.4	173.9	1.19
Annigeri	49.6	48.0	50.8	148.5	192.9	1.28
ICCV 10	78.5	57.7	45.9	182.1	165.7	1.72
Mean	76.3	58.0	31.9	166.3	186.5	1.91
S.Ed (±)	5.60	5.68	5.57	10.4	16.2	0.206
Optimally irrigated						
ICC 4958	87.0	88.9	24.2	200.2	229.4	2.64
ICC 8261	114.1	105.0	4.1	223.2	226.1	3.44
ICC 867	99.9	74.0	16.1	189.9	270.0	3.61
ICC 3325	119.8	89.8	9.6	219.2	306.4	4.91
ICC 14778	103.9	82.4	6.5	192.9	278.2	3.91
ICC 14799	99.1	95.3	4.6	199.0	244.7	3.21
ICC 1882	118.1	101.2	13.3	232.5	258.1	4.06
ICC 283	100.8	98.0	18.9	217.8	244.8	3.31
ICC 3776	94.8	90.8	5.1	190.6	237.9	3.00
ICC 7184	76.3	124.2	10.2	210.7	226.2	2.36
Annigeri	105.7	92.2	17.3	215.2	248.6	3.47
ICCV 10	103.9	85.8	21.9	211.6	237.1	3.25
Mean	102.0	94.0	12.6	208.6	250.6	3.43
S.Ed (±)	9.72	8.60	4.77	13.4	27.0	0.516

SLA= Specific leaf area; LAI= Leaf area index

reproductive parts development and leaf fall. Under DS condition, the leaf biomass of ICC 8261, ICC 14778 and ICC 14799 were greater than that of the mean while that of ICC 7184 and Annigeri were smaller than the mean. The leaf weight of remaining seven genotypes was close to the mean. Similarly under OI condition, the leaf biomass of ICC 3325 was greater than that of the mean while that of ICC 7184 was smaller than the mean. The leaf weight of remaining ten genotypes were close the mean. Under DS condition, the stem biomass produced by ICC 8261 and ICC 3325 was greater than that of the mean and that of genotypes ICC 1882, ICC 7184 and Annigeri were smaller than the mean. Under OI condition, the stem biomass of genotype of ICC 7184 was greater while the stem weight of ICC 867 was smaller than the mean. The stem weights of remaining ten genotypes were closer to the mean. The reproductive biomass produced by ICC 4958 was substantially higher than the rest of the genotypes. Genotypes ICC 283, Annigeri and ICCV 10 produced greater reproductive part biomass and ICC 8261, ICC 867, ICC 14778, ICC 3776 and ICC 7184 produced smaller reproductive part biomass than the mean under DS environment. The reproductive part weight of rest of the three was close to the mean. Under OI condition the partitioning to the reproductive plant parts was reduced to less than half compared to the DS plants but the trend of genotypic distribution was close to the DS treatment. The leaf area indices ranged from 1.19 to 2.65 under DS condition and 2.36 to 4.91 in OI condition. Under DS condition, the genotypes ICC 8261, ICC 3325 and ICC 14778

produced higher LAI compared to the mean and genotypes ICC 7184 and Annigeri produced smaller LAI compared to the mean. Under OI condition, the genotype ICC 3325 produced greater LAI and ICC 7184 produced the smaller LAI compared to the mean. The genotypes varied for the SLA under both DS and OI environment in both the years. Under DS environment ICC 867 had larger SLA while ICC 4958 had smaller SLA compared to the mean. Under OI environment, ICC 3325 produced the greatest SLA and none of the genotype had smaller SLA than the mean.

4.1.1.1.6 Shoot growth at 84 days after sowing in 2009-10 and 80 after sowing in 2010-11

Growth stage 84 days in 2009-10 and 80 days in 2010-11 represents the late pod fill to close to maturity stages of various genotypes under DS environment. Under DS condition at these stages the shoot biomass produced by ICC 4958 was greater than the mean biomass and that of ICC 14778 was smaller than the mean in 2009-10 while that of ICC 8261, ICC 867, ICC 1882 and ICCV 10 was greater than the mean and that of ICC 14799, ICC 3776 and ICC 7184 was smaller than the mean (Table 4.1h and 4.1i). The shoot biomass of rest of the genotypes was similar to the mean. Under OI condition, the genotypes ICC 8261 and ICC 3776 produced greater shoot biomass and genotypes ICC 14778 and ICC 1882 produced smaller shoot biomass than the mean in 2009-10 and genotypes ICC 1882, Annigeri and ICCV 10 produced greater shoot biomass and genotypes ICC 867, ICC 14799 and ICC 7184 produced smaller shoot biomass

Table 4.1h: Shoot growth of 12 diverse genotypes of chickpea at 84 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})	SLA (cm^2 g^{-1})	LAI
Drought stressed						
ICC 4958	89.7	76.4	164.8	331.0	146.5	1.76
ICC 8261	125.9	106.0	43.9	275.8	130.0	2.19
ICC 867	101.3	92.2	105.1	298.5	188.3	2.56
ICC 3325	109.2	85.3	96.2	290.8	173.9	2.56
ICC 14778	85.0	69.0	45.7	199.7	179.8	2.07
ICC 14799	67.0	86.1	57.3	210.3	189.6	1.73
ICC 1882	86.1	47.1	80.9	214.1	160.0	1.85
ICC 283	88.7	69.3	123.3	281.2	160.2	1.92
ICC 3776	92.2	91.1	65.7	249.1	179.3	2.20
ICC 7184	111.7	126.7	57.6	296.0	159.6	2.40
Annigeri	82.6	65.7	143.0	291.2	179.5	1.97
ICCV 10	76.3	72.5	97.3	246.1	173.1	1.76
Mean	93.0	82.3	90.1	265.3	168.3	2.08
S.Ed (±)	9.16	9.21	20.1	32.6	21.2	0.392
Optimally irrigated						
ICC 4958	178.6	186.6	31.1	396.2	165.4	3.94
ICC 8261	285.8	152.4	27.1	465.3	151.8	5.81
ICC 867	183.9	129.2	68.3	381.4	230.8	5.67
ICC 3325	193.4	135.3	44.3	373.0	215.1	5.70
ICC 14778	180.5	129.8	14.9	325.3	192.8	4.71
ICC 14799	212.6	158.8	10.5	381.9	205.1	5.83
ICC 1882	179.6	118.5	36.2	334.3	220.9	5.45
ICC 283	166.4	126.6	75.3	368.3	145.7	3.36
ICC 3776	215.7	241.7	36.2	493.6	175.8	5.11
ICC 7184	179.6	168.0	24.6	372.3	182.8	4.45
Annigeri	201.3	174.2	45.1	420.7	194.3	5.20
ICCV 10	179.3	131.0	80.3	390.5	156.0	3.74
Mean	196.4	154.4	41.2	391.9	186.4	4.91
S.Ed (±)	17.4	14.0	18.1	25.6	30.3	0.985

SLA= Specific leaf area; LAI= Leaf area index

Table 4.1i: Shoot growth of 12 diverse genotypes of chickpea at 80 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})	SLA (cm^2 g^{-1})	LAI
Drought stressed						
ICC 4958	47.9	47.6	135.0	230.5	156.1	0.99
ICC 8261	104.5	91.8	53.7	250.1	147.9	2.06
ICC 867	71.7	60.3	117.1	249.1	197.4	1.89
ICC 3325	68.3	62.0	70.6	200.9	174.5	1.58
ICC 14778	67.6	68.8	70.4	206.8	181.9	1.65
ICC 14799	64.1	56.9	69.2	190.1	192.9	1.65
ICC 1882	82.1	67.6	132.8	282.6	167.8	1.84
ICC 283	59.7	49.8	108.3	217.8	169.7	1.35
ICC 3776	66.7	60.6	59.7	187.0	163.4	1.45
ICC 7184	78.2	67.7	54.4	200.3	142.8	1.49
Annigeri	55.1	46.4	126.5	228.1	170.7	1.25
ICCV 10	74.1	62.0	126.7	262.7	190.7	1.89
Mean	70.0	61.8	93.7	225.5	171.3	1.59
S.Ed (±)	4.38	6.49	7.80	12.7	12.8	0.166
Optimally irrigated						
ICC 4958	113.1	111.3	110.9	335.4	188.1	2.80
ICC 8261	152.7	147.5	48.2	348.4	167.7	3.43
ICC 867	104.8	98.3	104.7	307.9	276.2	3.85
ICC 3325	106.0	122.9	95.0	323.9	244.9	3.48
ICC 14778	118.8	107.2	93.3	319.4	249.4	3.98
ICC 14799	113.4	110.9	83.5	307.7	231.2	3.52
ICC 1882	123.1	123.7	134.2	381.0	235.5	3.95
ICC 283	115.4	109.5	136.4	361.4	183.6	2.82
ICC 3776	125.0	151.2	89.5	365.6	192.1	3.21
ICC 7184	113.1	114.8	57.9	285.8	206.7	3.11
Annigeri	136.3	122.1	120.9	379.3	231.1	4.35
ICCV 10	121.8	97.2	163.1	382.2	163.8	2.70
Mean	120.3	118.1	103.1	341.5	214.2	3.43
S.Ed (±)	12.1	9.94	19.6	13.8	28.2	0.69

SLA= Specific leaf area; LAI= Leaf area index

than the mean. Generally, the total shoot biomass was not associated with the leaf or stem biomass at this stage particularly under DS condition. Under OI condition, there was a sparse association in 2009-10 and no association in 2010-11. As already mentioned for the previous sample, it was primarily due to variation in maturity time and a major progression in pinnule drop in the early duration genotypes like ICC 4958 and Annigeri.

Under DS condition, the leaf biomass of ICC 8261 and ICC 7184 in 2009-10 and of ICC 8261, ICC 1882 and ICC 7184 in 2010-11 were greater than that of the mean while that of ICC 14799 and ICCV 10 in 2009-10 and ICC 4958, ICC 283 and Annigeri in 2010-11 were smaller than the mean. Under OI condition, the leaf biomass of ICC 8261 was the highest in both the years and leaf biomass of all the others were closer to the mean. Under DS condition, the stem biomass produced by ICC 8261 and ICC 7184 in 2009-10 and ICC 8261 in 2010-11 was greater than the mean and that of genotype ICC 1882 in 2009-10 and genotypes ICC 4958, ICC 283 and Annigeri were smaller than the mean. Under OI condition, the stem biomass of genotype of ICC 4958 and ICC 3776 in 2009-10 and ICC 8261 and ICC 3776 in 2010-11 were greater than the mean while the stem weight of ICC 1882 and ICC 283 in 2009-10 and ICC 867 and ICCV 10 were smaller than the mean. The reproductive part biomass started to get closely associated with the total shoot weight in this sample in all the environment except under OI 2009-10 indicating that the appearance reproductive parts was in close proportion to the shoot. Under DS

condition, the reproductive biomass produced by ICC 4958 and Annigeri in both the years and additionally by ICC 867, ICC 1882, ICC 283 and ICCV 10 in 2010-11 were greater than the mean whereas ICC 8261 and ICC 14778 in 2009-10 and ICC 8261, ICC 3325, ICC 14778, ICC 14799, ICC 3776 and ICC 7184 in 2010-11 were smaller than the mean. Under OI condition, genotypes ICC 283 and ICCV 10 in both years produced greater reproductive part biomass and none of them in 2009-10 and ICC 8261 and ICC 7184 produced smaller reproductive part biomass than the mean. Under OI condition, the partitioning to the reproductive plant parts remained to be less than half compared to the DS plants in 2009-10 whereas it was marginally greater and less variable across the genotypes.

Under DS condition, the leaf area indices ranged from 1.73 to 2.56 in 2009-10 and 0.99 to 2.06 in 2010-11 and under OI condition from 3.36 to 5.83 in 2009-10 and 2.70 to 4.35 in 2010-11. Under both year and irrigation treatments, the LAI of all the genotypes were close to the mean except for the genotype ICC 8261 under DS condition in 2010-11 with a greater LAI than the mean and with a lower LAI than the mean in Annigeri and ICC 4958. Under DS condition, the SLA of all genotypes were close to the mean except for ICC 8261 that had smaller SLA compared to the mean in 2009-10 and ICC 867 that had greater SLA but ICC 8261 and ICC 7184 that had smaller SLA compared to the mean in 2010-11. Under OI condition, again the SLA of all the genotype were close to the mean in both the years except for ICC 867 that had greater SLA compared to the mean in 2010-11.

4.1.1.1.7 Shoot growth at 96 days after sowing in 2009-10 and 101 days after sowing in 2010-11

Growth stage 96 days in 2009-10 represents a stage after complete maturity of nine genotypes under DS environment and 15-20 days prior to maturity under OI environment. Growth stage 101 days in 2010-11 represents a stage 7 days after complete maturity of all the genotypes under DS environment and 6 days short of maturity under OI environment. The shoot biomass comparison between years was possible only under OI condition as all the genotypes under DS condition in 2010-11 had matured well before. Under DS condition, the shoot biomass produced by ICC 3776, ICC 8261, ICC 14778 and ICC 7184 were greater than the mean biomass while that of ICC 3325, Annigeri and ICC 4958 were smaller than the mean in 2009-10. The shoot biomass of the remaining genotypes was similar to the mean.

Under OI condition, the genotype ICC 4958 had greater shoot biomass and genotype ICC 1882 had smaller shoot biomass than the mean in 2009-10 and genotype ICCV 10 had greater shoot biomass than the mean and the shoot biomass remaining genotypes were close to the mean in 2010-11 (Table 4.1j and 4.1k). To elaborate further ICC 4958, ICC 867, Annigeri and ICCV 10 had produced consistently greater shoot biomass when two year performance was considered. In contrast to the previous samplings, the total shoot biomass showed no association either with the leaf or stem biomass at this stage as the leaf fall was more variable and governed by the growth duration and the stem biomass depended more on erect plant habit. The total

Table 4.1j: Shoot growth of 12 diverse genotypes of chickpea at 96 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})
Drought stressed				
ICC 4958	29.3	58.7	162.3	250.3
ICC 8261	116.1	126.3	200.0	442.3
ICC 867	37.7	47.0	229.0	313.7
ICC 3325	58.6	57.5	190.0	306.1
ICC 14778	63.8	120.2	255.0	439.0
ICC 14799	71.8	63.8	209.0	344.7
ICC 1882	38.9	60.5	242.0	341.4
ICC 283	24.2	65.1	259.3	348.7
ICC 3776	145.5	145.5	204.3	495.3
ICC 7184	122.7	126.0	172.3	421.0
Annigeri	23.1	51.9	183.9	258.9
ICCV 10	38.5	52.1	227.7	318.3
Mean	64.2	81.2	211.2	356.6
S.Ed (±)	10.2	11.4	21.1	26.1
Optimally irrigated				
ICC 4958	293.6	349.1	197.7	840.3
ICC 8261	276.0	341.3	75.3	692.7
ICC 867	210.8	248.9	300.0	759.7
ICC 3325	227.3	297.3	213.7	738.3
ICC 14778	264.4	292.0	76.3	632.7
ICC 14799	282.7	282.7	76.7	642.0
ICC 1882	232.5	240.2	132.7	605.3
ICC 283	184.6	275.4	257.0	717.0
ICC 3776	230.9	318.1	115.3	664.3
ICC 7184	244.3	330.0	195.3	769.7
Annigeri	260.9	297.8	191.0	749.7
ICCV 10	110.1	219.2	367.7	697.0
Mean	234.8	291.0	183.2	709.1
S.Ed (±)	37.7	41.5	70.4	49.3

Table 4.1k: Shoot growth of 12 diverse genotypes of chickpea at 101 days after sowing under optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Leaf weight (g m^{-2})	Stem weight (g m^{-2})	Reproductive parts weight (g m^{-2})	Total shoot biomass (g m^{-2})
Optimally irrigated				
ICC 4958	70.5	141.4	391.9	603.8
ICC 8261	175.1	282.3	268.1	725.5
ICC 867	111.2	224.4	465.5	801.1
ICC 3325	82.6	181.5	398.0	662.1
ICC 14778	53.3	167.2	325.9	546.5
ICC 14799	143.5	161.1	367.2	671.8
ICC 1882	101.8	137.8	422.8	662.4
ICC 283	97.8	164.9	448.7	711.4
ICC 3776	154.5	217.5	304.1	676.0
ICC 7184	128.0	203.0	257.4	588.5
Annigeri	101.1	245.1	458.5	804.7
ICCV 10	139.9	149.8	627.5	917.2
Mean	113.3	189.7	395.0	697.6
S.Ed (±)	30.7	52.9	83.3	125.4

shoot biomass was associated with the reproductive parts (or the pods at this stage) in 2010-11 but a low pod production in ICC 8261 and a substantially high production of pods in ICCV 10 made them deviants from this association in 2009-10. Under optimal irrigation, considering the reproductive biomass of both 2009-10 and 2010-11, the top genotypes were ICCV 10, ICC 867 and ICC 283. The moderate ones were ICC 4958, ICC 3325 and Annigeri and the poor ones were ICC 8261, ICC 14778, ICC 14799, ICC 1882, ICC 3776 and ICC 7184.

4.1.1.2 CTD and canopy proportion at various days after sowing in both 2009-10 and 2010-11

At reproductive stage, CTD and canopy proportion were measured at 66, 70, 76 and 81 in 2009-10, and 63, 70, 72 and 80 DAS in 2010-11 in both irrigation treatments. Under DS condition, the range of grand mean for canopy proportion was 0.914 to 0.935 in 2009-10 and 0.919 to 0.941 in 2010-11, and for CTD was -5.77 to -0.020 in 2009-10 and -4.78 to -1.41 in 2010-11 (Table 4.1l). Under OI condition, the range of grand mean for canopy proportion was 0.974 to 0.982 in 2009-10 and 0.979 to 0.987 in 2010-11, and for CTD was 1.08 to 4.99 in 2009-10 and 2.07 to 3.35 in 2010-11 (Table 4.1m).

The canopy proportion of all the genotypes measured at different DAS was close to mean except ICC 7184 at 70 DAS in both the years, and ICC 4958 at 76 DAS in 2009-10 and 72 DAS in 2010-11, were lower than the mean under DS condition. Similar pattern was also followed under OI condition except in both the years except ICC 7184 as it was lower than the mean in 2010-11.

In 2009-10, at 66 DAS the genotype ICC 283 under DS and ICC 867 under OI condition had highest CTD than the mean. The CTD of remaining genotypes were close to the mean except the genotype ICC 7184 which had the lowest CTD than the mean in both irrigation treatments. At 70 DAS, the genotypes ICC 1882 and ICCV 10 under DS, and ICCV 10 and ICC 14799 under OI condition were had highest CTD than the mean. The CTD of remaining genotypes were close to mean except ICC 7184 under DS and ICC 3776 and ICC 7184 under

Table 4.1l: Canopy proportion and canopy temperature depression of 12 diverse genotypes of chickpea measured at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Canopy proportion (%)				Canopy temperature depression (°C)			
	66-DAS	70-DAS	76-DAS	81-DAS	66-DAS	70-DAS	76-DAS	81-DAS
Drought stressed								
ICC 4958	0.905	0.923	0.854	0.898	-0.31	-1.54	-3.42	-8.21
ICC 8261	0.925	0.964	0.947	0.944	0.12	-1.44	-3.18	-6.36
ICC 867	0.916	0.936	0.928	0.924	0.47	-0.72	-2.31	-5.52
ICC 3325	0.925	0.936	0.950	0.973	-0.49	-0.12	-1.90	-5.44
ICC 14778	0.926	0.906	0.951	0.955	-0.08	-0.99	-1.69	-5.17
ICC 14799	0.923	0.935	0.928	0.950	0.39	-0.39	-2.44	-3.94
ICC 1882	0.898	0.969	0.952	0.871	0.72	0.42	-1.96	-4.96
ICC 283	0.924	0.950	0.946	0.969	1.03	-0.38	-2.84	-6.02
ICC 3776	0.889	0.949	0.940	0.966	-0.81	-0.92	-3.10	-4.91
ICC 7184	0.881	0.869	0.939	0.916	-2.45	-2.70	-3.82	-7.04
Annigeri	0.918	0.941	0.906	0.944	0.51	-0.04	-2.28	-5.77
ICCV 10	0.938	0.909	0.933	0.909	0.69	0.59	-2.32	-5.83
Mean	0.914	0.932	0.931	0.935	-0.020	-0.690	-2.61	-5.77
S.Ed (±)	0.041	0.033	0.032	0.046	0.533	0.475	0.664	0.476
Optimally irrigated								
ICC 4958	0.980	0.981	0.965	0.977	5.12	3.32	0.30	4.62
ICC 8261	0.982	0.985	0.983	0.977	4.66	2.92	0.29	4.22
ICC 867	0.979	0.978	0.979	0.977	5.61	4.05	1.18	5.35
ICC 3325	0.984	0.984	0.971	0.976	4.95	4.22	1.61	5.52
ICC 14778	0.970	0.981	0.973	0.975	5.04	3.71	1.76	5.01
ICC 14799	0.983	0.981	0.980	0.972	5.46	4.25	2.23	5.85
ICC 1882	0.985	0.978	0.961	0.976	4.83	4.16	1.81	5.46
ICC 283	0.980	0.988	0.961	0.981	4.56	4.01	1.57	5.31
ICC 3776	0.986	0.986	0.973	0.975	4.82	2.15	0.05	3.45
ICC 7184	0.977	0.979	0.985	0.980	4.06	1.04	-0.84	1.84
Annigeri	0.977	0.981	0.977	0.980	5.29	3.94	1.85	5.24
ICCV 10	0.994	0.985	0.979	0.989	5.46	4.31	1.12	5.31
Mean	0.981	0.982	0.974	0.978	4.99	3.51	1.08	4.76
S.Ed (±)	0.008	0.008	0.008	0.007	0.333	0.333	0.487	0.333

Table 4.1m: Canopy proportion and canopy temperature depression of 12 diverse genotypes of chickpea measured at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Canopy proportion (%)				Canopy temperature depression (°C)			
	63-DAS	70-DAS	72-DAS	82-DAS	63-DAS	70-DAS	72-DAS	82-DAS
Drought stressed								
ICC 4958	0.914	0.925	0.849	0.907	-2.11	-3.57	-2.22	-7.98
ICC 8261	0.934	0.960	0.948	0.951	-1.68	-3.14	-1.98	-5.46
ICC 867	0.923	0.945	0.923	0.932	-1.32	-1.76	-1.11	-3.83
ICC 3325	0.924	0.944	0.943	0.978	-2.20	-1.16	-0.70	-4.21
ICC 14778	0.935	0.912	0.941	0.959	-1.88	-2.02	-0.49	-3.56
ICC 14799	0.929	0.939	0.931	0.958	-1.41	-1.76	-1.24	-3.04
ICC 1882	0.902	0.969	0.943	0.876	-1.08	-0.95	-0.76	-4.06
ICC 283	0.926	0.952	0.939	0.976	-1.44	-0.59	-1.64	-4.64
ICC 3776	0.891	0.952	0.933	0.967	-2.61	-3.29	-1.90	-4.01
ICC 7184	0.878	0.878	0.936	0.926	-4.25	-4.40	-2.62	-5.48
Annigeri	0.928	0.949	0.904	0.947	-1.29	-1.74	-1.08	-5.54
ICCV 10	0.938	0.916	0.926	0.916	-1.11	-1.44	-1.12	-5.60
Mean	0.919	0.937	0.926	0.941	-1.87	-2.15	-1.41	-4.78
S.Ed (±)	0.041	0.033	0.030	0.046	0.736	0.867	0.664	0.733
Optimally irrigated								
ICC 4958	0.989	0.983	0.970	0.986	3.32	2.72	1.66	3.57
ICC 8261	0.991	0.990	0.982	0.983	2.46	2.35	1.69	2.51
ICC 867	0.985	0.988	0.984	0.985	3.81	3.51	1.88	3.75
ICC 3325	0.982	0.992	0.978	0.982	3.49	4.19	2.90	4.89
ICC 14778	0.987	0.987	0.982	0.985	3.39	3.68	2.46	4.34
ICC 14799	0.989	0.985	0.977	0.980	4.20	5.31	3.53	5.19
ICC 1882	0.991	0.978	0.971	0.981	3.48	4.16	3.18	3.23
ICC 283	0.982	0.990	0.968	0.989	2.76	3.31	2.27	2.11
ICC 3776	0.988	0.988	0.980	0.976	1.62	1.24	1.08	2.46
ICC 7184	0.974	0.988	0.988	0.990	-0.12	-0.56	-0.14	0.42
Annigeri	0.992	0.989	0.978	0.983	3.57	3.59	2.55	4.37
ICCV 10	0.994	0.993	0.986	0.996	3.23	3.21	1.82	3.38
Mean	0.987	0.987	0.979	0.985	2.93	3.06	2.07	3.35
S.Ed (±)	0.006	0.008	0.009	0.007	0.610	0.809	0.603	0.627

OI condition as it were lower than the mean. At 76 DAS the genotype ICC 14799 under OI condition had highest CTD than the mean. The CTD of the remaining genotypes were close to the mean except ICC 7184 under DS and ICC 3776 and ICC 7184 under OI condition as it were lower than the mean. At 81 DAS the genotypes ICC 14799 under DS and ICC 14799, ICC 3325 and ICC 1882 under OI condition were had higher CTD than the mean. The CTD of the remaining genotypes were close to the mean except ICC 4958 and ICC 7184 under DS, and ICC 3776 and ICC 7184 under OI condition as it were lower than the mean.

In 2010-11, at 63 DAS the genotype ICC 14799 under OI condition had highest CTD than the mean. The CTD of the remaining genotypes were close to the mean except ICC 7184 under DS and ICC 3776 and ICC 7184 under OI condition as it were lower than the mean. At 70 DAS the genotype ICC 283 under DS and ICC 14799 under OI condition had highest CTD than the mean. The CTD of the remaining genotypes were close to the mean except ICC 7184 under DS and ICC 3776 and ICC 7184 under OI condition as it were lower than the mean. At 72 DAS the genotypes ICC 14799 and ICC 1882 under OI condition had highest CTD than the mean. The CTD of the remaining genotypes were close to the mean except ICC 7184 under both irrigation treatments.

At 82 DAS the genotype ICC 14799 under DS and ICC 14799 and ICC 3325 under OI condition had highest CTD than the mean. The CTD of the remaining genotypes were close to the mean except

ICC 4958 under DS and ICC 283 and ICC 7184 under OI condition as it were lower than the mean.

4.1.1.3 Performance of root traits across growth stages both under drought stressed and optimally irrigated conditions

4.1.1.3.1 Root growth at 35DAS in both years

The first irrigation was provided on 38 DAS in 2009-10 and 30 DAS in 2010-11. Therefore the differences in root growth between the DS and OI treatments can not be large. Growth stage 35 DAS is a stage when the early duration genotype ICC 4958 had flowered whiles the others in various stages of progression towards flowering. At this stage the RDp was observed to be of a maximum of 60 cm and varied from 45 to 60 cm (Table 4.2a and 4.2b). The roots of most genotypes in 2009-10 and ICC 4958, ICC 8261, ICC 867, ICC 14778, ICCV 10 in the DS treatment in 2010-11 had reached the soil zone of 45-60 cm. The mean RLD in 2009-10, across all the depths, was 0.199 cm cm^{-3} under DS and 0.235 cm cm^{-3} under OI condition. This means in 2010-11 was 0.148 cm cm^{-3} under DS and 0.120cm cm^{-3} under OI condition. Genotypes ICC 4958, ICC 8261, Annigeri and ICC 14799 produced significantly greater RLD than the mean in 2009-10 and in addition ICC 283 also produced greater RLD in 2010-11. In both the years and irrigation treatments ICC 4958 produced the highest RLD except for OI environment in 2009-10. With a few exceptions, RLD of genotypes ICC 3325, ICC 14778, ICC 1882 and ICCV 10 were close to the mean while that of ICC 283, ICC 7184, ICC 867 and ICC 3776 were lower than the mean under both irrigation treatments and years.

Table 4.2a. Root growth of 12 diverse genotypes of chickpea at 35 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})					Root dry weight (g m^{-3})				
	0-15	15-30	30-45	45-60	Mean 0-60	0-15	15-30	30-45	45-60	Total 0-60
Drought stressed										
ICC 4958	0.397	0.303	0.179	0.113	0.248	60.1	23.8	10.9	4.12	24.8
ICC 8261	0.281	0.287	0.152	0.214	0.233	33.7	22.1	10.1	9.95	19.0
ICC 867	0.247	0.240	0.158	0.000	0.161	22.5	11.6	9.26	0.00	10.8
ICC 3325	0.255	0.262	0.177	0.131	0.206	25.3	16.3	9.46	2.15	13.3
ICC 14778	0.363	0.283	0.157	0.000	0.201	45.8	16.9	7.63	0.00	17.6
ICC 14799	0.390	0.264	0.160	0.055	0.217	57.2	15.1	9.69	1.35	20.8
ICC 1882	0.265	0.253	0.180	0.099	0.199	25.4	11.7	10.0	1.54	12.2
ICC 283	0.343	0.226	0.132	0.000	0.175	38.5	13.2	5.56	0.00	14.23
ICC 3776	0.240	0.212	0.175	0.000	0.157	14.1	9.7	8.07	0.00	8.0
ICC 7184	0.253	0.240	0.141	0.065	0.175	22.0	12.9	6.71	2.64	11.1
Annigeri	0.344	0.247	0.164	0.120	0.219	34.2	18.6	9.53	1.47	15.9
ICCV 10	0.310	0.189	0.162	0.106	0.191	29.4	10.3	6.87	1.17	11.9
Mean	0.307	0.251	0.161	0.075	0.199	34.0	15.2	8.65	2.03	15.0
S.Ed (±)	0.014	0.014	0.016	0.012	0.007	3.13	3.33	1.74	0.83	1.45
Optimally irrigated										
ICC 4958	0.481	0.367	0.217	0.136	0.300	72.8	28.8	13.2	4.98	30.0
ICC 8261	0.450	0.348	0.238	0.258	0.324	57.3	23.4	12.2	12.0	26.2
ICC 867	0.299	0.302	0.192	0.000	0.198	27.2	18.9	11.2	0.00	14.3
ICC 3325	0.308	0.317	0.214	0.159	0.249	30.6	19.8	11.5	2.60	16.1
ICC 14778	0.362	0.342	0.190	0.000	0.224	42.3	20.4	10.2	0.00	18.2
ICC 14799	0.395	0.319	0.194	0.066	0.244	52.7	18.2	11.7	1.64	21.1
ICC 1882	0.320	0.306	0.173	0.120	0.230	30.7	14.1	8.82	1.86	13.9
ICC 283	0.415	0.274	0.159	0.000	0.212	46.6	15.9	7.56	0.00	17.5
ICC 3776	0.312	0.257	0.212	0.000	0.195	33.5	11.7	9.76	0.00	13.7
ICC 7184	0.307	0.291	0.171	0.078	0.212	26.6	15.7	8.11	3.20	13.4
Annigeri	0.306	0.299	0.144	0.145	0.223	24.9	17.5	8.23	1.78	13.1
ICCV 10	0.265	0.228	0.196	0.128	0.204	19.1	12.4	9.14	1.41	10.5
Mean	0.352	0.304	0.192	0.091	0.235	38.7	18.1	10.1	2.46	17.3
S.Ed (±)	0.015	0.016	0.017	0.013	0.008	3.44	3.66	0.92	0.91	1.59

Table 4.2b: Root growth of 12 diverse genotypes of chickpea at 35 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})					Root dry weight (g m^{-3})				
	0-15	15-30	30-45	45-60	Mean 0-60	0-15	15-30	30-45	45-60	Total 0-60
Drought stressed										
ICC 4958	0.578	0.176	0.069	0.031	0.213	106.3	17.6	7.92	0.73	33.1
ICC 8261	0.497	0.156	0.066	0.064	0.196	92.1	15.4	5.77	3.69	29.2
ICC 867	0.234	0.089	0.035	0.035	0.098	37.3	4.7	3.23	0.55	11.4
ICC 3325	0.368	0.123	0.067	0.000	0.140	65.4	21.4	7.86	0.00	23.7
ICC 14778	0.190	0.090	0.032	0.061	0.093	31.2	2.6	3.60	1.78	9.8
ICC 14799	0.471	0.162	0.072	0.000	0.176	102.5	15.2	7.41	0.00	31.3
ICC 1882	0.301	0.134	0.050	0.000	0.121	54.7	10.3	4.12	0.00	17.3
ICC 283	0.504	0.175	0.072	0.000	0.188	97.9	33.7	7.31	0.00	34.7
ICC 3776	0.249	0.097	0.006	0.000	0.088	37.1	2.2	3.34	0.00	10.7
ICC 7184	0.391	0.079	0.027	0.000	0.124	54.7	2.2	5.65	0.00	15.6
Annigeri	0.525	0.168	0.075	0.000	0.192	86.6	12.7	8.03	0.00	26.8
ICCV 10	0.396	0.115	0.067	0.017	0.149	68.7	9.6	6.33	0.73	21.3
Mean	0.390	0.130	0.053	0.017	0.148	69.5	12.3	5.88	0.62	22.1
S.Ed (±)	0.016	0.010	0.007	0.004	0.006	5.13	1.39	1.31	0.251	1.56
Optimally irrigated										
ICC 4958	0.395	0.189	0.073	0.000	0.164	66.5	17.0	6.20	0.00	22.4
ICC 8261	0.367	0.171	0.062	0.000	0.150	78.7	10.3	5.80	0.00	23.7
ICC 867	0.200	0.178	0.073	0.000	0.113	39.7	15.4	5.40	0.00	15.1
ICC 3325	0.245	0.149	0.086	0.000	0.120	45.6	14.5	7.97	0.00	17.0
ICC 14778	0.209	0.128	0.028	0.000	0.091	31.0	8.1	2.09	0.00	10.3
ICC 14799	0.252	0.144	0.067	0.000	0.116	43.4	11.9	3.62	0.00	14.7
ICC 1882	0.265	0.153	0.055	0.000	0.118	44.7	12.1	3.00	0.00	15.0
ICC 283	0.306	0.169	0.048	0.000	0.131	62.1	13.0	4.02	0.00	19.8
ICC 3776	0.259	0.126	0.060	0.000	0.111	42.0	9.71	5.09	0.00	14.2
ICC 7184	0.186	0.107	0.031	0.000	0.081	32.3	6.76	2.21	0.00	10.3
Annigeri	0.253	0.150	0.033	0.000	0.109	28.5	10.5	2.03	0.00	10.3
ICCV 10	0.277	0.195	0.065	0.000	0.134	65.8	17.4	5.55	0.00	22.2
Mean	0.268	0.155	0.057	0.000	0.120	48.3	12.2	4.41	0.00	16.2
S.Ed (±)	0.024	0.012	0.008	0.000	0.006	5.80	1.65	0.984	0.00	1.51

At this stage the RLD of ICC 4958, ICC 8261 and ICCV 10 was consistently greater in the 45-60 cm soil depth. The RLD of each individual soil depth was regressed with the mean RLD across all the depths to find if there are any genotype × soil depth interactions in promoting root proliferation. Under DS condition, the depth wise RLD was significantly proportionate to the mean RLD 0-60 at all the RDps except at the 30-45 cm RDp in 2009-10 and 45-60 cm in 2010-11. Under OI condition in 2009-10, genotypes ICC 4958, ICC 8261, ICC 3325, ICC 1882, Annigeri and ICCV 10 produced significantly greater RLD than the mean while ICC 8261 produced the highest RLD. The depth wise RLD was significantly proportionate to the mean RLD 0-60 at all the RDps.

The total RDW in 2009-10, across all the depths, was 15.00 g m^{-3} under DS and 17.30 g m^{-3} under OI condition (Table 4.2a). These means in 2010-11 were 22.10 g m^{-3} under DS and 16.20 g m^{-3} under OI condition (Table 4.2b). Considering the total RDW, genotypes ICC 4958 and ICC 8261 in both irrigation treatments and years, ICC 14799 except in OI condition under 2010-11 produced significantly greater RDW than the overall mean but only in 2010-11 Annigeri and ICC 283 also produced greater RDW. In 2009-10 under both the irrigation treatment, ICC 4958 produced the highest RDW but it was ICC 283 under DS and ICC 8261 under OI condition in 2010-11. RDW of genotype ICC 3325 was close to the mean in both irrigation environments and years whereas that of ICC 283 was close to the mean in 2009-10 and greater than the mean in 2010-11. The RDW of

ICCV 10 was lesser than the mean in 2009-10 but close to mean or close to higher category in 2010-11. RDW of genotypes ICC 7184 in all environments and that of ICC 1882, ICC 867 and ICC 3776, except under OI condition in 2010-11, were lower than the mean. In both the year, the depth wise RDW was significantly proportionate to the total RDW at all the RDps under OI condition. This pattern was the same for 0-15 and 15-30 cm RDps in 2009-10, and 0-15, 15-30 and 30-45 cm in 2010-11 under DS condition. At this stage the RDW of ICC 4958 and ICC 8261 were consistently greater in the 45-60 cm soil depth.

4.1.1.3.2 Root growth at 45DAS in 2010-11

A sampling of root at 45 DAS had been carried out only during 2010-11. At this stage, almost half of the genotypes had flowered under DS condition. However under OI conditions none of them had flowered. At this stage the RDp was a maximum of 75 cm and the RDp of genotypes largely varied from 45 to 60 cm (Table 4.2c). The mean RLD across all the depths was 0.251 cm cm^{-3} under DS and 0.233 cm cm^{-3} under OI condition. Under DS condition, genotypes ICC 4958, ICC 8261 and ICC 867 produced significantly greater RLD than the mean while ICC 4958 produced the highest RLD. RLD of genotypes ICC 3325, ICC 14799, ICC 1882, Annigeri and ICCV 10 were close and comparable to the mean while that of ICC 283, ICC 3776 and ICC 7184 were significantly lower than the mean. The genotype ICC 14778 produced RLD similar to the mean under DS condition but less significant under OI condition. The depth wise RLD

Table 4.2c: Root growth of 12 diverse genotypes of chickpea at 45 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})						Root dry weight (g m^{-3})					
	0-15	15-30	30-45	45-60	60-75	Mean 0-75	0-15	15-30	30-45	45-60	60-75	Total 0-75
Drought stressed												
ICC 4958	0.731	0.287	0.254	0.230	0.095	0.319	119.2	38.4	38.3	20.0	8.97	45.0
ICC 8261	0.590	0.284	0.247	0.185	0.093	0.280	79.6	39.9	33.3	15.9	5.77	34.9
ICC 867	0.711	0.240	0.172	0.204	0.075	0.281	131.3	27.5	23.2	14.7	10.7	41.5
ICC 3325	0.543	0.260	0.228	0.165	0.068	0.253	81.7	33.9	33.8	10.8	14.3	34.9
ICC 14778	0.651	0.285	0.196	0.125	0.047	0.261	81.3	34.7	20.6	8.72	3.19	29.7
ICC 14799	0.554	0.272	0.204	0.145	0.034	0.242	87.1	47.2	25.4	12.6	3.38	35.1
ICC 1882	0.546	0.278	0.193	0.137	0.075	0.246	89.6	33.9	18.5	13.6	3.19	31.8
ICC 283	0.470	0.209	0.174	0.119	0.023	0.199	68.1	25.1	17.2	8.66	4.67	24.8
ICC 3776	0.451	0.232	0.148	0.123	0.038	0.198	57.2	16.0	17.8	8.42	2.27	20.4
ICC 7184	0.537	0.211	0.124	0.092	0.028	0.198	81.2	14.4	13.8	6.57	1.72	23.5
Annigeri	0.615	0.275	0.216	0.169	0.064	0.268	84.7	24.5	21.6	14.2	8.05	30.6
ICCV 10	0.692	0.278	0.172	0.136	0.041	0.264	131.4	36.1	21.0	11.3	2.70	40.5
Mean	0.591	0.259	0.194	0.153	0.057	0.251	91.0	31.0	23.7	12.1	5.74	32.7
S.Ed (±)	0.043	0.010	0.021	0.020	0.015	0.013	6.38	4.88	4.65	2.78	2.47	2.22
Optimally irrigated												
ICC 4958	0.713	0.484	0.155	0.083	0.028	0.293	112.7	49.8	14.3	3.81	0.860	36.3
ICC 8261	0.572	0.328	0.163	0.129	0.037	0.246	79.7	37.2	12.3	8.06	1.54	27.8
ICC 867	0.662	0.301	0.133	0.107	0.041	0.249	99.6	31.5	13.6	8.34	3.59	31.3
ICC 3325	0.714	0.328	0.164	0.092	0.029	0.265	113.9	35.1	13.3	5.90	2.80	34.2
ICC 14778	0.343	0.406	0.079	0.115	0.051	0.199	55.4	41.5	8.85	6.27	4.51	23.3
ICC 14799	0.555	0.384	0.150	0.090	0.031	0.242	84.3	48.6	19.5	3.01	3.11	31.7
ICC 1882	0.794	0.244	0.091	0.072	0.026	0.245	118.6	23.1	7.80	2.89	2.59	31.0
ICC 283	0.623	0.245	0.101	0.071	0.043	0.217	99.5	29.9	6.51	3.56	2.83	28.5
ICC 3776	0.496	0.196	0.143	0.057	0.012	0.181	66.0	12.0	8.91	3.43	1.90	18.5
ICC 7184	0.771	0.157	0.046	0.057	0.023	0.211	120.3	10.7	6.36	2.64	0.700	28.1
Annigeri	0.634	0.386	0.084	0.041	0.008	0.231	116.3	43.5	12.5	1.78	1.07	35.0
ICCV 10	0.602	0.288	0.125	0.083	0.021	0.224	105.9	28.9	15.7	5.10	1.54	31.4
Mean	0.623	0.312	0.120	0.083	0.029	0.233	97.7	32.7	11.6	4.57	2.25	29.8
S.Ed (±)	0.026	0.014	0.014	0.010	0.006	0.008	4.24	2.57	1.35	0.892	0.568	0.700

was closely proportionate to the mean RLD 0-75 at all the RDps under DS condition whereas under OI condition this proportion was only significant at 15-30 cm.

The total RDW across all the depth was 32.70 g m^{-3} under DS condition and 29.80 g m^{-3} under OI condition (Table 4.2c). Under DS condition, genotypes ICC 4958, ICC 867 and ICCV 10 produced significantly greater RDW than the mean while ICC 4958 produced the highest RDW. RDW of genotypes ICC 14799, ICC 3325, ICC 8261, ICC 1882, Annigeri and ICC 14778 were close to the mean while that of ICC 283, ICC 7184 and ICC 3776 were lower than the mean. The depth wise RDW was also proportionate to the total RDW at all the RDps except 60-75 cm. Under OI condition, genotypes ICC 4958, Annigeri, ICC 3325, ICC 14799, ICCV 10 and ICC 867 produced significantly greater RDW than the mean while ICC 4958 produced the highest RDW. RDW of genotype ICC 1882 was close to the mean while that of ICC 283, ICC 7184, ICC 8261, ICC 14778 and ICC 3776 was lower than the mean. The depth wise RDW was proportionate to the total RDW only at 0-15 cm RDp.

4.1.1.3.3 Root growth at 50 DAS in 2009-10 and 55 DAS in 2010-11

In 2009-10, growth stage 50 DAS was a stage when early duration genotypes like ICC 4958 and Annigeri were at pod filling stage and all the genotypes except ICC 14778 had attained 50% flowering under DS condition. In 2010-11, at the growth stage of 55 DAS all the genotypes crossed the stage of 50% flowering and most of

the early duration genotypes were in early pod-fill stage under DS condition. At this stage the RDp was a maximum of 90 cm (Table 4.2d and 4.2e). In 2009-10, the mean RLD across all the depths was 0.368 cm cm^{-3} under DS and 0.330 cm cm^{-3} under OI condition. Similarly in 2010-11, the mean RLD across all the depths was 0.265 cm cm^{-3} under DS and 0.261 cm cm^{-3} under OI condition. In 2009-10, under DS condition, genotypes ICC 4958, ICC 8261, ICCV 10 and ICC 14799 produced significantly greater RLD than the mean and in the OI condition Annigeri also had greater RLD. Similarly, except ICC 8261 under DS condition, the same genotypes had greater RLD in 2010-11 also. However under OI condition, ICC 14778 and ICCV 10 also had greater RLD than the mean. Overall, ICC 4958 had greater consistency in being the top in RLD. In 2009-10 under DS condition RLD of genotypes ICC 867, ICC 14778 and Annigeri were close to the mean while that of ICC 7184, ICC 3325, ICC 3776, ICC 1882 and ICC 283 were lower than the mean. In 2009-10 under OI condition RLD of genotypes ICC 867, ICC 3325 and ICC 14778 were close to the mean while that of ICC 1882, ICC 283, ICC 3776 and ICC 7184 and were lower than the mean. In 2010-11 under DS condition RLD of genotypes ICC 8261, ICC 867, ICC 3325, ICC 1882, ICC 283 and ICCV 10 were close to the mean while that of ICC 7184, ICC 3325, ICC 3776, ICC 1882 and ICC 283 were lower than the mean. A close genotypic variation in RLD was also seen under OI condition. Under DS condition, the depth wise RLD was significantly proportionate to the mean RLD 0-90 at all the RDp in both the year except 15-30 and

Table 4.2d: Root growth of 12 diverse genotypes of chickpea at 50 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})							Root dry weight (g m^{-3})						
	0-15	15-30	30-45	45-60	60-75	75-90	Mean 0-90	0-15	15-30	30-45	45-60	60-75	75-90	Total 0-90
Drought stressed														
ICC 4958	0.750	0.484	0.426	0.450	0.311	0.144	0.428	76.3	31.5	26.2	21.4	13.9	16.9	31.0
ICC 8261	0.704	0.605	0.457	0.416	0.242	0.095	0.420	93.1	24.0	26.9	9.40	9.48	12.0	29.1
ICC 867	0.550	0.576	0.459	0.414	0.201	0.073	0.379	45.9	33.1	19.2	12.2	9.26	6.36	21.0
ICC 3325	0.486	0.549	0.307	0.327	0.198	0.122	0.332	40.3	27.5	12.6	11.7	11.2	13.6	19.5
ICC 14778	0.567	0.539	0.422	0.429	0.189	0.093	0.373	65.3	25.0	15.9	15.9	8.29	1.87	22.0
ICC 14799	0.562	0.608	0.421	0.444	0.202	0.126	0.394	48.1	52.7	19.9	13.1	11.0	7.45	25.4
ICC 1882	0.466	0.482	0.360	0.307	0.215	0.107	0.323	60.8	17.6	16.8	9.90	8.40	11.5	20.8
ICC 283	0.473	0.525	0.320	0.266	0.235	0.097	0.319	47.6	21.8	12.4	4.48	10.7	8.66	17.6
ICC 3776	0.554	0.480	0.330	0.382	0.164	0.044	0.326	54.5	15.1	13.8	9.18	8.42	2.03	17.2
ICC 7184	0.577	0.532	0.341	0.339	0.170	0.055	0.336	59.5	24.5	13.1	11.4	7.10	0.922	19.4
Annigeri	0.530	0.562	0.399	0.408	0.241	0.076	0.369	44.5	21.9	18.1	13.3	10.3	4.42	18.8
ICCV 10	0.659	0.606	0.438	0.430	0.244	0.098	0.412	69.7	37.5	20.8	19.5	10.2	4.24	27.0
Mean	0.573	0.546	0.390	0.384	0.218	0.094	0.368	58.8	27.7	18.0	12.6	9.85	7.49	22.4
S.Ed (±)	0.022	0.020	0.017	0.021	0.021	0.021	0.017	4.90	5.01	3.94	3.31	1.89	2.78	2.82
Optimally irrigated														
ICC 4958	0.760	0.692	0.444	0.387	0.18	0.05	0.419	131.3	44.6	38.0	15.2	6.42	1.91	39.6
ICC 8261	0.687	0.604	0.428	0.288	0.15	0.03	0.364	106.7	37.1	36.0	13.2	7.14	0.96	33.5
ICC 867	0.607	0.571	0.350	0.341	0.17	0.07	0.352	89.9	25.1	15.9	14.1	9.21	1.92	26.0
ICC 3325	0.639	0.427	0.244	0.403	0.19	0.05	0.326	101.0	32.7	16.3	18.6	8.70	1.67	29.9
ICC 14778	0.572	0.470	0.390	0.310	0.16	0.04	0.324	67.0	34.5	39.0	14.0	7.14	1.91	27.2
ICC 14799	0.631	0.524	0.441	0.329	0.18	0.07	0.363	77.8	35.5	37.3	19.5	9.18	2.66	30.3
ICC 1882	0.464	0.341	0.252	0.169	0.16	0.06	0.241	49.3	18.7	10.9	8.17	6.98	2.30	16.1
ICC 283	0.507	0.388	0.287	0.267	0.13	0.03	0.267	63.8	25.4	23.4	11.5	6.03	1.53	21.9
ICC 3776	0.534	0.409	0.232	0.362	0.12	0.03	0.281	69.2	15.3	32.0	13.9	3.68	1.34	22.6
ICC 7184	0.532	0.469	0.293	0.306	0.12	0.04	0.293	66.0	23.9	14.8	12.6	4.92	1.02	20.5
Annigeri	0.676	0.578	0.409	0.290	0.162	0.071	0.364	112.7	42.2	25.7	13.8	6.33	2.77	33.9
ICCV 10	0.741	0.614	0.272	0.303	0.17	0.08	0.364	117.1	30.3	13.4	17.1	7.85	3.44	31.5
Mean	0.613	0.507	0.337	0.313	0.157	0.052	0.330	87.6	30.5	25.2	14.3	6.96	1.95	27.8
S.Ed (±)	0.021	0.019	0.021	0.021	0.021	0.009	0.014	3.95	4.51	3.88	2.39	1.46	0.318	1.98

Table 4.2e: Root growth of 12 diverse genotypes of chickpea at 55 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})							Root dry weight (g m^{-3})						
	0-15	15-30	30-45	45-60	60-75	75-90	Mean 0-90	0-15	15-30	30-45	45-60	60-75	75-90	Total 0-90
Drought stressed														
ICC 4958	0.628	0.260	0.332	0.273	0.311	0.134	0.323	76.7	38.7	28.0	26.5	25.9	13.27	34.9
ICC 8261	0.547	0.278	0.255	0.210	0.202	0.095	0.264	77.3	35.8	25.0	17.9	13.3	7.99	29.5
ICC 867	0.519	0.229	0.257	0.211	0.221	0.133	0.262	75.6	28.4	18.9	21.1	17.7	12.84	29.1
ICC 3325	0.545	0.294	0.303	0.206	0.238	0.091	0.279	68.3	39.7	27.7	25.3	13.7	9.09	30.6
ICC 14778	0.476	0.243	0.291	0.206	0.133	0.043	0.232	62.6	32.6	26.5	20.2	5.53	0.246	24.6
ICC 14799	0.622	0.304	0.371	0.218	0.402	0.136	0.342	87.6	35.5	32.1	29.2	25.6	1.97	35.3
ICC 1882	0.594	0.277	0.283	0.194	0.215	0.117	0.280	73.7	30.0	25.9	22.4	16.1	9.65	29.6
ICC 283	0.495	0.224	0.370	0.262	0.235	0.097	0.280	79.7	40.7	28.6	26.5	19.6	5.77	33.5
ICC 3776	0.364	0.179	0.214	0.162	0.164	0.044	0.188	55.7	25.8	14.8	13.9	9.61	1.35	20.2
ICC 7184	0.362	0.191	0.195	0.127	0.090	0.021	0.164	61.7	20.9	11.4	10.1	4.73	0.614	18.2
Annigeri	0.546	0.270	0.315	0.283	0.271	0.076	0.294	73.4	30.4	21.9	31.3	26.4	2.95	31.0
ICCV 10	0.660	0.305	0.270	0.199	0.188	0.034	0.276	96.0	41.3	18.1	17.3	10.8	2.83	31.1
Mean	0.530	0.255	0.288	0.213	0.222	0.085	0.265	74.0	33.3	23.3	21.8	15.7	5.71	29.0
S.Ed (±)	0.038	0.017	0.023	0.026	0.026	0.018	0.012	6.49	5.90	4.27	2.55	5.88	2.64	2.78
Optimally irrigated														
ICC 4958	0.818	0.296	0.269	0.130	0.149	0.042	0.284	116.7	38.2	21.2	13.2	5.28	1.47	32.7
ICC 8261	0.890	0.304	0.297	0.176	0.100	0.020	0.298	134.4	39.7	31.0	17.6	3.56	0.830	37.9
ICC 867	0.467	0.316	0.372	0.200	0.140	0.056	0.259	63.1	43.1	40.5	20.2	6.94	1.95	29.3
ICC 3325	0.533	0.360	0.393	0.213	0.159	0.040	0.283	71.1	48.5	36.1	23.7	6.20	1.31	31.1
ICC 14778	0.868	0.398	0.245	0.123	0.131	0.032	0.299	121.3	42.6	21.0	6.4	5.16	1.47	33.0
ICC 14799	0.846	0.274	0.290	0.173	0.149	0.057	0.298	123.3	37.0	23.5	17.9	6.52	1.97	35.0
ICC 1882	0.761	0.251	0.294	0.119	0.133	0.045	0.267	114.0	30.7	28.2	10.2	5.53	1.54	31.7
ICC 283	0.567	0.335	0.294	0.119	0.105	0.020	0.240	88.2	37.2	27.7	11.1	3.56	0.320	28.0
ICC 3776	0.463	0.170	0.198	0.078	0.101	0.022	0.172	46.6	29.1	16.7	4.6	1.47	0.903	16.6
ICC 7184	0.422	0.233	0.131	0.057	0.083	0.030	0.159	47.8	25.2	11.8	2.2	1.81	0.300	14.9
Annigeri	0.616	0.402	0.362	0.150	0.127	0.055	0.285	68.9	48.7	33.4	15.3	3.57	1.84	28.6
ICCV 10	0.654	0.401	0.377	0.188	0.124	0.012	0.293	82.7	43.7	36.6	10.0	4.61	0.59	29.7
Mean	0.659	0.312	0.293	0.144	0.125	0.036	0.261	89.8	38.6	27.3	12.7	4.52	1.21	29.0
S.Ed (±)	0.033	0.028	0.024	0.025	0.022	0.009	0.015	6.78	5.46	5.67	4.24	0.975	0.380	2.64

75-90 cm RDp in 2009-10. Under OI condition, this proportion was significant at all the RDp in both the year except 45-60 and 75-90 cm RDp in 2009-10, and 75-90 cm in 2010-11.

In 2009-10 the total RDW across all the depth was 22.40 g m^{-3} under DS condition and 27.80 g m^{-3} under OI condition (Table 4.2d) whereas in 2010-11, it was 29.0 g m^{-3} under DS condition and 29.0 g m^{-3} under OI condition (Table 4.2e). Under DS condition, genotypes ICC 4958 and ICC 8261 produced significantly greater RDW than the mean. RDW of remaining 10 genotypes were close to the mean. Under OI condition, genotypes ICC 4958, Annigeri and ICC 8261 produced significantly greater RDW than the mean. RDW of genotypes ICCV 10, ICC 14799, ICC 3325, ICC 14778 and ICC 867 were close to the mean while that of ICC 3776, ICC 283, ICC 7184 and ICC 1882 were lower than the mean. In 2010-11 under DS condition, genotypes ICC 14799 and ICC 4958 produced significantly greater RDW than the mean. RDW of genotypes ICC 283, ICCV 10, Annigeri, ICC 3325, ICC 1882, ICC 8261, ICC 867, and ICC 14778, were close to the mean while that of ICC 3776 and ICC 7184 were lower than the mean. In 2010-11 under optimal irrigation genotypes ICC 8261 and ICC 14799 produced significantly greater RDW than the mean. RDW of genotypes ICC 14778, ICC 4958, ICC 1882, ICC 3325, ICCV 10, ICC 867, Annigeri and ICC 283 were close to the mean while that of ICC 3776 and ICC 7184 were lower than the mean. Under DS condition, the depth wise RDW was significantly proportionate to the total RDW at all the RDps except 15-30, 60-75 and 75-90 cm in 2009-10, and 75-90 cm in

2010-11. Under OI condition, the depth wise RDW was significantly proportionate to the total RDW at all the RDps except 30-45, 60-75 and 75-90 cm in 2009-10, and 30-45 and 75-90 cm in 2010-11.

4.1.1.3.4 Root growth at 65 DAS in 2010-11

Sampling at 65 DAS was carried out only in year 2010-11 and growth stage 65 DAS is a stage when majority of the genotypes were at the mid-pod fill stage under DS condition and at early pod fill stage at OI condition. At this stage the RDp was a maximum of 105 cm (Table 4.2f). The mean RLD across all the depths was 0.352 cm cm^{-3} under DS and 0.422 cm cm^{-3} under OI condition. Under DS condition, genotypes ICC 3325, ICC 14778, ICC 14799 and ICC 283 produced significantly greater RLD than the mean and ICC 3325 produced the highest RLD. This had demonstrated that the early-stage moderate root producing genotypes tend to become the top root producers at the mid reproductive stage. RLD of genotypes ICC 1882, ICC 867, ICCV 10, ICC 4958, Annigeri, ICC 8261 and ICC 3776 were close to the mean while that of ICC 7184 was lower than the mean. The depth wise RLD was significantly proportionate to the mean RLD 0-105 at all the RDps except 0-15, 15-30 and 90-105 cm. Contrastingly under OI condition, genotypes ICC 4958, ICC 8261 and ICC 3325 produced significantly greater RLD than the mean while ICC 3325 produced the highest RLD demonstrating a contrasting performance of genotypes across irrigation levels. RLD of genotypes ICCV 10, ICC 867, Annigeri, ICC 283, ICC 14799, ICC 14778 and ICC 1882 were close to the mean while that of ICC 3776 and ICC 7184 were lower than the mean.

Table 4.2f: Root growth of 12 diverse genotypes of chickpea at 65 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})								Root dry weight (g m^{-3})							
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	Mean 0-105	0-15	15-30	30-45	45-60	60-75	75-90	90-105	Total 0-105
Drought stressed																
ICC 4958	0.859	0.340	0.301	0.289	0.275	0.228	0.106	0.343	134.4	38.7	35.9	32.6	22.6	22.6	8.85	42.2
ICC 8261	0.813	0.297	0.306	0.244	0.257	0.262	0.185	0.338	135.4	47.3	38.4	25.0	33.7	32.1	21.3	47.6
ICC 867	0.645	0.378	0.308	0.290	0.357	0.262	0.181	0.346	99.8	54.1	25.9	28.1	32.0	21.9	13.5	39.3
ICC 3325	0.850	0.318	0.365	0.355	0.390	0.341	0.261	0.411	129.6	53.0	39.6	41.6	41.8	32.0	17.2	50.7
ICC 14778	0.816	0.387	0.358	0.324	0.398	0.263	0.135	0.383	126.6	52.7	45.8	50.8	37.1	23.7	4.48	48.7
ICC 14799	0.896	0.339	0.342	0.362	0.346	0.335	0.122	0.392	148.9	43.4	50.7	63.0	35.7	35.8	4.12	54.5
ICC 1882	0.697	0.382	0.374	0.359	0.329	0.293	0.178	0.373	99.0	46.2	33.9	38.0	37.0	30.0	14.7	42.7
ICC 283	0.805	0.471	0.357	0.331	0.300	0.225	0.249	0.391	113.8	61.1	34.5	38.5	19.8	22.1	21.0	44.4
ICC 3776	0.685	0.324	0.225	0.232	0.239	0.180	0.215	0.300	98.7	28.6	12.4	18.4	15.3	21.2	12.9	29.7
ICC 7184	0.735	0.327	0.272	0.199	0.155	0.095	0.063	0.264	116.0	33.6	21.4	14.7	7.5	6.1	3.38	29.0
Annigeri	0.576	0.307	0.361	0.432	0.346	0.281	0.063	0.338	80.8	54.2	43.8	40.5	33.6	25.5	2.27	40.1
ICCV 10	0.725	0.357	0.368	0.346	0.343	0.199	0.082	0.346	113.5	44.6	44.8	36.1	31.3	19.1	1.97	41.6
Mean	0.758	0.352	0.328	0.314	0.311	0.247	0.153	0.352	116.4	46.5	35.6	35.6	28.9	24.3	10.5	42.5
S.Ed (±)	0.024	0.033	0.027	0.029	0.034	0.027	0.022	0.016	5.52	5.13	4.83	5.45	5.43	5.41	3.65	3.30
Optimally irrigated																
ICC 4958	0.792	0.621	0.653	0.445	0.450	0.168	0.105	0.462	146.6	63.8	54.1	47.1	45.6	13.5	3.32	53.4
ICC 8261	0.984	0.599	0.630	0.439	0.284	0.183	0.129	0.464	238.7	75.7	61.6	43.6	20.5	10.1	5.50	65.1
ICC 867	0.780	0.658	0.527	0.480	0.298	0.179	0.119	0.435	103.0	79.5	46.3	42.9	32.9	15.1	4.65	46.4
ICC 3325	0.925	0.568	0.702	0.548	0.454	0.200	0.065	0.495	205.1	59.6	64.0	49.2	49.2	14.2	3.37	63.5
ICC 14778	0.711	0.692	0.584	0.370	0.357	0.080	0.054	0.407	170.7	74.5	45.5	34.4	30.0	6.21	1.04	51.8
ICC 14799	0.818	0.565	0.550	0.464	0.263	0.155	0.088	0.415	179.7	62.5	45.3	44.3	25.9	16.0	1.90	53.6
ICC 1882	0.717	0.483	0.484	0.411	0.350	0.233	0.093	0.396	109.8	57.1	54.8	41.9	23.7	12.8	4.13	43.5
ICC 283	0.699	0.594	0.537	0.478	0.299	0.156	0.145	0.415	98.3	66.6	50.8	44.3	28.0	14.4	6.45	44.1
ICC 3776	0.851	0.477	0.440	0.342	0.173	0.116	0.120	0.360	153.5	51.4	36.0	31.2	14.1	5.22	3.44	42.1
ICC 7184	0.807	0.467	0.403	0.371	0.192	0.087	0.065	0.342	109.9	60.0	31.8	33.4	24.6	4.18	3.11	38.1
Annigeri	0.745	0.605	0.529	0.411	0.363	0.211	0.101	0.424	141.6	64.9	48.6	41.4	30.5	23.7	5.65	50.9
ICCV 10	0.751	0.697	0.683	0.415	0.269	0.159	0.141	0.445	199.9	88.3	62.5	43.4	19.2	5.49	5.47	60.6
Mean	0.798	0.586	0.560	0.431	0.313	0.161	0.102	0.422	154.7	67.0	50.1	41.4	28.7	11.7	4.00	51.1
S.Ed (±)	0.054	0.032	0.025	0.027	0.031	0.023	0.019	0.016	11.3	5.67	5.62	5.27	4.50	4.34	1.56	2.48

The depth wise RLD was significantly proportionate to the mean RLD 0-105 at all the RDps except 0-15, 75-90 and 90-105 cm.

The total RDW across all the depth was 42.50 g m^{-3} under DS condition and 51.10 g m^{-3} under OI condition (Table 4.2f). Under DS condition, genotypes ICC 14799, ICC 3325 and ICC 14778 produced significantly greater RDW than the mean while ICC 14799 produced the highest RDW. RDW of genotypes ICC 8261, ICC 283, ICC 1882, ICC 4958, ICCV 10, Annigeri and ICC 867 were close to the mean while that of ICC 3776 and ICC 7184 were lower than the mean. The depth wise RDW was significantly proportionate to the total RDW at all the RDps except 15-30 and 90-105 cm. Under OI condition, genotypes ICC 8261, ICC 3325 and ICCV 10 produced significantly greater RDW than the mean while ICC 8261 produced the highest RDW. RDW of genotypes ICC 14799, ICC 4958, ICC 14778 and Annigeri were close to the mean while that of ICC 867, ICC 283, ICC 1882, ICC 3776 and ICC 7184 were lower than the mean. The depth wise RDW was significantly proportionate to the total RDW at all the RDps except 15-30, 60-75, 75-90 and 90-105 cm.

4.1.1.3.5 Root growth at 80 DAS in 2009-10 and 75 DAS in 2010-11

The two root samplings that were done at 80 DAS in 2009-10 and at 75 DAS 2010-11 were close in calendar days and therefore the genotypic performance at these two days across years can be close. At this stage, under DS environment, some of the early duration

genotypes like ICC 4958 and Annigeri were between physiological maturity and maturity while the others were progressing towards physiological maturity. At this stage the RDp was a maximum of 120 cm (Table 4.2g and 4.2h). In 2009-10, the mean RLD across all the depths was 0.273 cm cm^{-3} under DS and 0.250 cm cm^{-3} under OI condition whereas in 2010-11 it was 0.413 cm cm^{-3} under DS and 0.300 cm cm^{-3} under OI condition. Under DS condition, genotype ICC 14778 produced significantly highest RLD than the mean in 2009-10 and ICC 8261, ICC 3325, ICC 14799 and ICCV 10 produced the highest RLD in 2010-11. Under DS condition, genotypes ICC 8261, ICC 867, ICC 3325, ICC 14799, ICC 1882, ICC 3776, ICC 7184 and ICCV 10 in 2009-10 and genotypes ICC 867, ICC 14778, ICC 283 and Annigeri in 2010-11 produced RLD close to mean. Genotypes ICC 4958, ICC 283 and Annigeri in 2009-10 and genotypes ICC 3776 and ICC 7184 in 2010-11 produced RLD lower than the mean. The depth wise RLD was significantly proportionate to the mean RLD 0-120 only at the RDps of 90-105 cm in 2009-10 and this proportion was significant at all the RDps except 15-30 cm in 2010-11. Under OI condition, genotypes ICC 8261, ICC 14778 and ICCV 10 in 2009-10and genotypes ICC 3325, ICC 14799 and ICCV 10 produced significantly greater RLD than the mean. RLD of the genotypes ICC 4958, ICC 867, ICC 14799, ICC 1882, ICC 7184 and Annigeri in 2009-10 and ICC 867, ICC 14778, ICC 283, ICC 7184 and Annigeri in 2010-11 were close to the mean. The RLD of genotypes ICC 3325, ICC 283 and ICC 3776 in 2009-10and ICC 4958, ICC 8261, ICC 1882 and ICC

Table 4.2g: Root growth of 12 diverse genotypes of chickpea at 80 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})									Root dry weight (g m^{-3})								
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Mean 0-120	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Total 0-120
Drought stressed																		
ICC 4958	0.486	0.233	0.180	0.194	0.202	0.282	0.091	0.320	0.249	77.2	12.0	12.1	8.17	7.42	9.40	6.40	3.40	17.0
ICC 8261	0.431	0.206	0.228	0.208	0.210	0.346	0.374	0.252	0.282	68.3	11.6	16.6	10.5	8.26	11.2	8.18	5.18	17.5
ICC 867	0.394	0.293	0.262	0.287	0.256	0.319	0.313	0.178	0.288	48.7	23.8	24.5	22.1	12.3	12.3	16.8	13.8	21.8
ICC 3325	0.360	0.225	0.221	0.261	0.260	0.234	0.479	0.251	0.286	42.0	23.2	15.0	14.1	11.8	10.3	8.82	5.82	16.4
ICC 14778	0.636	0.352	0.210	0.266	0.248	0.236	0.258	0.156	0.295	97.6	28.5	11.1	12.9	13.7	10.7	10.7	7.65	24.1
ICC 14799	0.537	0.251	0.234	0.261	0.238	0.308	0.287	0.196	0.289	92.8	14.0	19.0	12.6	10.3	10.3	7.34	4.34	21.4
ICC 1882	0.449	0.308	0.284	0.210	0.190	0.325	0.313	0.192	0.284	64.2	21.9	16.8	18.4	8.62	11.6	8.62	5.62	19.5
ICC 283	0.382	0.342	0.247	0.208	0.222	0.320	0.203	0.094	0.252	58.8	30.0	21.0	14.0	11.7	13.2	11.7	8.70	21.1
ICC 3776	0.418	0.362	0.246	0.241	0.238	0.238	0.203	0.173	0.265	46.3	24.9	15.1	8.42	12.2	10.7	9.17	6.17	16.6
ICC 7184	0.568	0.325	0.199	0.250	0.246	0.187	0.206	0.109	0.261	88.8	24.8	8.48	15.6	13.4	7.35	7.35	4.35	21.3
Annigeri	0.332	0.255	0.245	0.260	0.240	0.261	0.230	0.095	0.240	47.5	21.1	15.1	12.3	10.0	8.54	7.04	4.04	15.7
ICCV 10	0.520	0.298	0.201	0.260	0.265	0.268	0.329	0.135	0.284	81.5	25.9	13.3	7.31	15.6	11.1	12.6	9.56	22.1
Mean	0.460	0.290	0.230	0.242	0.235	0.277	0.274	0.179	0.273	67.8	21.8	15.7	13.0	11.3	10.6	9.55	6.55	19.5
S.Ed (±)	0.015	0.015	0.015	0.014	0.014	0.014	0.014	0.014	0.010	10.56	2.23	2.77	1.80	2.22	1.71	1.81	1.53	1.36
Optimally irrigated																		
ICC 4958	0.690	0.378	0.273	0.259	0.224	0.090	0.065	0.034	0.252	139.2	38.4	24.0	15.3	13.2	10.1	3.17	1.38	30.6
ICC 8261	0.886	0.490	0.288	0.291	0.206	0.110	0.092	0.050	0.302	149.3	49.5	30.2	17.6	11.4	10.8	5.40	2.70	34.6
ICC 867	0.742	0.323	0.287	0.215	0.183	0.137	0.115	0.065	0.258	104.1	26.1	24.5	11.2	9.50	8.00	5.00	2.00	23.8
ICC 3325	0.533	0.349	0.243	0.218	0.197	0.088	0.121	0.062	0.226	143.7	37.7	15.7	11.4	9.33	6.33	4.83	1.83	28.9
ICC 14778	0.816	0.415	0.298	0.224	0.161	0.117	0.117	0.070	0.277	147.9	35.2	18.7	9.3	7.56	6.06	4.56	0.900	28.8
ICC 14799	0.777	0.370	0.299	0.199	0.159	0.108	0.071	0.059	0.255	132.0	32.9	28.6	11.2	8.00	6.33	3.33	1.32	28.0
ICC 1882	0.738	0.291	0.293	0.261	0.142	0.059	0.078	0.060	0.240	102.0	23.0	17.8	14.6	6.48	6.17	3.17	0.980	21.8
ICC 283	0.545	0.319	0.279	0.248	0.220	0.056	0.088	0.046	0.225	93.8	28.9	22.9	12.8	9.65	6.84	3.84	0.84	22.4
ICC 3776	0.657	0.390	0.244	0.184	0.114	0.043	0.053	0.056	0.218	84.3	30.5	13.5	6.97	4.22	3.33	2.16	0.975	18.2
ICC 7184	0.707	0.363	0.316	0.227	0.127	0.033	0.077	0.042	0.237	101.8	30.2	20.6	9.09	4.98	3.48	2.88	1.17	21.8
Annigeri	0.652	0.284	0.225	0.236	0.146	0.125	0.126	0.059	0.232	89.5	25.8	16.2	11.2	7.85	7.85	5.45	1.85	20.7
ICCV 10	0.988	0.305	0.253	0.168	0.185	0.146	0.128	0.063	0.279	102.7	21.7	19.6	6.81	12.9	11.1	5.13	2.13	22.8
Mean	0.728	0.357	0.275	0.227	0.172	0.093	0.094	0.055	0.250	115.9	31.7	21.0	11.5	8.76	7.20	4.08	1.51	25.2
S.Ed (±)	0.019	0.019	0.020	0.014	0.014	0.014	0.014	0.007	0.011	6.14	4.29	4.78	2.96	1.55	1.65	1.23	0.616	2.07

Table 4.2h: Root growth of 12 diverse genotypes of chickpea at 75 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})									Root dry weight (g m^{-3})								
									Mean									Total
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	0-120	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	0-120
Drought stressed																		
ICC 4958	0.825	0.344	0.403	0.363	0.323	0.247	0.191	0.140	0.355	121.1	32.6	36.4	30.9	27.1	25.6	15.8	22.4	39.0
ICC 8261	0.922	0.309	0.437	0.386	0.435	0.370	0.374	0.252	0.436	128.3	26.9	34.2	36.8	30.2	23.7	22.1	16.3	39.8
ICC 867	0.876	0.382	0.467	0.393	0.461	0.319	0.313	0.178	0.424	111.0	40.1	33.6	36.4	34.1	24.6	18.4	9.58	38.5
ICC 3325	0.980	0.323	0.496	0.384	0.422	0.434	0.479	0.251	0.471	121.9	33.1	42.6	42.3	29.5	38.2	41.2	17.5	45.8
ICC 14778	0.728	0.311	0.449	0.431	0.485	0.443	0.258	0.156	0.408	100.1	28.4	40.1	39.4	35.0	41.2	14.1	7.37	38.2
ICC 14799	0.746	0.423	0.499	0.468	0.450	0.408	0.287	0.196	0.435	93.1	49.3	42.1	45.8	30.5	33.1	18.4	14.8	40.9
ICC 1882	0.801	0.407	0.450	0.479	0.410	0.425	0.313	0.192	0.435	118.6	43.4	43.3	32.9	28.1	43.3	16.5	9.09	41.9
ICC 283	0.857	0.376	0.496	0.392	0.408	0.362	0.203	0.094	0.398	113.4	36.4	39.8	36.7	27.3	34.2	7.68	2.27	37.2
ICC 3776	0.726	0.271	0.401	0.330	0.256	0.278	0.203	0.173	0.330	116.9	20.6	32.4	20.4	17.1	16.6	4.73	8.93	29.7
ICC 7184	0.644	0.402	0.442	0.283	0.301	0.187	0.206	0.109	0.322	96.3	35.8	43.6	28.3	13.6	8.9	6.94	3.87	29.7
Annigeri	0.762	0.303	0.416	0.426	0.415	0.411	0.230	0.095	0.382	107.8	24.5	32.9	35.4	36.2	38.2	7.99	5.77	36.1
ICCV 10	0.697	0.362	0.544	0.454	0.509	0.468	0.329	0.135	0.437	87.7	52.2	42.4	40.5	41.1	38.2	16.6	7.80	40.8
Mean	0.797	0.351	0.459	0.399	0.406	0.363	0.282	0.164	0.403	109.7	35.3	38.6	35.5	29.1	30.5	15.9	10.5	38.1
S.Ed (±)	0.040	0.031	0.028	0.023	0.028	0.031	0.026	0.023	0.014	5.32	5.31	5.45	4.68	4.52	5.50	4.59	1.93	2.17
Optimally irrigated																		
ICC 4958	0.493	0.431	0.404	0.289	0.234	0.150	0.115	0.064	0.273	99.3	67.5	59.5	30.3	23.8	20.7	6.82	3.75	38.9
ICC 8261	0.533	0.354	0.416	0.316	0.306	0.170	0.082	0.050	0.278	124.4	55.2	52.8	36.0	28.2	21.2	6.45	0.799	40.6
ICC 867	0.479	0.422	0.328	0.322	0.283	0.277	0.199	0.085	0.299	98.9	61.3	32.8	37.7	29.0	26.4	13.6	6.17	38.2
ICC 3325	0.777	0.366	0.413	0.363	0.297	0.228	0.141	0.070	0.332	135.7	60.1	55.1	39.8	33.1	23.4	9.09	2.70	44.9
ICC 14778	0.727	0.498	0.389	0.266	0.211	0.157	0.117	0.070	0.304	125.1	73.7	57.0	30.5	22.3	20.0	9.28	2.10	42.5
ICC 14799	0.872	0.504	0.409	0.300	0.259	0.168	0.191	0.059	0.345	151.4	76.6	57.4	38.1	33.7	20.0	13.0	2.95	49.1
ICC 1882	0.805	0.310	0.416	0.328	0.209	0.099	0.038	0.060	0.283	133.6	43.1	52.8	36.4	20.3	9.77	7.06	3.39	38.3
ICC 283	0.617	0.371	0.410	0.387	0.320	0.116	0.111	0.086	0.302	132.6	44.8	45.1	38.5	36.7	15.8	9.59	5.87	41.1
ICC 3776	0.655	0.464	0.388	0.225	0.144	0.103	0.113	0.056	0.268	125.1	54.0	44.4	25.6	12.2	7.25	7.43	1.30	34.7
ICC 7184	0.862	0.384	0.301	0.250	0.197	0.093	0.102	0.087	0.284	138.6	49.5	30.4	28.7	18.2	9.78	8.11	4.60	36.0
Annigeri	0.645	0.462	0.368	0.313	0.256	0.185	0.050	0.059	0.292	148.0	69.4	48.8	35.3	33.0	22.5	8.49	3.38	46.1
ICCV 10	0.734	0.487	0.405	0.297	0.285	0.206	0.204	0.063	0.335	141.2	65.6	42.3	38.9	31.2	17.7	12.9	3.58	44.2
Mean	0.683	0.421	0.387	0.305	0.250	0.163	0.122	0.067	0.300	129.5	60.1	48.2	34.7	26.8	17.9	9.32	3.38	41.2
S.Ed (±)	0.022	0.020	0.018	0.019	0.020	0.015	0.013	0.012	0.009	6.54	5.96	5.06	2.63	2.39	2.38	2.12	0.66	1.75

3776 in 2010-11 were lower than the mean. The depth wise RLD was significantly proportionate to the mean RLD 0-120 only at the RDps of 0-15 and 75-90 cm in 2009-10, and 90-105 cm in 2010-11.

Under DS condition, genotypes ICC 14778 and ICCV 10 in 2009-10, and ICC 3325 in 2010-11 produced significantly greater RDW than the mean while ICC 14778 and ICC 3325 produced the highest, respectively. RDW of genotypes ICC 867, ICC 14799, ICC 7184, ICC 283, ICC 1882 and ICC 8261 in 2009-10 and genotypes ICC 1882, ICC 14799, ICCV 10, ICC 8261, ICC 4958, ICC 867, ICC 14778, ICC 283 and Annigeri in 2010-11 were close to the mean. Genotypes ICC 4958, ICC 3776, ICC 3325, Annigeri in 2009-10 and genotypes ICC 3776 and ICC 7184 in 2010-11 produced RDW lower than the mean. The depth wise RDW was significantly proportionate to the total RDW only at the RDps of 0-15 and 60-75 cm in 2009-10, and 45-60, 75-90 and 90-105 cm in 2010-11. Under OI condition, genotypes ICC 8261 and ICC 4958 in 2009-10 and ICC 14799, Annigeri and ICC 3325 in 2010-11 produced significantly greater RDW than the mean while ICC 8261 and ICC 14799 produced the highest RDW, respectively. RDW of genotypes ICC 3325, ICC 14778, ICC 14799, ICC 867, ICCV 10, ICC 283, ICC 7184 and ICC 1882 in 2009-10 and genotypes ICCV 10, ICC 14778, ICC 283, ICC 8261, ICC 4958, ICC 1882 and ICC 867 in 2010-11 were close to the mean. Genotypes ICC 3776 and Annigeri in 2009-10 and genotypes ICC 3776 and ICC 7184 in 2010-11 produced RDW lower than the mean. The depth wise RDW was significantly proportionate to the total RDW

only at the initial five RDps in 2009-10, and 15-30, 45-60 and 60-75 cm in 2010-11.

4.1.1.3.6 Root growth at 90 DAS in 2010-11

Growth stage 90 DAS is a stage when some of the genotypes like ICC 4958, ICC 867, ICC 283, Annigeri, and ICCV 10 were already matured while the others were close to maturity under DS condition. At this stage the RDp was at its maximum reaching up to 120 cm (Table 4.2i). The mean RLD across all the depths was 0.195 cm cm^{-3} under DS and 0.332 cm cm^{-3} under OI condition. Under DS condition, genotypes ICC 3325 and ICC 283 produced significantly greater RLD than the mean while ICC 3325 produced the highest RLD. RLD of genotypes ICC 14799, ICC 8261, ICCV 10, ICC 7184, ICC 867and ICC 14778 were close to the mean while that Annigeri, ICC 4958, ICC 1882 and ICC 3776 were lower than the mean. The depth wise RLD was significantly proportionate to the mean RLD 0-120 at all the RDps except 15-30 and 105-120 cm. Under OI condition, genotypes ICC 867, ICC 3325, Annigeri and ICC 14799 produced significantly greater RLD than the mean while ICC 867 produced the highest RLD. RLD of genotypes ICC 7184 and ICC3776 were close to the mean while that of ICCV 10, ICC 283, ICC 8261, ICC 1882, ICC 4958 and ICC 14778 were lower than the mean. The depth wise RLD was significantly proportionate to the total RLD only at the RDps of 0-15, 75-90 and 90-105 cm. The total RDW across all the depth was 22.10 g m^{-3} under DS condition and 44.20 g m^{-3} under OI condition. Under DS condition, genotype ICC 3325 produced significantly greater RDW

Table 4.2i: Root growth of 12 diverse genotypes of chickpea at 90 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Root length density (cm cm^{-3})									Root dry weight (g m^{-3})								
									Mean									Total
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	0-120	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	0-120
Drought stressed																		
ICC 4958	0.480	0.092	0.194	0.158	0.119	0.139	0.118	0.016	0.164	63.8	12.2	15.4	18.9	19.7	17.1	8.11	1.29	19.6
ICC 8261	0.556	0.247	0.227	0.102	0.182	0.102	0.187	0.108	0.214	86.7	30.4	22.3	10.0	11.4	10.7	12.6	8.54	24.1
ICC 867	0.595	0.116	0.161	0.098	0.216	0.111	0.138	0.063	0.187	81.4	16.0	17.9	11.1	19.5	13.2	5.59	6.27	21.4
ICC 3325	0.694	0.141	0.209	0.201	0.281	0.231	0.208	0.129	0.262	102.3	27.3	26.4	36.4	20.8	27.0	20.1	13.0	34.1
ICC 14778	0.498	0.177	0.223	0.122	0.227	0.068	0.066	0.062	0.180	76.0	19.2	21.8	8.85	18.1	5.96	4.3	7.49	20.2
ICC 14799	0.481	0.263	0.214	0.183	0.211	0.152	0.191	0.072	0.221	64.4	34.4	19.1	24.5	23.0	15.6	19.2	6.02	25.8
ICC 1882	0.411	0.098	0.154	0.158	0.153	0.102	0.087	0.069	0.154	62.2	11.8	8.54	26.6	11.2	11.5	6.51	12.0	18.8
ICC 283	0.633	0.280	0.341	0.258	0.236	0.165	0.124	0.011	0.256	80.4	37.8	29.1	27.1	19.0	15.9	8.85	0.799	27.4
ICC 3776	0.349	0.167	0.164	0.061	0.136	0.072	0.118	0.033	0.138	41.6	17.5	14.1	5.47	8.29	7.31	4.67	2.58	12.7
ICC 7184	0.571	0.269	0.228	0.129	0.200	0.071	0.080	0.008	0.195	66.5	31.8	14.4	11.8	12.7	5.65	2.58	0.43	18.2
Annigeri	0.314	0.118	0.170	0.186	0.250	0.104	0.113	0.080	0.167	35.9	28.7	13.8	26.7	25.5	9.22	4.24	10.6	19.3
ICCV 10	0.606	0.157	0.191	0.123	0.168	0.075	0.143	0.139	0.200	89.3	18.5	16.8	12.9	10.1	7.49	12.9	18.7	23.3
Mean	0.516	0.177	0.206	0.148	0.198	0.116	0.131	0.066	0.195	70.9	23.8	18.3	18.4	16.6	12.2	9.13	7.30	22.1
S.Ed (±)	0.029	0.030	0.024	0.027	0.024	0.025	0.026	0.023	0.015	5.68	5.52	5.54	3.81	6.61	4.16	3.26	3.83	2.93
Optimally irrigated																		
ICC 4958	0.316	0.496	0.526	0.364	0.226	0.129	0.107	0.022	0.273	65.6	68.0	59.4	36.4	17.9	16.3	10.6	6.83	35.1
ICC 8261	0.886	0.331	0.328	0.178	0.200	0.212	0.127	0.090	0.294	159.1	42.8	35.0	32.1	21.9	26.1	8.24	10.4	41.9
ICC 867	1.114	0.428	0.547	0.310	0.244	0.253	0.254	0.138	0.411	170.4	79.4	63.1	36.8	24.9	38.0	20.5	13.0	55.7
ICC 3325	1.112	0.414	0.474	0.296	0.334	0.283	0.266	0.095	0.409	159.3	56.7	41.9	30.6	41.6	36.9	20.8	8.85	49.6
ICC 14778	0.574	0.342	0.471	0.187	0.195	0.065	0.034	0.044	0.239	84.1	38.2	45.0	21.9	12.8	10.6	1.93	3.5	27.2
ICC 14799	0.707	0.679	0.485	0.402	0.261	0.209	0.193	0.045	0.373	120.8	95.6	60.2	53.9	26.4	29.2	12.7	3.19	50.2
ICC 1882	0.668	0.365	0.426	0.292	0.288	0.130	0.140	0.028	0.292	162.5	61.8	50.4	46.7	26.0	17.0	13.5	2.09	47.5
ICC 283	0.619	0.387	0.454	0.348	0.240	0.154	0.167	0.025	0.299	107.0	51.5	44.4	47.5	18.0	20.4	16.1	3.19	38.5
ICC 3776	0.969	0.658	0.437	0.275	0.260	0.122	0.071	0.014	0.351	137.0	78.9	45.2	38.5	28.3	16.7	9.75	1.72	44.5
ICC 7184	1.262	0.457	0.415	0.253	0.165	0.143	0.134	0.007	0.355	207.2	52.2	34.7	26.2	11.1	16.3	15.2	0.86	45.5
Annigeri	0.879	0.682	0.442	0.375	0.335	0.194	0.139	0.024	0.384	141.0	115.9	48.5	43.4	28.4	21.0	12.6	6.76	52.2
ICCV 10	1.048	0.302	0.290	0.193	0.273	0.152	0.171	0.017	0.306	182.5	39.1	28.0	21.4	30.2	19.3	16.0	1.11	42.2
Mean	0.846	0.462	0.441	0.289	0.252	0.170	0.150	0.046	0.332	141.4	65.0	46.3	36.3	24.0	22.3	13.2	5.12	44.2
S.Ed (±)	0.027	0.027	0.029	0.030	0.029	0.029	0.026	0.013	0.014	6.01	5.50	5.20	5.80	5.21	5.51	4.60	2.48	2.52

than the mean while ICC 3325 produced the highest RDW. RDW of genotypes ICC 283, ICC 14799, ICC 8261, ICCV 10, ICC 867, ICC 14778, ICC 4958, Annigeri, ICC 1882 and ICC 7184 were close to the mean while that of ICC 3776 was lower than the mean. The depth wise RDW was significantly proportionate to the total RDW at all the RDps except 15-30, 60-75 and 105-120 cm. Under OI condition, genotypes ICC 867, Annigeri, ICC 14799 and ICC 3325 produced significantly greater RDW than the mean while ICC 867 produced the highest RDW. RDW of genotypes ICC 1882, ICC 7184, ICC 3776, ICCV 10 and ICC 8261 were close to the mean while that of ICC 283, ICC 4958 and ICC 14778 were lower than the mean. The depth wise RDW was significantly proportionate to the total RDW at all the RDps except 30-45, 45-60 and 105-120 cm.

4.1.1.4 Pattern of crop phenology, shoot biomass, grain yield and yield components both under drought stressed and optimally irrigated conditions

The crop was sown on 31 October 2009 and 20 November 2010. In spite of the plan to sow at the optimum chickpea sowing time, the last week of October, this 21 day delay had happened due to the late cessation of rainy season rains in 2010. Over all, this delay seemed to hasten the developmental stages of the crop in 2010-11.

4.1.1.4.1 Variation in Crop phenology

Under DS condition, the mean flowering time and maturity of the genotypes was advanced by two days in the late sown 2010-11 (Table 4.3a and 4.3b). But under OI condition, the mean flowering

time remained the same across years but the maturity of the genotypes was advanced by nine days in the 2010-11. In late-sown 2010-11, the 50% flowering occurred earlier in ICC 4958, ICC 1882, ICC 283, ICC 3776, ICC 7184, Annigeri and ICCV 10; occurred close to the trial mean in ICC 867, ICC 3325, ICC 14778 and ICC 14799 but later in the kabuli genotype ICC 8261 in the DS condition. However under OI condition, the days to 50% flowering occurred earlier in ICC 4958, ICC 1882 and ICC 283; occurred close to the trial mean in ICC 867, ICC 14778, ICC 3776, ICC 7184, Annigeri and, ICCV 10 but later in ICC 8261, ICC 3325 and ICC 14799. In 2010-11, the genotypes matured earlier in most cases except the early ICC 4958, Annigeri and ICC 1882 in the DS condition. However under OI condition, the crop matured earlier invariably in all the genotypes. Irrigation extended the flowering time by 5 to 6 days in both the years and the maturity by 20 days in 2009-10 and 13 days in 2010-11.

Among the 12 genotypes, ICC 4958 flowered earliest. It took 38 DAS in 2009-10 and 33 DAS in 2010-11 under DS condition and 49 in 2009-10 and 47 in 2010-11 under OI condition. Though individual genotypes differed from each other significantly in flowering and maturity times, for the convenience of discussion the genotypes can be grouped in to four groups, in the order of increasing time taken to flowering under DS condition. Genotypes ICC 4958 and Annigeri with their earliest flowering could be categorized as group 1, genotypes ICC 1882, ICC 283, ICC 7184 and ICCV 10 flowering later as a second

Table 4.3a: Phenology, grain yield, morphological and analytical yield components of 12 diverse genotypes of chickpea both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Days to 50% flowering	Days to maturity	Total shoot biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index (%)	DTI	Pod number (m^{-2})	Seed number (m^{-2})	Seed number (pod^{-1})	100-seed weight (g)	Dv (°Cd)	Dr (°Cd)	C (kg ha^{-1} °Cd^{-1})	p
Drought stressed														
ICC 4958	38	79	3507	1915	54.6	0.24	384	394	1.03	27.6	879	862	2.44	0.91
ICC 8261	48	97	4605	1674	36.3	1.31	288	283	0.98	31.9	1094	1027	2.63	0.62
ICC 867	48	90	3858	2078	54.9	0.52	716	765	1.07	16.0	1094	878	2.35	1.04
ICC 3325	48	93	3480	1752	50.4	-0.86	612	645	1.05	16.2	1101	932	2.07	0.91
ICC 14778	52	96	4232	2016	48.2	0.76	683	910	1.33	13.5	1180	920	2.43	0.91
ICC 14799	50	94	3844	1734	45.0	-0.10	502	623	1.25	13.9	1136	919	2.26	0.83
ICC 1882	45	89	3506	1871	53.6	0.08	604	631	1.04	14.0	1035	914	2.17	0.95
ICC 283	45	87	3395	1789	52.7	-0.46	700	810	1.16	13.3	1021	887	2.16	0.94
ICC 3776	49	98	4091	1628	39.9	0.34	571	622	1.09	16.7	1108	1035	2.31	0.68
ICC 7184	50	100	3756	1093	29.1	-1.63	590	846	1.44	10.4	1136	1050	2.08	0.50
Annigeri	41	82	3567	1923	53.9	0.05	548	564	1.03	18.8	949	858	2.38	0.94
ICCV 10	47	93	3669	2069	56.4	-0.24	549	610	1.11	18.0	1064	976	2.18	0.98
Mean	47.0	92.0	3792.5	1795.2	47.9	0.00	562.2	641.9	1.13	17.5	1066.4	938.2	2.29	0.852
S.Ed (±)	0.80	2.20	285.0	102.4	2.29	0.51	41.0	49.4	0.05	0.93	16.5	54.1	0.15	0.072
Optimally irrigated														
ICC 4958	49	111	7116	1894	26.7		487	432	0.89	29.5	1122	1337	3.50	0.41
ICC 8261	53	115	7529	1308	17.4		224	228	1.01	28.7	1207	1361	3.55	0.27
ICC 867	51	111	7348	2158	29.2		749	793	1.07	16.9	1158	1311	3.60	0.45
ICC 3325	51	113	6846	2086	30.8		1013	855	0.89	15.6	1151	1363	3.30	0.47
ICC 14778	54	112	6404	2035	32.2		815	1027	1.27	12.6	1219	1267	3.12	0.52
ICC 14799	53	113	7378	1842	25.0		563	725	1.29	12.7	1207	1298	3.56	0.40
ICC 1882	51	114	6578	1949	29.8		1021	915	0.90	15.5	1151	1390	3.13	0.45
ICC 283	51	113	6935	1982	28.9		819	909	1.12	14.0	1165	1340	3.36	0.45
ICC 3776	53	110	7653	1529	20.0		536	707	1.31	11.6	1194	1239	3.81	0.33
ICC 7184	53	112	6171	1309	21.2		319	520	1.63	8.6	1201	1277	3.01	0.34
Annigeri	50	114	7233	1993	27.6		678	709	1.05	20.8	1144	1388	3.46	0.42
ICCV 10	50	115	7682	2362	30.7		877	861	0.99	17.1	1144	1432	3.61	0.46
Mean	51.7	112.7	7072.7	1870.5	26.6		675.1	723.4	1.12	17.0	1171.7	1333.6	3.42	0.413
S.Ed (±)	1.04	0.93	369.0	149.6	2.12		102.0	72.5	0.08	0.68	22.2	33.6	0.19	0.031

↑DTI= Drought tolerance index; Dv= Vegetative duration; Dr= Reproductive duration; C= Crop growth rate; p= Partitioning coefficient

Table 4.3b: Phenology, grain yield, morphological and analytical yield components of 12 diverse genotypes of chickpea both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Days to 50% flowering	Days to maturity	Total shoot biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index (%)	DTI	Pod number (m^{-2})	Seed number (m^{-2})	Seed number (pod^{-1})	100-seed weight (g)	Dv (°Cd)	Dr (°Cd)	C (kg ha^{-1} °Cd^{-1})	p
Drought stressed														
ICC 4958	33	83	3680	1905	51.8	1.33	593	526	0.89	25.3	709	1008	2.59	0.73
ICC 8261	52	95	4133	1131	27.3	-0.89	359	340	0.96	28.2	1074	920	2.51	0.49
ICC 867	47	90	3871	1878	48.6	0.72	692	856	1.24	13.4	989	896	2.49	0.85
ICC 3325	49	92	3907	1894	48.5	0.93	868	973	1.12	12.2	1011	917	2.45	0.84
ICC 14778	52	93	3822	1911	50.0	1.16	1118	1685	1.51	10.8	1074	888	2.36	0.91
ICC 14799	51	92	3639	1694	46.5	-0.39	926	1171	1.26	12.0	1047	873	2.30	0.85
ICC 1882	43	93	3636	1797	49.4	0.26	915	1013	1.11	12.5	914	1030	2.26	0.77
ICC 283	41	86	3198	1535	48.0	-1.12	884	1002	1.13	11.6	857	926	2.17	0.76
ICC 3776	47	94	3698	1355	36.5	-0.33	682	916	1.34	10.0	979	999	2.26	0.60
ICC 7184	44	91	3339	1078	32.3	-0.10	1051	1254	1.19	8.5	928	982	2.11	0.52
Annigeri	35	87	3554	1873	52.7	-0.53	764	812	1.06	16.9	747	1067	2.37	0.74
ICCV 10	44	90	3921	2118	54.0	-1.06	833	1154	1.39	15.2	921	947	2.54	0.88
Mean	44.8	90.5	3699.8	1680.7	45.5	0.00	807.2	975.1	1.18	14.7	937.6	954.4	2.40	0.75
S.Ed (±)	0.48	0.82	134.3	71.1	1.21	0.48	64.0	88.4	0.08	0.96	8.9	22.3	0.09	0.02
Optimally irrigated														
ICC 4958	47	103	6582	3141	47.8		1042	867	0.83	31.0	984	1218	3.62	0.71
ICC 8261	55	107	6740	2183	32.5		707	555	0.78	33.9	1123	1191	3.53	0.52
ICC 867	51	103	7215	3205	44.5		1770	1749	0.99	14.4	1052	1158	3.95	0.70
ICC 3325	53	104	7277	3174	43.6		1473	1605	1.09	14.9	1091	1137	3.95	0.71
ICC 14778	54	103	6345	3134	49.4		1700	2291	1.36	10.6	1097	1113	3.47	0.81
ICC 14799	54	105	7928	3161	39.9		1523	1891	1.24	12.1	1097	1156	4.26	0.64
ICC 1882	49	95	6918	3194	46.3		2162	1718	0.80	14.8	1017	985	4.22	0.79
ICC 283	49	104	6436	3094	48.4		1729	1992	1.15	13.2	1017	1202	3.51	0.74
ICC 3776	53	106	7205	2485	34.5		1203	1683	1.39	10.2	1080	1191	3.84	0.54
ICC 7184	53	106	5652	1876	33.2		1116	1594	1.43	8.7	1080	1191	3.01	0.52
Annigeri	50	103	7280	3597	49.6		1342	1318	0.98	18.8	1029	1173	4.00	0.77
ICCV 10	50	103	7527	4202	55.8		1275	1622	1.28	15.0	1041	1162	4.14	0.87
Mean	51.4	103.5	6925.6	3037.2	43.8		1420.1	1573.8	1.11	16.5	1059.0	1156.5	3.79	0.69
S.Ed (±)	0.54	1.92	381.3	89.87	1.89		129.6	119.3	0.06	0.78	9.24	49.6	0.25	0.03

↑DTI= Drought tolerance index; Dv= Vegetative duration; Dr= Reproductive duration; C= Crop growth rate; p= Partitioning coefficient

group, ICC 867, ICC 3325 and ICC 3776 as the third and ICC 8261, ICC 14778 and ICC 14799 as the fourth and longest in flowering among the tested genotypes. A close pattern of grouping also emerged under OI condition though the absolute flowering times were high under OI condition.

Individual genotypes did not follow the same order in maturity as that of flowering. Under DS condition genotypes ICC 4958 and Annigeri matured earliest flowing early as group 1, genotype ICC 283 maturing later as second group, ICC 867, ICC 3325, ICC 14799, ICC 1882 and ICCV 10 as the third and ICC 3776, ICC 7184, ICC 14778 and ICC 8261 as the fourth and longest in maturity among the tested genotypes. Generally similar pattern of grouping also emerged under OI condition though the differences among genotypes were very narrow under OI condition.

4.1.1.4.2 Variation in shoot biomass, grain yield and harvest index

Under DS conditions, the mean shoot biomass production was 3792.5 kg ha^{-1} in 2009-10 (Table 4.3a) and 3699.8 kg ha^{-1} in 2010-11 (Table 4.3b). Under OI condition, this was 7072.7 kg ha^{-1} in 2009-10, and 6925.6 kg ha^{-1} in 2010-11. In 2009-10, under DS condition, the shoot biomass of genotypes ICC 8261, ICC 14778 and ICC 3776 was greater than the genotypes ICC 4958, ICC 3325, ICC 1882, ICC 283 and Annigeri. The shoot biomass of rest of the four genotypes (ICC 867, ICC 14799, ICC 7184 and ICCV 10) was close to the mean. In 2010-11, under DS condition, the shoot biomass of genotypes ICC

8261, ICC 867, ICC 3325, ICC 14778 and ICCV 10 was greater than that of ICC 283, ICC 7184 and Annigeri. The shoot biomass of rest of the four genotypes (ICC 4958, ICC 14799, ICC 1882 and 3776) was close to the mean. In 2009-10, under OI condition, the shoot biomass of genotypes ICC 8261, ICC 867, ICC 14799, ICC 3776 and ICCV 10 was greater than the genotypes ICC 1882, ICC 14778 and ICC 7184. The shoot biomass of rest of the four genotypes (ICC 4958, ICC 3325, ICC 283 and Annigeri) was close to the mean. In 2010-11, under OI condition, the shoot biomass of genotypes ICC 867, ICC 3325, ICC 14799, ICC 3776, Annigeri and ICCV 10 was greater than that of ICC 283, ICC 14778 and ICC 7184. The shoot biomass of rest of the three genotypes (ICC 4958, ICC 8261 and ICC 1882) was close to the mean. In general, the genotypes that produced greater shoot biomass under DS were the early and strong rooting kabuli ICC 8261, the drought tolerant ICC 14778 and the drought sensitive ICC 3776. Additionally, only in 2010-11, the other two drought tolerant genotypes ICC 867 and ICC 3325 and the well adapted genotype ICCV 10 produced greater shoot biomass. Early weak rooted ICC 283 and the best adapted Annigeri produced the least shoot biomass across the years.

Under DS conditions, the mean grain yield production was 1795.2 kg ha^{-1} in 2009-10 (Table 4.3a) and 1680.7 kg ha^{-1} in 2010-11 (Table 4.3b). Under OI condition, this was 1870.5 kg ha^{-1} in 2009-10, and 3037.2 kg ha^{-1} in 2010-11. In 2009-10, under DS condition, the grain yield of genotypes ICC 867, ICC 14778 and ICCV 10 were greater than the mean. In 2010-11 three more genotypes ICC 4958, ICC 3325

and Annigeri yielded greater grain yield than the mean. In 2009-10, the grain yield of genotypes ICC 3776 and ICC 7184 were lesser than the mean while in 2010-11 ICC 283 and ICC 8261 also yielded lesser than the mean. Grain yields of genotypes ICC 14799 and ICC 1882 were consistently moderate across years. Under OI condition in 2009-10, the grain yield of genotypes ICC 867 and ICCV 10 were greater than the mean. In 2010-11 one more genotype Annigeri also yielded greater than the mean. The grain yields of genotypes ICC 8261, ICC 3776 and ICC 7184 were lesser than the mean in both the years. The grain yields of genotypes ICC 4958, ICC 3325, ICC 14778, ICC 14799, ICC 1882 and ICC 283 were moderate and comparable to the mean. In general, the genotypes that produced consistently greater grain yield under DS were the two drought-tolerant genotypes ICC 867 and ICC 14778 and the best adapted genotype ICCV 10. Early large rooting ICC 4958, drought tolerant ICC 3325 and another best adapted genotype Annigeri yielded higher in 2010-11. And the genotypes that produced consistently lesser grain yield under DS were the two drought-sensitive genotypes ICC 3776 and ICC 7184 along with the early strong rooting kabuli ICC 8261.

Under DS conditions, the mean HI was 47.9% in 2009-10 (Table 4.3a) and 45.5% in 2010-11 (Table 4.3b). Under OI condition, this was very poor with 26.6% in 2009-10, and 43.8% in 2010-11. The genotypic distribution for HI followed similar pattern as that of the grain yield and the regression coefficients derived by regressing grain yield with the HI were more than 80% under both irrigations and

years. It confirmed ICCV 10 producing significantly greatest HI while ICC 3776, ICC 8261 and ICC 7184 producing significantly lower HI than the mean under both years and irrigation environments. The remaining genotypes, including all the drought tolerant genotypes (ICC 867, ICC 3325, ICC 14778 and 14799), one large root genotype (ICC 4958), and one best adapted genotype (Annigeri), and small root genotypes (ICC 1882 and ICC 283) were closer to the mean.

4.1.1.4.3 Variation in morphological yield components

Year 2010-11 had seen an increase in pod number m^{-2} most likely as a consequence of late sowing and pod formation at a warmer temperature. As seen from the means, the pod number m^{-2} had increased from 562 in 2009-10 to 807 in 2010-11 under DS condition and from 675 in 2009-10 to1420 in 2010-11 under OI condition as a consequence late sowing (Table 4.3a and 4.3b). Irrigation also enhanced the pod number production and the increase was substantial in 2010-11. Under DS condition highest pod number was produced in genotypes ICC 867, ICC 14778 and ICC 283 in 2009-10 with ICC 14778 producing the highest number of pods per unit area. In 2010-11 genotypes ICC 3325, ICC 14799, ICC1882, ICC 283 and ICC 7184 also produced greater number of pods. Genotypes Annigeri and ICCV 10 produced pod numbers comparable to mean but that of ICC 4958 and ICC 8261 was the least. Under OI condition, ICC 14778 and ICC 1882 in 2009-10 and ICC 1882 in 2010-11 produced the highest number of pods. Genotypes ICC 867, ICC 14778, ICC 283 and ICCV 10 produced higher levels of pod number. Genotypes ICC 4958

and ICC 7184 produced lesser pod numbers while ICC 8261 produced the least.

The genotype distribution for seed number m^{-2} followed similar pattern as that of the pod number m^{-2}, with minor exceptions, confirming that ICC 14778 produced significantly greatest seed number m^{-2} while ICC 4958 and ICC 8261 produced significantly lower seed number m^{-2} than the mean under both years and irrigation environments. The remaining genotypes, including the drought tolerant genotypes (ICC 867, ICC 3325 and 14799), best adapted genotypes (Annigeri and ICCV 10), and small root genotypes (ICC 1882 and ICC 283) were closer to the mean and in few cases it found to be higher.

Seed number pod^{-1} showed an increasing trend in 2010-11 in many of the genotypes and also there was trend to show that optimum irrigation enhanced the seed number pod^{-1} but not in ICC 4958, ICC 8261 and ICC 283. Under DS condition, seed number pod^{-1} of genotypes ICC 7184, ICC 14778 and ICC 14799 in 2009-10, and ICC 14778, ICCV 10 and ICC 3776 in 2010-11 were greater than the mean value. The remaining genotypes were close to the mean except for ICC 4958 and ICC 8261 with consistently lower seeds number pod^{-1} than the mean. Under OI condition, seed number pod^{-1} of genotypes ICC 7184, ICC 3776, ICC 14778 and ICC 14799 were consistently greater than the mean value in both years. Genotypes ICC 1882, ICC 3325 and ICC 4958 in 2009-10, and ICC 867, Annigeri, ICC 4958, ICC 1882 and ICC 8261 in 2010-11 had lower seeds number pod^{-1} than the

mean. The seeds number pod^{-1} of theremaining genotypes were close to the mean. Largely, among the genotypes ICC 14778 performed consistently greater for the morphological yield components pod number m^{-2}, seed number m^{-2}, seed number pod^{-1} than the mean across irrigation treatments and years. And this ability in establishing superior pod number and seeds per pod might be helping it to be a greater producer to maintain stability under terminal DS.

The genotype distribution for 100-seed weight followed directly inverse pattern as that of the pod number m^2 distribution, with few exceptions. 100-seed weight of genotypes ICC 4958, ICC 8261 and Annigeri were greater than the mean in both irrigation treatment and years. 100-seed weight both ICC 4958 and ICC 8261 were at least two-fold greater than that of the largest of other genotypes. With few exceptions, genotypes ICC 1882, ICC 3325, ICC 14799, ICC 283, ICC 14778, ICC 3776 and ICC 7184 had consistently lower 100-seed weight than the mean.

4.1.1.4.4 Variation in analytical yield components

Under DS condition, the mean of analytical yield components Dv, Dr, C and p were 1066.4 (°Cd), 938.2 (°Cd), 2.29 (kg ha^{-1} °Cd) and 0.852 in 2009-10 (Table 4.3a), and 937.6 (°Cd), 954.4 (°Cd), 2.4 (kg ha^{-1} °Cd) and 0.745 in 2010-11 (Table 4.3b), respectively. Under OI condition, these were 1171.7 (°Cd), 1333.6 (°Cd), 3.42 (kg ha^{-1} °Cd) and 0.413 in 2009-10, and 1059.0 (°Cd), 1156.4 (°Cd), 3.8 (kg ha^{-1} °Cd) and 0.694 in 2010-11, respectively.

The Dv of genotypes ICC 14778, ICC 14799, ICC 3776 and ICC 3325 were consistently greater while ICC 1882, ICC 283, Annigeri and ICC 4958 were consistently lower than the mean under DS condition. The Dv of the remaining genotypes were close and greater thanthe mean in few cases. Under OI condition, Dv of genotypes ICC 14778 in 2009-10, and ICC 8261, ICC 14778, ICC 14799, ICC 3325, ICC 3776 and ICC 7184 in 2010-11 were greater than the mean. The remaining genotypes were close to the mean except ICC 4958 in 2009-10, and ICCV 10, Annigeri, ICC 1882, ICC 283 and ICC 4958, which were lower than the mean.

Under DS condition, Dr of genotypes ICC 8261, ICC 3776 and ICC 7184 in 2009-10 and ICC 4958, ICC 1882 and Annigeri in 2010-11 were greater while ICC 4958, ICC 14778, ICC 14799, ICC 1882, ICC 283 and Annigeri in 2009-10 and ICC 8261, ICC 867, ICC 14778, ICC 14799, ICC 283 and ICCV 10 in 2010-11 were lower than the previously mentioned greater ones. The remaining genotypes were close to the mean. Interestingly, in 2010-11 under DS condition, genotypes Annigeri, ICC 1882 and ICC 4958 were lower in Dv but greater in Dr whereas ICC 867, ICC 14778 and ICC 14799 were greater in Dv but lower in Dr. Under OI condition, Dr of genotype ICCV 10 in 2009-10, and ICC 4958 and ICC 283 in 2010-11 were greater than ICC 14778 and ICC 3776 in 2009-10, and ICC 1882 in 2010-11. The Dr of the remaining genotypes were close to the mean. The range of Dr of the genotypes under OI condition in 2010-11 was

relatively narrow likely due to the excessively extended season due to late planting and optimal irrigation.

Overall, the component C did not change across years under DS condition but under optimal irrigation it increased substantially in 2010-11. Also the C increased with optimal irrigation compared to the DS treatment in both the years. The range of genetic variation for C was low. Under DS condition, C of genotype ICC 8261 in 2009-10, and ICC 4958 in 2010-11 were greater than the mean while none of them in 2009-10 and ICC 283 and ICC 7184 in 2010-11 were lower than the mean. The remaining genotypes were close to the mean. Under OI condition, C of genotypes ICC 3776 in 2009-10, and ICC 14799 in 2010-11 were greater than the mean while ICC 7184 in both the years were lower than the mean. The remaining genotypes were close to the mean. Overall ICC 7184 found to be poor in C across irrigation treatment and years.

The component p was acutely sensitive and has changed across years. Overall, under DS condition, it was higher in 2009-10 compared to 2010-11 but substantially higher in 2010-11 under optimal irrigation. Also p has decreased with optimal irrigation compared to the DS treatment in both the years. The range of genetic variation for p was high. Under DS condition, the p of genotypes ICC 14778 and ICCV 10 were the highest when considered both years together. In addition, genotype ICC 867 in 2009-10 and, ICC 867, ICC 14799 and ICC 3325 in 2010-11 had greater p than the mean while ICC 3776, ICC 8261 and ICC 7184 in both the years had lower p than

the mean. The p of remaining genotypes were close to the mean. Under OI condition, the p of genotypes ICC 867, ICC 3325, ICC 14778, ICC 1882, ICC 283 and ICCV 10 in 2009-10 and ICC 14778, ICC 1882, Annigeri and ICCV 10 in 2010-11 were greater than the mean while that of ICC 8261, ICC 3776, and ICC 7184 in both the years were lower than the mean. The remaining genotypes were close to the mean. When the component p was regressed with the grain yield it explained 76 to 82% of the variation.

4.1.1. 5 Pattern of soil water use by crop across growth stages both underdrought stressed and optimally irrigated conditions

4.1.1.5.1 Soil water use by crop at 35 DAS both in 2009-10 and 2010-11

At 35 DAS, OI treatment did not receive any irrigation in 2009-10 whereas the first irrigation was applied at 30 DAS in 2010-11 and the irrigation differences are expected in this year. At this stage, crop had the potential to use water up to 60 cm soil depth as the roots of most genotypes penetrated till this depth. Genotypes whose root presence was only up to 30- 45 cm were ICC 867, ICC 14778, ICC 283 and ICC 3776 both under DS and OI environment in 2009-10, ICC 3325, ICC 14778, ICC 14799, ICC 1882, ICC 283, ICC 3776, ICC 7184 and Annigeri under DS condition in 2010-11 and all the 12 genotypes under OI condition in 2010-11. The overall mean of total crop utilized soil moisture from 0-60 cm depth was 43.2 mm in 2009-10 and 26.5 in 2010-11 under DS condition and 42.5 mm in 2009-10 and 40.4 mm in 2010-11 under OI condition (Table 4.4a and 4.4b).

At this stage there was no significant difference in the mean of total crop used soil moisture between the OI and DS condition in 2009-10 but a significant difference had existed in 2010-11. Under DS condition, all the studied genotypes showed minor but significant differences among them. The genotypes ICC 4958, ICC 8261, ICC 14799, and ICC 14778 used more water than ICC 1882, ICC 283 and ICC 7184 in 2009-10 and, ICC 4958, ICC 3325, ICC 14799, ICC 283 and Annigeri used more water than ICC 7184 in 2010-11 (Table 4.4a and 4.4b). Under DS condition, the depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture only at 30-45 and 45-60 cm soil depths. It had indicated that the crop used water only at 30-45 and 45-60 cm soil depths did differ among genotypes. In the 30-45 cm soil depth all the genotypes used more water than ICC 283 and ICC 7184 in 2009-10 and ICC 14799 and Annigeri used more water than ICC 3776 and ICC 7184 in 2010-11. Similarly, in the 45-60 cm soil depth the genotype ICC 14799 used more water than ICC 283 and ICC 7184 in 2009-10 and ICC3325 used more water than ICC 283 and ICC7184 in 2009-10 and ICC 3325 used more water than ICC 283 and ICC 7184 in 2010-11. The differences in soil water use in depths 30-45 cm and 45-60 cm collectively explained the genotypic variation in total soil water use.

Under OI condition the mean total water used by genotypes varied. Genotypes ICC 4958, ICC 8261 and ICC 14799 used more water than ICC 1882, ICC 3776 and ICC 7184 in 2009-10 and, ICC

Table 4.4a: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 35 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)				
	0-15	15-30	30-45	45-60	0-60
Drought stressed					
ICC 4958	15.99	12.60	9.54	7.79	45.92
ICC 8261	15.50	12.53	8.66	6.54	43.21
ICC 867	15.32	12.46	9.66	7.62	45.07
ICC 3325	15.52	12.67	8.94	5.80	42.92
ICC 14778	15.97	12.59	8.86	7.10	44.51
ICC 14799	15.75	12.37	9.33	7.39	44.83
ICC 1882	15.49	12.17	9.93	3.29	40.87
ICC 283	15.81	12.26	6.80	5.59	40.46
ICC 3776	15.36	12.10	8.81	7.16	43.43
ICC 7184	15.42	12.20	7.55	5.88	41.05
Annigeri	15.55	12.45	8.79	6.09	42.89
ICCV 10	15.66	11.88	8.68	6.36	42.58
Mean	15.61	12.36	8.79	6.38	43.15
S.Ed (±)	0.498	0.552	0.971	1.03	2.29
Optimally irrigated					
ICC 4958	17.03	16.50	9.08	5.79	48.41
ICC 8261	16.54	13.47	9.14	7.30	46.46
ICC 867	15.11	14.00	8.70	6.09	43.90
ICC 3325	14.64	13.86	9.22	5.77	43.49
ICC 14778	14.59	13.15	8.93	7.12	43.79
ICC 14799	14.96	13.59	9.06	6.77	44.39
ICC 1882	14.58	13.44	7.54	4.15	39.72
ICC 283	15.84	12.48	8.13	5.29	41.74
ICC 3776	15.03	11.94	8.46	4.32	39.74
ICC 7184	14.22	11.57	7.83	4.29	37.91
Annigeri	14.09	12.73	7.54	5.85	40.22
ICCV 10	13.85	11.44	8.71	6.39	40.39
Mean	15.04	13.18	8.53	5.76	42.51
S.Ed (±)	0.497	1.28	1.08	1.07	2.40

Table 4.4b: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 35 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)				
	0-15	15-30	30-45	45-60	0-60
Drought stressed					
ICC 4958	8.73	6.41	6.02	8.34	29.49
ICC 8261	9.72	5.51	5.11	5.42	25.77
ICC 867	8.44	4.75	4.17	9.17	26.52
ICC 3325	7.75	5.49	6.03	10.39	29.66
ICC 14778	9.06	4.90	4.61	7.43	26.00
ICC 14799	7.31	4.95	7.21	9.30	28.77
ICC 1882	9.30	6.24	4.81	6.54	26.89
ICC 283	9.19	6.18	6.02	6.42	27.81
ICC 3776	8.04	4.84	2.84	7.36	23.07
ICC 7184	6.94	3.65	3.29	6.48	20.36
Annigeri	8.99	5.89	6.89	8.09	29.87
ICCV 10	7.62	4.70	4.92	6.93	24.18
Mean	8.42	5.29	5.16	7.66	26.53
S.Ed (±)	1.22	2.00	1.96	2.14	3.99
Optimally irrigated					
ICC 4958	9.88	8.61	13.38	12.33	44.20
ICC 8261	7.88	6.81	12.37	12.44	39.50
ICC 867	8.86	8.12	14.86	13.00	44.84
ICC 3325	9.38	7.81	15.13	13.86	46.17
ICC 14778	7.28	6.01	10.99	13.18	37.47
ICC 14799	9.47	7.28	13.29	13.66	43.71
ICC 1882	6.03	6.82	12.04	11.41	36.29
ICC 283	8.83	6.79	13.12	13.28	42.02
ICC 3776	4.23	5.73	15.09	12.50	37.55
ICC 7184	7.05	4.36	11.66	12.70	35.77
Annigeri	7.41	5.94	9.56	9.42	32.33
ICCV 10	8.46	8.36	15.27	13.09	45.18
Mean	7.90	6.89	13.06	12.57	40.42
S.Ed (±)	1.96	1.71	2.01	1.34	4.56

4958, ICC 867, ICC 3325, ICC 14799 and ICCV 10 used more water than ICC 7184 and Annigeri in 2010-11. The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture at all soil depths in both the years. It had been seen that there was a further closer association at the 15-30 and 30-45 cm soil depths in both the years. In the 0-15 cm soil depth it was clear that the genotypes ICC 4958, ICC 8261, ICC 867 and ICC 283 used more water than ICC 7184, Annigeri, and ICCV 10 in 2009-10 and genotypes ICC 4958, ICC 8261, ICC 867, ICC 3325, ICC 14799, ICC 283 and ICCV 10 used more water than genotype ICC 3776 in 2010-11. In the15-30 cm soil depth the genotypes ICC 4958, ICC 867 and ICC 3325 used more water than ICC 7184 and ICCV 10 in 2009-10 and genotypes ICC 4958, ICC 867, ICC 3325 and ICCV 10 used more water than genotype ICC 7184 in 2010-11. In the 30-45 cm soil depth the genotypic differences were not different but the trend was ICC 4958, ICC 867, ICC 3325 and ICC 14799 used more water than ICC 1882, ICC 7184 and Annigeri in 2009-10 and, genotypes ICC 4958, ICC 867, ICC 3325, ICC 14799, ICC 283, ICC 3776 and ICCV 10 used more water than genotype Annigeri in 2010-11. In the 45-60 cm soil depth the genotypes ICC 8261, ICC 867, ICC 14778, ICC 14799 and ICC 10 used more water than ICC 1882, ICC 3776 and ICC 7184 in 2009-10 and, all the genotypes except ICC 1882 and Annigeri in 2010-11. Under OI condition, the differences in soil water use in all thedepths collectively contributed to the genotypic variation in total soil water use.

4.1.1.5.2 Soil water use by crop at 45 DAS in 2010-11

At 45 DAS, 50% of the genotypes had already flowered under DS condition and others in progress. OI treatment was irrigated at 30 DAS in 2009-10. This irrigation substantially delayed the 50% flowering of all the genotypes under OI treatment compared to DS treatment. Consequently the irrigation effects are also expected to appear in soil water use. At this stage, crops can effectively use the soil moisture up to 75 cm as the RDp reached was 60-75 cm in all the genotypes.

The mean of total crop utilized soil moisture from 0-75 cm depth was 44.4 mm under DS and 72.5 mm under OI condition exhibiting a large variation in water use by the two irrigation treatments (Table 4.4c). Under DS condition, all the studied genotypes showed greater soil water use except ICC 283, ICC 3776 and ICC 7184. Genotype ICC 7184 used the least quantity of water and ICC 4958 used the highest quantity of water at this stage (Table 4.4c). The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture and it wasparticularly associated very close (r^2 = >0.8) in the 15-30, 30-45, and 45-60 cm soil depths. This indicated that the depth wise soil water use was a close indication of total soil water use.

Under OI condition the mean total soil water used by genotypes varied. Genotypes ICC 4958, ICC 8261, ICC 867, ICC 3325, ICC 14778, ICC14799, ICC 283 and ICCV 10 used more soil water than Annigeri. Genotypes ICC 1882, ICC 3776 and ICC 7184 used less soil

Table 4.4c: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 45 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)					
	0-15	15-30	30-45	45-60	60-75	0-75
Drought stressed						
ICC 4958	11.59	12.78	10.25	13.06	4.41	52.09
ICC 8261	11.92	12.19	9.41	9.83	3.94	47.28
ICC 867	11.71	11.25	8.77	11.13	2.96	45.81
ICC 3325	11.85	11.55	11.31	10.85	2.49	48.06
ICC 14778	11.53	11.39	8.04	9.36	3.22	43.55
ICC 14799	11.39	11.99	10.80	10.83	3.94	48.95
ICC 1882	11.95	12.65	8.23	8.93	3.95	45.71
ICC 283	11.73	9.85	8.58	7.75	1.91	39.82
ICC 3776	10.89	9.71	6.51	8.76	3.65	39.52
ICC 7184	11.11	7.80	4.79	6.53	1.85	32.08
Annigeri	11.59	11.18	8.85	9.44	3.99	45.05
ICCV 10	11.88	11.17	8.70	9.94	3.24	44.93
Mean	11.59	11.13	8.69	9.70	3.30	44.40
S.Ed (±)	0.406	0.978	1.67	2.08	1.99	4.66
Optimally irrigated						
ICC 4958	13.91	12.78	18.45	15.90	15.96	76.99
ICC 8261	11.40	10.29	17.44	17.89	16.91	73.93
ICC 867	12.14	11.73	20.04	16.52	17.70	78.12
ICC 3325	12.79	11.61	21.26	17.73	18.14	81.52
ICC 14778	11.10	10.82	15.57	16.74	19.27	73.52
ICC 14799	13.27	10.85	18.61	17.30	18.38	78.40
ICC 1882	8.66	9.72	16.71	14.42	16.20	65.70
ICC 283	12.37	10.38	18.38	16.86	17.34	75.32
ICC 3776	6.58	8.58	20.14	14.82	14.53	64.65
ICC 7184	9.72	7.05	15.91	15.98	16.82	65.48
Annigeri	10.84	10.53	14.39	12.13	12.53	60.41
ICCV 10	12.44	11.26	20.95	16.29	15.51	76.46
Mean	11.27	10.47	18.15	16.05	16.61	72.54
S.Ed (±)	2.27	2.06	2.34	1.59	1.69	6.18

water than the rest of the genotypes. The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture at all soil depths but was not that close as seen under DS environment. Under OI condition, the differences in soil water use in all the depths collectively contributed to the genotypic variation in total soil water use.

4.1.1.5.3 Soil water use by crop at 50 DAS in 2009-10 and 55 DAS in 2010-11

Till the growth stage of 50 DAS in 2009-10 and 55 DAS in 2010-11, crop under OI condition had received only a single irrigation, at 38 DAS in 2009-10 and 30 DAS in 2010-11. However the second irrigation was applied in 2010-11 after the soil samplings were completed. This irrigation under OI condition delayed the 50% flowering of all the genotypes compared to the DS condition. At this stage, crops can effectively use the soil moisture up to 90 cm as the roots had reached 75-90 cm soil depth in all the genotypes. The mean of total crop utilized soil moisture from 0-90 cm depth was 72.3 mm in 2009-10 and 61.7 mm in 2010-11 under DS condition and 84.6 mm in 2009-10 and 107.0 mm in 2010-11 under OI condition (Table 4.4d and 4.4e).

Under DS condition, the genotype ICC 4958 utilized significantly greater soil water than the mean. Crop utilized soil moisture of genotypes ICC 8261, ICC 867, ICC 3325, ICC 14778, ICC 14799, Annigeri and ICCV 10 were greater than that of ICC1882, ICC 283, ICC 3776 and ICC 7184 in 2009-10 and ICC 7184 in 2010-11.

Table 4.4d: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 50 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)						
	0-15	15-30	30-45	45-60	60-75	75-90	0-90
Drought stressed							
ICC 4958	20.99	16.81	13.52	11.72	10.46	5.46	78.96
ICC 8261	20.67	17.28	12.82	10.89	8.16	3.49	73.31
ICC 867	20.16	18.28	13.67	12.09	6.19	1.93	72.31
ICC 3325	20.36	17.68	12.60	10.42	7.46	3.94	72.46
ICC 14778	20.57	17.38	12.95	11.70	7.79	3.16	73.56
ICC 14799	20.51	18.29	13.07	11.30	6.56	3.74	73.47
ICC 1882	20.26	16.86	12.84	9.27	6.53	3.23	68.97
ICC 283	20.07	17.21	12.20	9.60	7.11	3.51	69.71
ICC 3776	20.27	16.66	12.74	11.99	4.98	1.99	68.62
ICC 7184	20.19	16.93	12.30	11.80	6.63	2.26	70.11
Annigeri	20.54	17.26	13.19	12.15	7.14	2.96	73.24
ICCV 10	20.51	17.69	12.95	11.82	7.58	2.64	73.19
Mean	20.43	17.36	12.91	11.23	7.21	3.19	72.33
S.Ed (±)	0.252	0.399	0.509	0.491	0.754	0.629	1.06
Optimally irrigated							
ICC 4958	26.47	28.21	16.95	12.78	8.43	4.63	97.48
ICC 8261	25.49	22.68	17.17	11.68	8.03	5.40	90.45
ICC 867	21.95	23.25	15.95	12.07	8.30	6.08	87.60
ICC 3325	22.30	23.60	16.19	12.53	7.30	4.08	86.00
ICC 14778	22.25	22.16	16.54	11.63	6.20	4.35	83.13
ICC 14799	22.85	23.93	16.75	12.98	6.78	5.73	89.03
ICC 1882	20.67	20.13	15.02	9.00	5.75	4.63	75.20
ICC 283	23.24	21.36	15.82	10.58	6.36	3.78	81.15
ICC 3776	21.99	19.86	15.70	10.58	5.63	3.63	77.40
ICC 7184	21.72	20.58	15.45	10.33	4.56	3.64	76.29
Annigeri	22.00	22.75	16.19	11.62	6.63	4.95	84.13
ICCV 10	24.15	22.80	15.72	12.32	8.13	4.75	87.86
Mean	22.92	22.61	16.12	11.51	6.84	4.64	84.64
S.Ed (±)	0.600	1.36	1.24	1.29	1.35	1.56	3.33

Table 4.4e: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 55 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)						
	0-15	15-30	30-45	45-60	60-75	75-90	0-90
Drought stressed							
ICC 4958	11.48	13.47	12.41	14.95	7.47	5.79	65.57
ICC 8261	11.75	13.28	11.88	13.49	5.36	3.34	59.08
ICC 867	11.89	13.33	12.25	13.92	5.04	5.61	62.03
ICC 3325	11.93	15.20	13.68	12.51	4.04	3.27	60.63
ICC 14778	11.80	14.62	13.32	12.26	5.38	4.46	61.83
ICC 14799	11.95	14.14	13.72	14.52	10.09	8.78	73.19
ICC 1882	11.92	14.69	13.54	12.91	7.31	4.68	65.05
ICC 283	11.78	14.57	14.15	13.64	4.98	3.22	62.34
ICC 3776	11.59	11.81	11.28	11.63	5.86	5.06	57.24
ICC 7184	11.74	10.69	9.21	9.51	2.14	3.03	46.32
Annigeri	11.81	14.07	12.28	15.21	8.94	7.02	69.33
ICCV 10	11.95	14.63	13.00	11.72	4.25	2.21	57.75
Mean	11.80	13.71	12.56	13.02	5.90	4.71	61.70
S.Ed (±)	0.255	1.28	1.06	1.65	1.89	1.93	5.52
Optimally irrigated							
ICC 4958	17.60	19.26	26.93	18.67	19.42	8.54	110.4
ICC 8261	16.31	19.63	26.18	18.62	18.57	8.99	108.3
ICC 867	17.59	19.65	28.30	19.37	20.68	11.38	117.0
ICC 3325	16.94	19.74	31.02	22.18	20.90	10.78	121.6
ICC 14778	15.79	18.40	23.60	17.14	21.15	8.66	104.7
ICC 14799	17.27	18.08	26.73	20.89	20.11	10.86	113.9
ICC 1882	14.65	17.02	24.96	17.33	17.84	10.41	102.2
ICC 283	17.01	18.02	25.38	19.41	18.93	8.82	107.6
ICC 3776	11.56	13.58	23.17	17.21	15.70	8.46	89.7
ICC 7184	14.85	14.37	20.82	17.00	17.19	8.80	93.0
Annigeri	15.01	18.65	24.57	17.55	17.60	10.01	103.4
ICCV 10	16.62	21.23	29.27	19.58	18.37	7.53	112.6
Mean	15.93	18.13	25.91	18.75	18.87	9.43	107.0
S.Ed (±)	2.01	1.82	2.24	1.58	1.97	1.24	7.08

The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture at all the soil depths except the surface 0.15cm soil depth as this layer is more prone to soil water loss through evaporation. The above mentioned eight genotypes used significantly greater amount of water, but use from certain depths seem to help some of these genotypes in this use. Genotypes ICC 867 and ICC 14799 used more water than others from soil depth 15-30 cm, ICC 4958 and ICC 867 used more water than ICC 3325, ICC 283 and ICC 7184 from soil depth 30-45 cm, all the genotypes other than ICC 8261, ICC 3325, ICC 1882 and ICC 283 used more water from soil depth 45-60 cm, ICC 4958 and ICC 8261 used more water than ICC 867, ICC 14799, ICC 1882, ICC 3776 and ICC 7184 from soil depth 60-75 cm and ICC 4958, ICC 3325 and ICC 14799 used more water than ICC 867, ICC 3776, ICC 7184, and ICCV 10 from soil depth 75-90 cm in 2009-10. Genotypes ICC 3325, ICC 14778, ICC 14799, ICC 1882, ICC 283 and ICCV 10 used more water than ICC 3776 and ICC 7184 from soil depths 15-30 cm and 30-45 cm, ICC 4958 and Annigeri used more water than ICC 3776 and ICC 7184 from soil depth 45-60 cm, ICC 14799 used more water than 7 others from soil depths 60-75 cm and 75-90 cm in 2010-11.

Under OI condition, a good level of consistency was noticeable among the genotypes in water use across years. Genotypes ICC 4958, ICC 8261, ICC 867, ICC 3325, ICC 14799 and ICCV 10 utilized significantly greater soil water than ICC 3776 and ICC 7184 in both the years. ICC 283 in 2009-10 and Annigeri in 2010-11 had also

utilized more water than ICC 3776 and ICC 7184. The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture at all the soil depths except the deepest 75-90 cm soil depth as this layer is more variation in the quantum of root presence. The above mentioned six genotypes used significantly greater amount of water, but their high use was limited to certain depths helping these genotypes in maximizing the total use. Genotype ICC 4958 in 0-15, 15-30, 45-60 and 60-75 cm soil depths, ICC 8261 in 0-15 cm soil depth, ICC 867 in 60-75 cm soil depth, ICC 14799 in 45-60 cm soil depth, ICCV 10 in 0-15 and 60-75 cm soil depth used significantly more soil water. ICC 3325 was unique in exploiting all the depths consistently more than average ensuring in a greater total use.

4.1.1.5.4 Soil water use by crop at 65 DAS in 2010-11

Growth stage at 65 DAS, crop under DS condition was at mid- to late pod fill stage while in the irrigated condition at the early pod fill stage. At this stage, the presence of roots was traced up to 90-105 cm in all the genotypes and the crop can effectively use the soil moisture up to this depth. The mean of total crop utilized soil moisture at the whole profile of 0-105 cm depth was 83.7 mm under DS and 131.3 mm under OI condition (Table 4.4f). Under DS condition, genotypes ICC 14778, ICC 14799, ICC 1882, Annigeri and ICCV 10 utilized significantly greater soil water than ICC 4958, ICC 3776 and ICC 7184. Soil water used by genotypes ICC 8261, ICC 867, ICC 3325 and

Table 4.4f: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 65 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)							
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	0-105
Drought stressed								
ICC 4958	11.44	13.55	11.72	15.01	7.86	7.35	8.95	75.87
ICC 8261	11.95	13.96	13.11	16.42	11.11	7.65	6.58	80.76
ICC 867	11.95	14.09	12.38	15.16	10.21	8.41	9.01	81.21
ICC 3325	11.84	14.16	15.20	16.53	11.16	9.67	7.23	85.80
ICC 14778	11.94	14.88	15.55	18.96	14.08	7.45	5.57	88.42
ICC 14799	11.95	14.28	15.83	19.25	14.62	13.02	10.06	99.02
ICC 1882	11.79	15.31	14.91	17.79	12.71	8.78	7.07	88.35
ICC 283	11.95	15.93	15.98	19.01	10.33	5.84	5.32	84.35
ICC 3776	11.72	11.85	11.94	14.75	8.93	7.65	7.23	74.06
ICC 7184	11.95	11.70	11.33	14.60	5.91	3.99	4.12	63.59
Annigeri	11.13	14.12	13.16	18.44	13.79	10.57	10.49	91.70
ICCV 10	11.95	15.95	16.98	18.90	13.19	7.46	6.92	91.35
Mean	11.79	14.15	14.01	17.07	11.16	8.15	7.38	83.71
S.Ed (±)	0.302	1.25	1.27	1.21	1.54	1.94	2.19	5.72
Optimally irrigated								
ICC 4958	19.59	21.33	30.84	20.98	23.85	9.52	8.43	134.5
ICC 8261	18.23	22.12	30.29	21.63	22.67	10.11	6.54	131.6
ICC 867	19.30	21.67	30.83	22.34	24.93	12.22	13.00	144.3
ICC 3325	18.81	22.23	34.65	25.19	25.23	12.57	11.13	149.8
ICC 14778	17.73	19.48	27.23	19.41	24.59	10.13	9.39	128.0
ICC 14799	19.23	20.56	30.77	23.32	23.50	11.23	10.76	139.4
ICC 1882	16.30	19.51	29.14	20.18	20.07	10.75	10.69	126.6
ICC 283	18.87	20.32	28.94	22.42	22.79	9.93	11.29	134.6
ICC 3776	12.68	16.67	26.60	19.23	17.16	8.80	8.96	110.1
ICC 7184	16.07	15.06	23.52	20.55	19.00	9.47	12.23	115.9
Annigeri	16.75	19.70	27.64	19.28	21.95	11.10	7.20	123.6
ICCV 10	18.32	23.43	32.91	22.59	22.68	8.66	8.63	137.2
Mean	17.66	20.17	29.45	21.42	22.37	10.37	9.85	131.3
S.Ed (±)	1.98	1.82	2.38	1.72	2.15	1.44	2.19	8.62

ICC 283 were close to the mean. The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture at all the soil depths except the surface (0-15 cm) and the deepest (90-105 cm) soil depths.

Under OI condition, genotypes ICC 4958, ICC 8261, ICC 867, ICC 3325, ICC 3325, ICC 14799, ICC 283 and ICCV 10 used significantly greater amount of soil water than ICC 3776 and ICC 7184. Soil water used by genotypes ICC 14778, ICC 1882 and Annigeri were close to the mean. Similar to the DS treatment, the depth wise soil water utilization was significantly proportionate to the total soil water use permitting visualization of soil water across various depths.

4.1.1.5.5 Soil water use by crop at 80 DAS in 2009-10 and 75 DAS in 2010-11

At this growth stage of 80 DAS in 2009-10 and 75 DAS in 2010-11 the DS crop was between mid pod fill stage to close to maturity with the earliest ICC 4958 already matured in 2009-10. But the OI crop was largely at mid pod fill stage and by this stage received three irrigations at 38, 64 and 79 DAS in 2009-10 and received two irrigations at 35 and 55 DAS. These irrigations delayed the maturity under OI condition compared to the DS condition. At this stage, the RDp was a maximum of 120 cm and the crops can effectively use the soil moisture up to this depth. All the genotypes had their root presence in the 105-120 cm soil depth. The mean of total crop utilized soil moisture from the 0-120 cm depth was 126.0 mm in 2009-10

(Table 4.4g) and 106.6 mm in 2010-11 (Table 4.4h) under DS condition while it was 238.9 mm in 2009-10 and 158.4 mm in 2010-11 under OI condition.

Under DS condition, genotypes ICC 867, ICC 14778, ICC 14799, ICC 283 and ICCV 10 used significantly greater quantum of soil water than the mean while ICCV 10 utilized the highest in 2009-10. Genotypes ICC 14778, ICC 14799, ICC 1882, Annigeri and ICCV 10 used more water in 2010-11. Genotypes ICC 4958, ICC 8261 and ICC 7184 in 2009-10 and ICC 8261, ICC 3776 and ICC 7184 in 2010-11 used lesser water than the mean. Rest of the genotypes used moderate levels of water. Under DS condition, the depth wise soil water use of the genotypes was significantly proportionate to the total water use from depth 60-75 onwards in all the deeper depths in 2009-10. In the four surface soil depths the genotypic variation in water use did not exist. Or in other words all the soil water that can be taken up was exhausted by both T and evaporation. In 2010-11 the depth wise soil water use was significantly proportionate to the total water use from depth 30-45 onwards in all the deeper depths. In the two surface soil depths the genotypic variation in water use did not exist.

Under OI condition, genotypes ICC 867, ICC 14778, ICC 14799, Annigeri and ICCV 10 used significantly greater quantum of soil water than the mean in 2009-10 and genotypes ICC 867, ICC 3325, ICC 14799, ICC 283 and ICCV 10 used more water in 2010-11. Genotypes ICC 1882, ICC 3776 and ICC 7184 in 2009-10 and ICC 3776, ICC 7184 and Annigeri in 2010-11 used lesser water than the

Table 4.4g: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 80 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)								
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	0-120
Drought stressed									
ICC 4958	17.56	19.79	21.70	21.39	18.01	14.23	7.92	1.06	121.7
ICC 8261	17.72	19.73	21.47	22.17	18.21	13.06	7.92	2.54	122.8
ICC 867	19.81	19.59	22.04	21.70	18.64	13.61	9.30	4.64	129.3
ICC 3325	19.47	19.14	21.45	21.80	19.33	11.91	8.05	3.79	125.0
ICC 14778	19.82	19.04	21.60	22.24	19.49	12.01	8.29	4.59	127.1
ICC 14799	19.77	19.54	21.74	22.04	19.18	13.61	9.94	3.94	129.8
ICC 1882	19.86	18.64	22.10	21.42	17.51	14.03	9.37	1.88	124.8
ICC 283	18.64	19.04	21.60	21.14	19.03	14.13	10.07	3.54	127.2
ICC 3776	19.59	19.23	21.87	21.80	18.23	12.68	8.72	2.96	125.1
ICC 7184	19.69	18.83	21.62	21.39	18.71	11.43	7.74	1.89	121.3
Annigeri	19.26	19.11	21.59	21.54	18.29	13.26	9.35	4.34	126.7
ICCV 10	19.56	19.33	21.49	22.15	19.43	13.78	9.70	5.48	130.9
Mean	19.23	19.25	21.69	21.73	18.67	13.14	8.87	3.39	126.0
S.Ed (±)	0.330	0.214	0.516	0.335	0.452	0.522	0.499	0.490	0.541
Optimally irrigated									
ICC 4958	48.52	46.98	38.56	34.78	32.75	25.29	11.43	2.30	240.6
ICC 8261	47.78	45.96	38.68	38.29	28.84	25.21	12.08	5.06	241.9
ICC 867	47.16	46.23	36.67	36.04	33.45	29.08	13.80	8.46	250.9
ICC 3325	46.77	45.93	35.89	36.83	28.28	20.03	14.05	13.70	241.5
ICC 14778	46.03	46.38	37.66	36.71	29.32	27.01	16.53	8.10	247.7
ICC 14799	47.60	45.70	38.90	35.23	32.50	28.83	11.57	8.00	248.3
ICC 1882	45.96	44.26	35.97	35.32	24.09	23.22	9.75	4.77	223.3
ICC 283	47.33	44.68	37.11	37.34	31.77	25.39	10.86	6.84	241.3
ICC 3776	46.16	45.06	34.80	32.77	24.63	19.62	9.98	7.41	220.4
ICC 7184	45.44	43.42	35.51	33.36	24.99	15.77	13.53	5.13	217.1
Annigeri	44.74	43.51	34.87	37.52	28.02	26.18	16.95	11.59	243.4
ICCV 10	45.90	43.11	36.29	33.62	35.34	30.28	15.14	10.03	249.7
Mean	46.62	45.10	36.74	35.65	29.50	24.66	12.97	7.62	238.9
S.Ed (±)	0.527	1.64	1.16	1.44	1.72	2.39	2.96	2.72	1.96

Table 4.4h: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 75 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)								
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	0-120
Drought stressed									
ICC 4958	11.70	15.65	12.87	15.66	11.68	10.47	11.65	12.88	102.6
ICC 8261	11.77	13.68	12.95	16.52	12.80	10.61	8.68	6.52	93.5
ICC 867	11.69	14.31	14.06	18.67	15.32	8.67	9.59	12.01	104.3
ICC 3325	11.95	14.66	15.51	18.10	12.99	11.97	9.67	11.18	106.0
ICC 14778	11.95	14.67	15.29	18.80	16.81	15.59	11.95	8.65	113.7
ICC 14799	11.95	15.62	16.52	18.78	15.41	14.01	13.12	12.99	118.4
ICC 1882	11.92	15.67	16.44	18.83	15.09	13.59	10.50	11.65	113.7
ICC 283	11.95	15.78	16.61	19.01	14.01	10.30	9.90	10.71	108.3
ICC 3776	11.83	11.85	12.29	14.85	10.56	10.57	10.87	10.47	93.3
ICC 7184	11.94	15.20	14.86	16.49	11.43	9.01	5.75	6.23	90.9
Annigeri	11.95	14.27	14.13	19.34	15.63	14.66	13.54	13.76	117.3
ICCV 10	11.95	15.81	16.94	19.35	15.10	12.98	11.94	13.26	117.3
Mean	11.88	14.76	14.87	17.87	13.90	11.87	10.60	10.86	106.6
S.Ed (±)	0.168	1.11	1.48	0.93	1.44	1.56	1.22	1.89	4.30
Optimally irrigated									
ICC 4958	21.92	23.93	35.13	23.38	26.12	10.46	8.91	9.02	158.9
ICC 8261	20.47	25.15	34.87	24.79	26.87	11.27	8.60	6.35	158.4
ICC 867	21.31	24.22	33.87	25.43	29.15	15.13	14.48	11.89	175.5
ICC 3325	21.10	25.23	38.69	28.25	29.43	14.42	12.21	11.24	180.6
ICC 14778	20.01	22.08	31.26	21.78	27.95	11.49	10.24	7.10	151.9
ICC 14799	21.56	23.55	35.30	25.94	26.88	13.67	11.65	8.94	167.5
ICC 1882	18.37	22.52	33.64	23.00	22.37	11.13	8.77	10.55	150.3
ICC 283	21.16	23.16	32.95	25.59	26.57	11.10	12.23	14.99	167.8
ICC 3776	14.23	19.33	30.54	21.62	18.89	9.26	9.29	9.23	132.4
ICC 7184	17.57	17.14	26.51	23.30	23.93	10.21	11.13	15.68	145.5
Annigeri	18.88	22.30	31.23	22.06	24.42	12.20	7.39	6.97	145.4
ICCV 10	20.44	26.17	37.01	25.83	27.05	10.81	9.66	10.14	167.1
Mean	19.75	22.90	33.42	24.25	25.80	11.76	10.38	10.17	158.4
S.Ed (±)	2.01	1.87	2.62	1.91	2.46	1.71	2.36	2.55	10.4

greater soil water using genotypes. Rest of the genotypes used moderate levels of water. Under OI condition, the depth wise soil water use of the genotypes was significantly proportionate to the total water use from depth 30-45 onwards in all the deeper depths except 105-

120 cm in 2009-10 and all the depths except 105-120 cm in 2010-11. The nonexistence of genotypic variation in water use in the two surface soil depths the genotypic variation was likely due to complete exhaustion of soil water by both T and evaporation.

4.1.1.5.6 Soil water use by crop at 90 DAS in 2010-11

By growth stage 90 DAS, crop under OI condition had received three irrigations at 30, 55 and 76 DAS. At this stage, under DS condition, genotypes ICC 4958, ICC 867, ICC 283, Annigeri, and ICCV 10 had already matured while the others were approaching maturity. Under DS condition, all the genotypes had matured 5-15 days later than this day. At this stage, the root system can be traced up to 120 cm providing for effective use of soil water up to this depth. At this the mean total crop water use was 112.0 mm under DS and 204.1 mm under OI conditions (Table 4.4i).

Under DS condition, genotypes ICC 3325, ICC 14778, ICC 14799, ICC 1882, ICC 283, Annigeri and ICCV 10 used significantly greater soil water than the genotypes ICC 4958, ICC 8261, ICC 867, ICC 3776 and ICC 7184. The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture at all the soil depths except 0-15 and 15-30 cm.

Under OI condition, genotypes ICC 867, ICC 3325, ICC 14799, ICC 283 and ICCV 10 used significantly greater soil water than the genotypes ICC 14778, ICC 1882, ICC 3776, ICC 7184 and Annigeri. The depth wise crop utilized soil moisture was significantly proportionate to the total crop utilized soil moisture at all

Table 4.4i: Crop utilized soil moisture of 12 diverse genotypes of chickpea at 90 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

Genotypes/ treatment	Crop utilized soil moisture (mm)								
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	0-120
Drought stressed									
ICC 4958	11.62	15.15	13.22	16.22	10.17	10.56	11.91	12.28	101.1
ICC 8261	11.95	15.14	12.79	16.47	11.22	13.01	10.27	10.41	101.2
ICC 867	11.82	14.88	13.11	15.75	11.28	10.01	11.38	11.08	99.3
ICC 3325	11.56	15.12	15.45	18.10	13.71	12.25	14.10	15.20	115.5
ICC 14778	11.95	14.66	15.47	19.93	15.95	13.64	12.65	12.68	116.9
ICC 14799	11.95	15.93	15.35	19.27	14.72	14.27	12.93	13.60	118.0
ICC 1882	11.97	16.45	16.77	18.92	14.69	13.97	11.65	13.16	117.6
ICC 283	11.95	15.69	15.89	19.80	14.24	12.95	13.76	15.39	119.7
ICC 3776	11.95	11.67	12.30	16.04	13.65	14.37	15.05	13.83	108.9
ICC 7184	11.54	14.03	13.77	16.80	11.70	12.15	10.13	6.91	97.0
Annigeri	11.95	16.52	17.33	18.20	14.48	15.47	14.87	13.87	122.7
ICCV 10	11.95	16.44	17.13	21.56	15.63	14.16	14.05	14.58	125.5
Mean	11.84	15.14	14.88	18.09	13.45	13.07	12.73	12.75	112.0
S.Ed (±)	0.252	1.22	0.922	1.09	1.62	1.03	0.849	1.87	3.54
Optimally irrigated									
ICC 4958	29.60	34.24	46.13	28.03	28.90	11.35	9.41	10.07	197.7
ICC 8261	27.99	36.34	47.40	31.22	34.23	13.59	9.93	6.58	207.3
ICC 867	28.10	34.48	44.73	31.46	35.05	18.66	16.85	13.46	222.8
ICC 3325	29.59	35.95	49.79	33.42	33.96	17.83	14.93	13.63	229.1
ICC 14778	27.60	32.17	42.16	26.62	32.01	12.28	9.64	7.47	189.9
ICC 14799	29.53	34.02	47.94	32.30	31.44	16.58	13.87	9.59	215.3
ICC 1882	26.65	33.38	44.19	26.85	26.61	12.17	11.57	11.00	192.4
ICC 283	29.74	34.16	44.46	32.28	31.11	13.70	14.76	17.53	217.7
ICC 3776	21.86	30.24	42.72	29.83	25.05	11.34	10.14	9.52	180.7
ICC 7184	23.46	25.13	34.72	30.05	29.88	12.27	13.08	19.08	187.7
Annigeri	26.86	32.95	42.89	26.96	30.88	14.18	7.99	7.87	190.6
ICCV 10	28.68	36.66	48.70	33.49	33.97	13.25	11.62	11.69	218.1
Mean	27.47	33.31	44.65	30.21	31.09	13.93	11.98	11.46	204.1
S.Ed (±)	2.17	2.06	2.80	2.07	3.46	2.12	2.82	2.99	12.4

the soil depths except 105-120 cm. But the differences in total use were more influenced by the use at the depths from 60-105 cm.

4.1.2 Contribution of physiological traits to the grain yield

4.1.2.1 Root attributes

4.1.2.1.1 Effect of root attributes on grain yield at 35 DAS in both years

RLD (cm cm^{-3}) and the RDW (g m^{-3}) measured at various depths and at various growth stages were used for association with grain yield recorded at crop maturity through path analysis. A path coefficient calculated through path analysis is a standardized partial regression coefficient and as such measures the direct influence of one variable upon another and permits the separation of the correlation coefficient into components of direct and indirect effects. Path analysis has certain additional advantages over correlations or regressions. This additional advantage is the availability of distribution matrix of coefficients that are interrelated among the contributory attributes in a range of negative and positive coefficients and indicating the contribution of one contributory attribute to all the others. The direct and indirect effects of variables that ranged between -0.05 to 0.05 were considered to be null and were not discussed in this result.

At 35 DAS, under DS condition in 2009-10, the RLD at 0-15 and 30-45 cm soil depth contributed to grain yield positively but these contributions did not lead to a significant correlation with grain yield (Table 4.5a). The RLD and RDW of other two depths did not possess considerable path coefficients (Table 4.5a). The RDW also showed a similar trend of path coefficient distribution. But the RDW at 45-60

soil depth had a negative path coefficient. Under OI condition in 2009-10, the RLD in none of the soil depths had contributed to grain yield but the collective negative effect was large to some extent but not significant. The RDW at 45-60 cm soil depth had a direct negative contribution which resulted in a significantly negative correlation with yield. This is understandable as live contributing roots at the depth will suffer oxygen deficiency caused due to transient water logging for a period of time immediately after the next irrigation particularly in heavier soils.

At 35 DAS, under DS condition in 2010-11 the RLD contribution pattern was closely similar to 2009-10 except that a massive negative contribution came from the RLD at 0-15 cm (Table 4.5b). This effect did not reflect on the correlation coefficient with the grain yield due to a large positive contribution from the RLD of 30-45 cm soil depth. The RDW contribution also followed similar trend as that of the RLD. Under OI condition both RLD and RDW of 15-30 cm soil depth had provided positive contribution to grain yield and this has emerged into a significant and positive correlation with grain yield in spite of some negative contributions from RLD and RDW of 0-15 cm soil depth. Another interesting observation at this stage is the complete absence of roots in the 45-60 cm soil in the OI condition while there were roots in the DS condition. This crop received the first treatmental irrigation five days before and this clearly seemed to arrest the progression of RDp.

4.1.2.1.2 Effect of root attributes on grain yield at 45 DAS in 2010-11

At 45 DAS, under DS condition in 2009-10, the correlation coefficients of RLD and RDW from all depths were positive unlike the mixed variation observed across depths at 35 DAS sample. Both the RLD and RDW at 0-15 cm soil depth had directly contributed to grain yield at <0.01 level and those at 15-30 cm soil depth at <0.05 level (Table 4.5c). But RLD from 30-45 cm depth had a high positive indirect contribution to the RLD at 15-30 cm leading to a positive correlation with grain yield. Also the direct contribution of RLD from the 30-45 cm soil depth was high but marginally short of significance at <0.05 level. RLD from depth60-75 was all negative. Largely the contributions of RDW were negative at the 30-45 cm soil depth and the RDW from 60-75 cm soil depth was all positive but these effects did not translate into a significance of the correlation coefficient.

Under OI condition, the overall positive correlation coefficients seen across all the depths under DS were not noticeable but the positive coefficients were limited to roots of 15-30 and 30-45 depths. The major direct contribution is noticeable for RLD at 15-30 cm depth and for RDW at 30-45 cm depth. This had emphasized these two depths to be important for contribution towards grain yield. Importantly a prominent contribution seen by RDW of 60-75 cm soil depth under DS condition could also be seen here.

Table 4.5a: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 35 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

	Root length density (cm cm^{-3})					Root dry weight (g m^{-3})				
	0-15	15-30	30-45	45-60	Yld kgha^{-1}	0-15	15-30	30-45	45-60	Yld kgha^{-1}
Drought stressed										
0-15	**0.273**	-0.032	-0.005	0.001	0.237	**0.155**	0.014	0.025	-0.040	0.153
15-30	0.109	**-0.081**	0.008	-0.015	0.022	0.085	**0.026**	0.049	-0.150	0.010
30-45	-0.008	-0.004	**0.178**	-0.007	0.159	0.034	0.012	**0.112**	-0.079	0.078
45-60	-0.008	-0.029	0.028	**-0.043**	-0.052	0.022	0.014	0.031	**-0.289**	-0.223
Optimally irrigated										
0-15	**-0.203**	-0.043	0.009	-0.029	-0.265	**-0.246**	0.128	0.125	-0.249	-0.242
15-30	-0.132	**-0.066**	0.007	-0.046	-0.237	-0.158	**0.198**	0.118	-0.231	-0.073
30-45	-0.063	-0.015	**0.029**	-0.042	-0.090	-0.135	0.103	**0.226**	-0.206	-0.012
45-60	-0.042	-0.022	0.009	**-0.138**	-0.194	-0.111	0.083	0.085	**-0.550**	-0.494**

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

Table 4.5b: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 35 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Root length density (cm cm^{-3})					Root dry weight (g m^{-3})				
	0-15	15-30	30-45	45-60	Yld kgha^{-1}	0-15	15-30	30-45	45-60	Yld kgha^{-1}
Drought stressed										
0-15	**-0.905**	0.123	0.657	0.011	-0.114	**-0.253**	0.093	0.138	-0.012	-0.034
15-30	-0.750	**0.149**	0.674	0.008	0.082	-0.185	**0.128**	0.119	0.013	0.075
30-45	-0.676	0.114	**0.879**	0.004	0.322	-0.175	0.076	**0.199**	0.028	0.128
45-60	0.138	-0.017	-0.054	**-0.073**	-0.005	-0.016	-0.009	-0.031	**-0.180**	-0.237
Optimally irrigated										
0-15	**-0.376**	0.381	0.004	NA	0.008	**-0.187**	0.300	-0.094	NA	0.019
15-30	-0.202	**0.710**	0.006	NA	0.514***	-0.076	**0.738**	-0.093	NA	0.569***
30-45	-0.094	0.287	**0.014**	NA	0.207	-0.096	0.374	**-0.183**	NA	0.094

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

Table 4.5c: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 45 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Root length density (cm cm^{-3})						Root dry weight (g m^{-3})					
	0-15	15-30	30-45	45-60	60-75	Yld $kgha^{-1}$	0-15	15-30	30-45	45-60	60-75	Yld $kgha^{-1}$
Drought stressed												
0-15	**0.358**	0.182	0.001	0.055	-0.099	0.498**	**0.421**	0.111	-0.059	-0.015	0.088	0.546***
15-30	0.173	**0.376**	0.003	0.043	-0.118	0.478**	0.123	**0.378**	-0.122	-0.013	0.017	0.383*
30-45	0.109	0.237	**0.005**	0.069	-0.151	0.268	0.094	0.177	**-0.261**	-0.027	0.176	0.160
45-60	0.193	0.157	0.003	**0.103**	-0.168	0.287	0.155	0.119	-0.171	**-0.041**	0.137	0.198
60-75	0.150	0.187	0.003	0.073	**-0.237**	0.177	0.119	0.021	-0.147	-0.018	**0.313**	0.287
Optimally irrigated												
0-15	**-0.049**	-0.102	0.000	0.047	0.019	-0.084	**0.271**	-0.013	0.001	0.072	-0.171	0.160
15-30	0.012	**0.430**	0.001	-0.047	-0.014	0.382*	-0.022	**0.157**	0.227	-0.028	0.063	0.396*
30-45	0.004	0.154	**0.004**	-0.063	-0.002	0.096	0.001	0.094	**0.378**	-0.038	0.014	0.449**
45-60	0.016	0.139	0.002	**-0.145**	-0.050	-0.039	-0.094	0.022	0.070	**-0.206**	0.185	-0.024
60-75	0.014	0.089	0.000	-0.107	**-0.067**	-0.072	-0.123	0.026	0.014	-0.101	**0.377**	0.193

Yld $kgha^{-1}$= Grain yield (kg ha^{-1}) at final maturity

4.1.2.1.3 Effect of root attributes on grain yield at 50 DAS in 2009-10 and 55 DAS in 2010-11

At 50 DAS, under DS condition in 2009-10, the path coefficients of RLD and RDW from all depths except 0-15 cm had positive contribution to grain yield like the variation seen at 45 DAS (Table 4.5d). The RLD at 0-15 cm soil depth had a direct negative contribution to grain yield. The RLD of 30-45 and 60-75 cm soil depths had a direct and relatively high positive contribution to the grain yield resulting with significant correlation coefficients. The RDW of 45-60 cm soil depth provided similar contribution except for the reduced significance level. Under OI condition, the path coefficients of RLD and RDW from all the depths except 30-45 and 45-60 cm were positive. RLD at 0-15 and 75-90 had a direct and highly positive contribution to the grain yield but only the soil depth 75-90 cm showed a significant relationship with the grain yield. The RDW was also followed the same pattern with the inclusion of the relatively moderate positive contribution from 60-75 cm soil depth. This stage represents early pod filling and demonstrates the importance of soil zones from where more water is absorbed influencing the grain yield.

At 55 DAS in 2010-11, the path coefficients of RLD and RDW from the initial four depths under DS, and 15-30, 30-45 and 60-75 cm under OI condition had contributed consistently and positively to grain yield (Table 4.5e). Under DS condition, all the initial four soil depths were significantly correlated with the grain yield and the roots from soil depth 0-15 cm showed a high positive direct effect followed

Table 4.5d: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 50 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

	Root length density (cm cm^{-3})							Root dry weight (g m^{-3})						
	0-15	15-30	30-45	45-60	60-75	75-90	Yld kgha^{-1}	0-15	15-30	30-45	45-60	60-75	75-90	Yld kgha^{-1}
Drought stressed														
0-15	**-0.596**	-0.013	0.287	0.143	0.250	-0.027	0.043	**-0.121**	0.001	0.033	0.083	-0.003	0.010	0.004
15-30	-0.157	**-0.049**	0.249	0.091	0.053	-0.021	0.166	-0.002	**0.057**	0.020	0.103	-0.008	0.005	0.174
30-45	-0.369	-0.026	**0.463**	0.171	0.209	-0.031	0.417**	-0.073	0.021	**0.055**	0.133	-0.011	0.019	0.143
45-60	-0.405	-0.021	0.376	**0.210**	0.181	-0.036	0.305	-0.039	0.023	0.028	**0.255**	-0.013	0.012	0.267
60-75	-0.321	-0.006	0.209	0.082	**0.464**	-0.082	0.347*	-0.017	0.023	0.029	0.166	**-0.020**	0.028	0.209
75-90	-0.148	-0.009	0.130	0.069	0.344	**-0.110**	0.275	-0.031	0.008	0.027	0.085	-0.015	**0.038**	0.112
Optimally irrigated														
0-15	**0.729**	-0.600	-0.036	-0.058	-0.090	0.250	0.193	**0.246**	-0.090	-0.020	-0.150	0.039	0.153	0.178
15-30	0.644	**-0.679**	-0.049	-0.050	-0.078	0.264	0.053	0.171	**-0.130**	-0.051	-0.171	0.071	0.174	0.066
30-45	0.363	-0.458	**-0.073**	-0.023	-0.070	0.132	-0.129	0.044	-0.058	**-0.115**	-0.092	-0.002	-0.063	-0.286
45-60	0.347	-0.277	-0.013	**-0.123**	-0.085	0.095	-0.058	0.111	-0.066	-0.032	**-0.333**	0.111	0.236	0.028
60-75	0.328	-0.263	-0.025	-0.052	**-0.201**	0.465	0.251	0.059	-0.056	0.002	-0.225	**0.165**	0.278	0.223
75-90	0.287	-0.282	-0.015	-0.018	-0.147	**0.635**	0.459**	0.071	-0.042	0.014	-0.147	0.086	**0.534**	0.514***

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

Table 4.5e: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 55 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Root length density (cm cm^{-3})							Root dry weight (g m^{-3})						
	0-15	15-30	30-45	45-60	60-75	75-90	Yld kgha^{-1}	0-15	15-30	30-45	45-60	60-75	75-90	Yld kgha^{-1}
Drought stressed														
0-15	**0.418**	0.102	0.018	0.119	-0.058	-0.050	0.549***	**0.130**	0.064	-0.035	0.195	-0.053	0.013	0.314
15-30	0.339	**0.125**	0.017	0.094	-0.058	-0.036	0.482**	0.064	**0.130**	-0.070	0.297	-0.093	0.013	0.341*
30-45	0.215	0.060	**0.035**	0.216	-0.076	-0.058	0.393*	0.031	0.062	**-0.146**	0.419	-0.120	0.010	0.256
45-60	0.165	0.039	0.025	**0.302**	-0.066	-0.046	0.419**	0.039	0.059	-0.094	**0.651**	-0.188	0.012	0.479**
60-75	0.222	0.066	0.025	0.183	**-0.109**	-0.073	0.315	0.027	0.048	-0.070	0.491	**-0.250**	0.014	0.260
75-90	0.196	0.042	0.019	0.130	-0.074	**-0.107**	0.206	0.039	0.041	-0.035	0.179	-0.081	**0.042**	0.186
Optimally irrigated														
0-15	**0.020**	0.071	0.060	-0.105	0.095	-0.003	0.138	**-0.049**	0.058	0.029	-0.136	0.150	0.035	0.087
15-30	0.004	**0.331**	0.478	-0.286	0.089	-0.007	0.611***	-0.007	**0.403**	0.297	-0.434	0.158	0.047	0.464**
30-45	0.002	0.203	**0.781**	-0.441	0.177	-0.030	0.692***	-0.003	0.248	**0.483**	-0.462	0.177	0.040	0.482**
45-60	0.004	0.178	0.648	**-0.531**	0.218	-0.037	0.481**	-0.010	0.257	0.327	**-0.682**	0.245	0.089	0.226
60-75	0.005	0.079	0.369	-0.308	**0.376**	-0.056	0.464**	-0.018	0.153	0.205	-0.401	**0.416**	0.114	0.470**
75-90	0.001	0.023	0.229	-0.196	0.209	**-0.101**	0.166	-0.009	0.101	0.102	-0.324	0.253	**0.188**	0.310

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

by roots at 45-60 and 15-30 cm. The RDW of 0-15, 15-30 and 45-60 cm soil depths have had a positive direct effect on grain yield and the RDW at soil depth 45-60 has showed relatively highest direct contribution to the grain yield at <0.01 significance level. Under OI condition, both RLD and RDW at 30-45 cm soil depth had a high direct and significant contribution to the grain yield and this significant contribution pattern was also followed by the roots at soil depths 60-75 and 15-30 cm. Even though the RLD and RDW at 45-60 cm soil depths have had a high negative direct contribution to grain yield, it was masked by the positive indirect effect of adjacent soil depths making the overall correlation coefficients significantly positive.

In both the years under DS condition, RLD and RDW at soil depth at 45-60 cm had a moderate to high, consistent positive contribution to grain yield across years and resulted into a significant correlation at p=<0.01 level in 2010-11. Under OI condition this significant contribution came largely from the roots of soil depth 75-90 cm in 2009-10 and 30-45 cm in 2010-11. Therefore at this stage, the roots at soil depth 45-60 cm had been critical to provide a consistent, relatively more direct contribution to the grain yield under DS condition.

4.1.2.1.4 Effect of root attributes on grain yield at 65 DAS in 2010-11

At 65 DAS in 2010-11, the correlation coefficients of RLD and RDW from all depths were positive with grain yield except at 0-15 cm

soil depth. The RLD and RDW of soil depths at 15-30, 45-60 and 60-75 cm under DS, and 15-30, 30-45 and 75-90 cm under OI condition had positive direct effect on grain yield (Table 4.5f).

Under DS condition, the direct contribution of RLD and RDW to grain yield was highest from 60-75 cm soil depth at p=<0.001 (Table 4.5f). Interestingly, similar direct contribution was seen from 45-60 cm soil depth at the crop age of 55 DAS (Table 4.5e), indicating that the critical contribution of RLD and RDW to grain yield had shifted towards the deeper soil zones with the advance in crop age or as the rooting front extends. In addition to roots of 60-75 cm, the RLD and RDW from soil depths 30-45 and 45-60 cm also exhibited highly significant correlation with grain yield at p=<0.001. Though the direct contribution of roots of 30-45 is less negative or null, a positive significant correlation had appeared through the indirect positive effects by roots from soil depths 45-60 and 60-75 cm. The similar pattern of contribution can also be seen by the RLD of 75-90 cm in translating a null direct effect in to a positive correlation coefficient at p=<0.01 level.

Under OI condition, the major direct and positive contribution has been noticeable by RLDs at 75-90, 15-30 and 30-45 cm, and by RDW at 15-30, 30-45 and 75-90 cm soil depths. Also, RLD and RDW of soil depths 15-30 and 30-45 cm had significantly contributed to grain yield at levels ranged from <0.05 to <0.001. RLD of 60-75 cm, through the indirect positive effects by 75-90 cm roots, contributed to a significant correlation with grain yield at p=<0.05 level.

Table 4.5f: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 65 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Root length density (cm cm^{-3})								Root dry weight (g m^{-3})							
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	Yld $kgha^{-1}$	0-15	15-30	30-45	45-60	60-75	75-90	90-105	Yld $kgha^{-1}$
Drought stressed																
0-15	**-0.049**	0.010	-0.001	-0.016	0.062	-0.008	-0.049	-0.051	**-0.224**	0.001	-0.005	0.079	0.077	0.005	-0.030	-0.098
15-30	-0.003	**0.153**	-0.002	0.039	0.095	-0.001	-0.082	0.200	-0.003	**0.122**	-0.006	0.106	0.212	0.004	-0.078	0.358*
30-45	-0.006	0.048	**-0.005**	0.149	0.421	-0.015	0.004	0.595***	-0.099	0.068	**-0.011**	0.175	0.271	0.007	0.068	0.478***
45-60	0.004	0.031	-0.004	**0.196**	0.451	-0.019	0.008	0.666***	-0.082	0.060	-0.009	**0.216**	0.250	0.006	0.055	0.497***
60-75	-0.005	0.022	-0.003	0.131	**0.675**	-0.021	-0.050	0.748***	-0.042	0.062	-0.007	0.131	**0.415**	0.009	-0.029	0.539***
75-90	-0.012	0.006	-0.003	0.122	0.457	**-0.031**	-0.089	0.451**	-0.077	0.039	-0.006	0.104	0.293	**0.013**	-0.104	0.262
90-105	-0.009	0.047	0.000	-0.006	0.128	-0.010	**-0.267**	-0.117	-0.020	0.029	0.002	-0.037	0.037	0.004	**-0.326**	-0.311
Optimally irrigated																
0-15	**-0.438**	-0.041	0.067	-0.030	-0.001	0.059	0.002	-0.383*	**-0.158**	0.097	0.173	-0.028	0.002	-0.043	0.008	0.051
15-30	0.049	**0.367**	0.190	-0.026	-0.022	-0.003	-0.002	0.554***	-0.037	**0.409**	0.118	-0.026	-0.015	-0.026	-0.026	0.398*
30-45	-0.091	0.216	**0.324**	-0.073	-0.044	0.118	-0.001	0.448**	-0.071	0.127	**0.383**	-0.115	0.033	0.074	-0.025	0.405**
45-60	-0.100	0.072	0.179	**-0.133**	-0.037	0.217	-0.002	0.195	-0.025	0.060	0.249	**-0.177**	0.057	0.134	-0.030	0.267
60-75	-0.003	0.115	0.199	-0.069	**-0.071**	0.219	0.004	0.393*	-0.002	-0.051	0.110	-0.088	**0.116**	0.103	0.004	0.190
75-90	-0.060	-0.003	0.088	-0.067	-0.036	**0.431**	-0.006	0.348*	0.026	-0.039	0.106	-0.089	0.045	**0.266**	-0.021	0.292
90-105	0.036	0.028	0.023	-0.010	0.012	0.127	**-0.020**	0.196	0.013	0.105	0.092	-0.052	-0.005	0.055	**-0.103**	0.105

Yld $kgha^{-1}$= Grain yield (kg ha^{-1}) at final maturity

4.1.2.1.5 Effect of root attributes on grain yield at 80 DAS in 2009-10 and 75 DAS in 2010-11

At 80 DAS, under DS condition in 2009-10, the path coefficients of RLD from 15-30, 45-60, 75-90 and 105-120 cm, and of RDW from 0-15, 15-30, 30-45, 75-90 and 90-105 cm exhibited a positive direct contribution to grain yield (Table 4.5g). The RLD of 45-60 cm soil depth had the highest direct contribution to grain yield and followed by 75-90, 15-30 and 105-120 cm soil depths. However, the correlation of RLD at 75-90 cm soil depth alone had a significant association with the grain yield at p=<0.01 level. RDW at 90-105 cm soil depth had a highest direct contribution to grain yield and followed by 30-45, 15-30 and 75-90 cm soil depths with a significance level ranging from p=<0.05 to p=<0.01. Also, the RDW at 30-45 and 105-120 cm soil depths showed a significant correlation with grain yield at p=<0.05 level. Though the direct contribution of RDW at 105-120 cm is negative, a positive significant correlation had resulted mostly through the indirect positive effect from adjacent soil depths such as at 90-105 cm.

Under OI condition, the path coefficients of RLD from 30-45, 60-75, 75-90 and 105-120 cm, and RDW from 0-15, 60-75, 75-90 and 90-105 cm soil depths had shown positive direct contribution to grain yield. The RLD of 60-75 cm soil depth had the highest direct positive contribution to grain yield followed by RLD of 75-90 and 105-120 cm soil depths. However, RLD at 75-90 and 105-120 cm soil depths alone

Table 4.5g: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 80 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

	Root length density (cm cm^{-3})									Root dry weight (g m^{-3})								
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Yld kgha^{-1}	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Yld kgha^{-1}
Drought stressed																		
0-15	**-0.261**	0.142	0.128	0.122	-0.072	-0.149	-0.005	0.004	-0.092	**0.111**	0.012	-0.049	0.030	-0.087	-0.002	-0.095	0.063	-0.016
15-30	-0.087	**0.423**	-0.108	0.181	-0.120	-0.128	-0.008	-0.111	0.042	0.008	**0.176**	0.025	-0.136	-0.303	0.042	0.575	-0.179	0.209
30-45	0.089	0.122	**-0.376**	0.204	-0.047	0.326	0.008	-0.022	0.305	-0.029	0.024	**0.184**	-0.176	-0.011	0.063	0.537	-0.189	0.403*
45-60	-0.039	0.093	-0.093	**0.823**	-0.460	-0.048	0.011	-0.031	0.255	-0.008	0.057	0.077	**-0.422**	-0.178	0.072	0.731	-0.208	0.120
60-75	-0.037	0.101	-0.035	0.756	**-0.501**	-0.078	0.010	-0.023	0.193	0.018	0.098	0.004	-0.138	**-0.543**	0.073	0.857	-0.249	0.120
75-90	0.064	-0.089	-0.201	-0.065	0.064	**0.609**	0.006	0.075	0.461**	-0.002	0.054	0.084	-0.219	-0.288	**0.138**	0.935	-0.265	0.437**
90-105	0.052	-0.124	-0.108	0.338	-0.194	0.129	**0.027**	0.039	0.158	-0.009	0.083	0.082	-0.254	-0.383	0.106	**1.215**	-0.370	0.470**
105-120	-0.005	-0.213	0.037	-0.117	0.051	0.205	0.005	**0.221**	0.184	-0.018	0.081	0.089	-0.224	-0.346	0.093	1.151	**-0.391**	0.435*
Optimally irrigated																		
0-15	**-0.066**	-0.142	0.008	0.054	-0.015	0.151	-0.008	0.027	0.009	**0.340**	-0.484	-0.059	-0.085	0.209	0.021	0.036	-0.072	-0.093
15-30	-0.019	**-0.505**	0.010	-0.118	0.068	0.000	0.009	-0.018	-0.571***	0.256	**-0.641**	-0.060	-0.089	0.113	0.011	0.011	-0.067	-0.465**
30-45	-0.014	-0.140	**0.038**	-0.119	0.035	-0.020	0.005	-0.003	-0.217	0.140	-0.270	**-0.142**	-0.067	0.178	0.023	0.019	-0.102	-0.221
45-60	0.009	-0.154	0.012	**-0.386**	0.226	0.028	-0.010	-0.010	-0.285	0.117	-0.231	-0.039	**-0.247**	0.308	0.044	0.092	-0.167	-0.122
60-75	0.002	-0.081	0.003	-0.208	**0.421**	0.152	-0.023	0.004	0.271	0.129	-0.132	-0.046	-0.138	**0.550**	0.067	0.117	-0.222	0.325*
75-90	-0.032	0.000	-0.002	-0.035	0.203	**0.316**	-0.040	0.081	0.490**	0.101	-0.101	-0.046	-0.153	0.518	**0.071**	0.133	-0.255	0.268
90-105	-0.010	0.089	-0.003	-0.072	0.187	0.248	**-0.051**	0.093	0.481**	0.068	-0.041	-0.015	-0.129	0.364	0.053	**0.176**	-0.265	0.212
105-120	-0.013	0.063	-0.001	0.028	0.012	0.182	-0.034	**0.140**	0.378*	0.073	-0.128	-0.043	-0.123	0.363	0.054	0.139	**-0.336**	0.000

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

had led to a significant correlation coefficient with the grain yield at p=<0.01 and p=<0.05 level, respectively. In addition, RLD at 90-105 cm soil depth also showed a significant correlation with grain yield at p=<0.01. Though the direct contribution of roots from 90-105 cm is low, a positive significant correlation was seen mainly through the indirect positive effects of adjacent soil depths as 75-90 and 60-75 cm. RDW at 60-75 cm soil depth had the highest direct contribution to grain yield followed by 0-15, 90-105 and 75-90 cm soil depths. RDW at 60-75 cm soil depth alone had exhibited a significant positive correlation with the grain yield at p=<0.05.

Under DS condition in 2010-11 at 75 DAS, the path coefficients of RLD from all the soil depths except at 15-30 and 105-120 cm, and RDW from all the depths except 0-15, 30-45 and 45-60 had shown positive direct contribution to grain yield (Table 4.5h). The RLD of 45-60 cm soil depth had a highest direct positive contribution followed by RLD at 75-90, 60-75, 0-15, 90-105 and 30-45 cm soil depths. Likewise, the RDW of 75-90 cm soil depth had the highest direct positive contribution to grain yield followed by 15-30, 60-75 and 105-120 cm soil depths. At this growth stage, the RLD at 45-60, 60-75 and 75-90 cm soil depths showed a significant positive contribution to grain yield with a significance level ranging from p=<0.01 to p=<0.001. In the case of RDW, this significance in contribution pattern was limited to 60-75 and 75-90 cm soil depths alone with a p=<0.001.

Under OI condition, the path coefficients of RLD from all the depths except 60-75 and 105-120 cm, and RDW from all the depths

Table 4.5h: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 75 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Root length density (cm cm^{-3})									Root dry weight (g m^{-3})								
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Yld $kgha^{-1}$	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Yld $kgha^{-1}$
Drought stressed																		
0-15	**0.080**	0.022	-0.001	0.027	0.021	0.041	0.037	-0.158	0.068	**-0.198**	-0.108	0.035	0.048	-0.047	-0.029	0.008	0.071	-0.220
15-30	-0.014	**-0.128**	0.024	0.077	0.021	-0.008	-0.001	0.020	-0.010	0.085	**0.252**	-0.079	-0.144	0.053	0.116	0.004	-0.004	0.283
30-45	-0.002	-0.053	**0.058**	0.127	0.067	0.085	0.025	-0.007	0.301	0.053	0.155	**-0.129**	-0.111	0.001	0.098	0.004	-0.018	0.053
45-60	0.006	-0.030	0.023	**0.330**	0.089	0.153	0.020	-0.044	0.547***	0.032	0.121	-0.048	**-0.300**	0.113	0.296	0.015	0.031	0.259
60-75	0.014	-0.021	0.031	0.232	**0.127**	0.149	0.032	-0.053	0.509**	0.044	0.063	-0.001	-0.159	**0.213**	0.403	0.008	0.015	0.586***
75-90	0.017	0.005	0.026	0.259	0.097	**0.194**	0.035	-0.082	0.552***	0.010	0.048	-0.021	-0.146	0.141	**0.609**	0.012	0.003	0.656***
90-105	0.045	0.002	0.023	0.103	0.063	0.107	**0.064**	-0.216	0.191	-0.055	0.031	-0.016	-0.144	0.057	0.241	**0.031**	0.105	0.251
105-120	0.043	0.009	0.001	0.050	0.023	0.054	0.047	**-0.295**	-0.068	-0.072	-0.005	0.012	-0.048	0.016	0.011	0.016	**0.196**	0.126
Optimally irrigated																		
0-15	**0.093**	0.027	0.002	-0.078	0.065	-0.120	0.000	-0.002	-0.013	**-0.006**	0.027	0.007	0.070	0.032	0.027	0.013	-0.028	0.143
15-30	0.005	**0.506**	-0.010	-0.259	0.047	0.080	0.002	0.004	0.375*	0.000	**0.323**	0.047	0.026	0.036	-0.051	0.050	-0.023	0.407**
30-45	0.001	-0.029	**0.174**	0.247	-0.073	-0.037	0.000	0.028	0.311	0.000	0.113	**0.133**	0.047	0.023	-0.022	-0.034	-0.074	0.186
45-60	-0.012	-0.211	0.069	**0.623**	-0.212	0.117	0.000	-0.024	0.352*	-0.001	0.029	0.022	**0.284**	0.104	-0.047	0.070	0.052	0.513***
60-75	-0.023	-0.089	0.047	0.494	**-0.267**	0.203	0.001	-0.021	0.345*	-0.001	0.088	0.023	0.225	**0.132**	-0.063	0.067	0.053	0.523***
75-90	-0.030	0.109	-0.017	0.196	-0.146	**0.372**	0.003	-0.013	0.474**	0.001	0.155	0.027	0.127	0.079	**-0.106**	0.051	0.029	0.365*
90-105	0.001	0.241	-0.014	0.028	-0.087	0.218	**0.004**	-0.029	0.363*	0.000	0.106	-0.030	0.129	0.057	-0.035	**0.153**	0.062	0.443**
105-120	0.002	-0.020	-0.051	0.155	-0.060	0.052	0.001	**-0.095**	-0.015	0.001	-0.044	-0.059	0.089	0.042	-0.019	0.057	**0.167**	0.234

Yld $kgha^{-1}$= Grain yield (kg ha^{-1}) at final maturity

except 0-15 and 75-90 cm soil depths had a positive direct contribution to grain yield. The RLD of 45-60 cm soil depth had the highest direct positive contribution to grain yield followed by 15-30, 75-90, 30-45 and 0-15 cm soil depths. Likewise, the RDW of 15-30 cm soil depth had a highest direct positive contribution to grain yield followed by 45-60, 105-120, 90-105, 30-45 and 60-75 cm soil depths. At this growth stage, the RLD and RDW at 15-30, 45-60, 60-75, 75-90 and 105-120 cm soil depths showed a significant positive contribution to the grain yield ranging from p=<0.05 to p=<0.001.

Overall under DS condition, RLD and RDW at soil depth 75-90 cm had a consistent, moderate to high, positive contribution to grain yield while it also reflected in a highly significant correlation. Under OI condition, this significant contribution mainly occurred in the soil depths 75-90 and 90-105 cm. Therefore at this stage, the roots from soil depth 75-90 cm were the critical one for its contribution to the final grain yield at harvest under both DS and OI environments.

4.1.2.1.6 Effect of root attributes on grain yield at 90 DAS in 2010-11

At 90 DAS in 2010-11, a stage when most genotypes were close to maturity, the high levels of significant contribution of RLD and RDW to grain yield that was observed from 55 to 75 DAS seemed to disappear (Table 4.5i). The RLD and RDW of soil depths at 0-15, 45-60, 60-75 and 105-120 cm under DS, and 15-30, 60-75 and 90-

Table 4.5i: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea at 90 days after sowing both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Root length density (cm cm^{-3})									Root dry weight (g m^{-3})								
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Yld $kgha^{-1}$	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	Yld $kgha^{-1}$
Drought stressed																		
0-15	**0.215**	-0.240	-0.061	0.152	0.010	-0.096	-0.007	0.045	0.018	**0.167**	-0.081	-0.038	0.058	0.018	-0.002	-0.049	0.074	0.146
15-30	0.071	**-0.723**	-0.086	0.162	0.006	-0.002	-0.003	-0.033	-0.606***	0.028	**-0.488**	-0.034	0.090	0.061	-0.001	-0.025	-0.045	-0.414**
30-45	0.105	-0.496	**-0.125**	0.316	0.011	-0.063	-0.002	-0.046	-0.300	0.082	-0.210	**-0.078**	0.071	0.105	-0.003	-0.046	0.030	-0.049
45-60	0.058	-0.207	-0.070	**0.566**	0.013	-0.148	-0.003	-0.009	0.201	0.031	-0.143	-0.018	**0.305**	0.111	-0.003	-0.040	0.053	0.296
60-75	0.079	-0.166	-0.053	0.283	**0.027**	-0.110	-0.004	0.049	0.104	0.013	-0.127	-0.035	0.145	**0.233**	-0.002	-0.026	-0.014	0.186
75-90	0.089	-0.006	-0.034	0.363	0.013	**-0.231**	-0.010	0.037	0.221	0.060	-0.052	-0.034	0.169	0.096	**-0.006**	-0.074	0.058	0.217
90-105	0.078	-0.100	-0.012	0.077	0.006	-0.123	**-0.018**	0.120	0.028	0.076	-0.111	-0.033	0.113	0.055	-0.004	**-0.109**	0.161	0.147
105-120	0.043	0.108	0.026	-0.023	0.006	-0.038	-0.010	**0.223**	0.334*	0.036	0.063	-0.007	0.047	-0.009	-0.001	-0.050	**0.346**	0.425**
Optimally irrigated																		
0-15	**-0.486**	-0.002	0.025	0.107	0.047	-0.185	0.313	-0.018	-0.200	**-0.359**	-0.014	0.005	0.044	0.100	-0.049	0.111	-0.001	-0.163
15-30	0.011	**0.111**	-0.031	-0.242	0.165	-0.053	-0.030	0.013	-0.055	0.032	**0.160**	-0.007	-0.132	0.123	-0.045	0.038	-0.008	0.162
30-45	0.141	0.040	**-0.085**	-0.232	0.043	-0.051	0.113	-0.010	-0.041	0.153	0.089	**-0.013**	-0.110	0.024	-0.038	-0.012	-0.008	0.085
45-60	0.136	0.070	-0.052	**-0.383**	0.264	-0.120	0.243	0.004	0.164	0.071	0.094	-0.006	**-0.225**	0.100	-0.034	0.053	-0.003	0.049
60-75	-0.038	0.031	-0.006	-0.170	**0.596**	-0.187	0.317	-0.010	0.533***	-0.077	0.042	-0.001	-0.049	**0.465**	-0.103	0.106	-0.011	0.373*
75-90	-0.213	0.014	-0.010	-0.109	0.264	**-0.423**	0.587	-0.043	0.068	-0.098	0.040	-0.003	-0.043	0.266	**-0.180**	0.135	-0.029	0.090
90-105	-0.206	-0.004	-0.013	-0.126	0.257	-0.337	**0.736**	-0.037	0.269	-0.151	0.023	0.001	-0.046	0.187	-0.092	**0.264**	-0.015	0.171
105-120	-0.129	-0.022	-0.013	0.024	0.093	-0.269	0.405	**-0.067**	0.022	-0.006	0.022	-0.002	-0.013	0.092	-0.094	0.073	**-0.055**	0.018

Yld $kgha^{-1}$= Grain yield (kg ha^{-1}) at final maturity

105 cm under OI condition had exhibited a positive contribution to grain yield (Table 4.5i).

Under DS condition, the RLD of 60-75 cm soil depth had the highest direct positive contribution to grain yield followed by roots at 105-120, 0-15 and 60-75 cm soil depths. This contribution by RDW was the highest at 105-120 cm followed by 45-60, 60-75 and 0-15 cm soil depths. However, RLD and RDW at 105-120 cm soil depths alone had a significant positive correlation with the grain yield either at p=<0.05 or p=<0.01 levels, respectively. Under OI condition, the RLD of 90-105 cm soil depth had the highest direct positive contribution to grain yield followed by RLD of 60-75 and 15-30 cm soil depths. The contribution RDW was the highest at 60-75 cm soil depth followed by 90-105 and 15-30 cm soil depths. However, RLD and RDW at 60-75 cm soil depth alone provided a significant positive correlation with the grain yield at p=<0.001 and p=<0.05 levels, respectively.

4.1.2.1.7 Effect of root attributes on grain yield at different DAS in 2009-10

Under DS condition, the path coefficients of average RLD and the total RDW of all the samplings with the grain yield were positive and direct (Table 4.5j). In 2009-10, the root traits at 50 and 80 DAS showed a relatively higher positive contribution to grain yield and this contribution was significant for RLD at 80 DAS at <0.05 level. Under OI condition, the root traits at 50 DAS showed a meager positive direct contribution to grain yield.

4.1.2.1.8 Effect of root attributes on grain yield at different DAS in 2010-11

In 2010-11, the correlation coefficients of RLD and RDW observed at all the samplings were positively correlated with the yield except at 35 and 90 DAS (Table 4.5k). The RLD and RDW sampled at 45, 55 and 65 DASunder DS, and 35, 55 and 75 DAS under OI condition were positively correlated with the grain yield.

Under DS condition, the direct effect of RLD at 65 DAS and RDW at 55 DAS were the highest. The correlation of root traits with grain yield was significant at 45, 55, 65 and 75 DAS with the significance level varying from p=<0.05 to p=<0.001. Though the direct effect of root traits at 75 DAS was negative, a positive significant correlation has occurred through the indirect positive effects at samplings 45, 55 and 65 DAS. Under OI condition, a major direct and positive contribution is noticeable by the RLD sampled at 35, 55 and 75 DAS, and by the RDW at 35, 45, 55 and 75 DAS. Also, the correlation coefficients of all the RLD and RDW samplings with grain yield at 45, 55, 65 and 75 DAS were positive and significant with the significance level ranging from p=<0.05 to p=<0.001.

Table 4.5j: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea sampling at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

	Average root length density (cm cm^{-3})				Total root dry weight (g m^{-2})			
	0-60_ 35DAS	0-90_ 50DAS	0-120_ 80DAS	Yld kgha^{-1}	0-60_ 35DAS	0-90_ 50DAS	0-120_ 80DAS	Yld kgha^{-1}
Drought stressed								
0-60_35DAS	**0.036**	0.137	-0.042	0.130	**0.093**	0.052	-0.056	0.090
0-90_50DAS	0.019	**0.250**	0.043	0.313	0.051	**0.097**	0.025	0.173
0-120_80DAS	-0.005	0.033	**0.324**	0.353*	-0.019	0.009	**0.274**	0.264
Optimally irrigated								
0-60_35DAS	**-0.434**	0.116	0.028	-0.290	**-0.335**	0.109	-0.020	-0.246
0-90_50DAS	-0.202	**0.250**	0.030	0.078	-0.160	**0.228**	-0.015	0.054
0-120_80DAS	-0.168	0.102	**0.072**	0.006	-0.223	0.114	**-0.030**	-0.139

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

Table 4.5k: Direct (Diagonal) and indirect effect of root traits on grain yield of 12 diverse genotypes of chickpea sampling at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Average root length density (cm cm^{-3})							Total root dry weight (g m^{-3})						
	0-60_ 35DAS	0-75_ 45DAS	0-90_ 55DAS	0-105_ 65DAS	0-120_ 75DAS	0-120_ 90DAS	Yld kgha^{-1}	0-60_ 35DAS	0-75_ 45DAS	0-90_ 55DAS	0-105_ 65DAS	0-120_ 75DAS	0-120_ 90DAS	Yld kgha^{-1}
Drought stressed														
0-60_35DAS	**-0.465**	0.140	0.265	0.091	-0.018	-0.035	-0.022	**-0.516**	0.105	0.321	0.086	-0.010	0.008	-0.005
0-75_45DAS	-0.161	**0.404**	0.221	0.080	-0.067	0.013	0.489**	-0.141	**0.385**	0.256	0.069	-0.025	0.005	0.548***
0-90_55DAS	-0.296	0.214	**0.417**	0.314	-0.109	-0.030	0.509**	-0.345	0.205	**0.480**	0.111	-0.021	0.007	0.437**
0-105_65DAS	-0.081	0.061	0.248	**0.527**	-0.158	-0.056	0.542***	-0.229	0.136	0.272	**0.195**	-0.027	0.011	0.359*
0-120_75DAS	-0.038	0.126	0.210	0.384	**-0.216**	-0.052	0.414**	-0.106	0.192	0.202	0.104	**-0.051**	0.007	0.349*
0-120_90DAS	-0.140	-0.045	0.106	0.255	-0.097	**-0.116**	-0.037	-0.222	0.099	0.183	0.114	-0.019	**0.020**	0.174
Optimally irrigated														
0-60_35DAS	**0.191**	-0.080	0.186	-0.035	-0.044	-0.010	0.209	**0.135**	0.053	0.039	-0.091	-0.014	0.011	0.133
0-75_45DAS	0.110	**-0.138**	0.208	-0.037	0.023	0.004	0.170	0.031	**0.233**	0.037	-0.060	0.199	-0.020	0.420**
0-90_55DAS	0.080	-0.065	**0.442**	-0.038	0.162	-0.007	0.574***	0.058	0.096	**0.090**	-0.108	0.199	0.006	0.343*
0-105_65DAS	0.119	-0.091	0.298	**-0.057**	0.120	0.001	0.390*	0.070	0.080	0.055	**-0.176**	0.256	0.005	0.291
0-120_75DAS	-0.020	-0.008	0.175	-0.017	**0.408**	0.011	0.550***	-0.003	0.088	0.034	-0.086	**0.526**	-0.010	0.549***
0-120_90DAS	-0.053	-0.015	-0.084	-0.002	0.127	**0.036**	0.009	-0.022	0.072	-0.009	0.015	0.079	**-0.065**	0.070

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

4.1.2.2 Shoot attributes

4.1.2.2.1 Effect of shoot attributes on grain yield at different DAS in 2009-10

The contribution of shoot attributes measured at peak vegetative (28 DAS), early pod filling (51DAS) and at near maturity stages (84 DAS) to grain yield was not consistent and it fluctuated between positive and negative depending on the crop growth stage. Under DS condition at 28 DAS, the correlation coefficients of all the shoot traits with the final grain yield were positive but under OI condition these coefficients were negative except for the SLA association (Table 4.6a). Under DS condition, though the direct effects of SBM and SLA as path coefficients were substantially negative, the total contribution had turned positive through the major direct positive contribution of LAI. Under OI condition, SLA had exhibited a positive correlation coefficient with grain yield though its direct effect was negative. This change was caused by LAI through its positive contribution making the total contribution of SLA to grain yield positive. At 51 DAS, the pattern of contribution and direct effects of shoot traits on grain yield were similar as seen at 28 DAS sampling with a few exceptions under both irrigated and DS condition. Also, the contribution of LAI and SLA to the grain yield had remained to be high under DS condition than under OI condition.

At 84 DAS, when most genotypes were near maturity under DS condition, the contribution of LAI to grain yield become negative under both irrigation treatments as these genotypes relatively were

Table 4.6a: Direct (Diagonal) and indirect effect of shoot traits on grain yield of 12 diverse genotypes of chickpea sampling at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

	Drought stressed				Optimally irrigated			
	↑SBM	SLA	LAI	Yld kgha^{-1}	SBM	SLA	LAI	Yld kgha^{-1}
28DAS								
SBM	**-2.283**	-0.060	2.527	0.185	**-2.208**	-0.045	2.006	-0.247
SLA	-0.111	**-1.224**	1.393	0.057	-0.138	**-0.723**	1.042	0.181
LAI	-2.004	-0.592	**2.878**	0.281	-1.977	-0.337	**2.240**	-0.074
51DAS								
SBM	**-1.259**	-0.157	1.415	-0.001	**-0.596**	-0.055	0.602	-0.049
SLA	-0.172	**-1.146**	1.434	0.116	-0.103	**-0.316**	0.589	0.170
LAI	-0.903	-0.834	**1.973**	0.236	-0.440	-0.228	**0.817**	0.148
84DAS								
SBM	**0.074**	-0.005	-0.221	-0.152	**-0.142**	-0.013	-0.213	-0.367**
SLA	-0.001	**0.658**	-0.362	0.295	0.003	**0.633**	-0.553	0.083
LAI	0.032	0.468	**-0.509**	-0.009	-0.048	0.553	**-0.633**	-0.127

↑SBM= Shoot biomass (g m^{-2}); SLA= Specific leaf area; LAI= Leaf area index; Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

longer in duration and poorer in grain yield. SLA had contributed the highest in both direct contribution and indirectly through LAI to the grain yield. Under DS condition, though the direct contribution of SBM to grain yield was positive, the correlation coefficient had turned negative by the greater negative influence of LAI.

4.1.2.2.2 Effect of shoot attributes on grain yield at different DAS in 2010-11

All the shoot traits measured at various growth stages (24, 37, 48, 58, 70 and 80 DAS) showed largely nonsignificant positive correlation coefficients with the grain yield except for SBM at 24 DAS and LAI at 80 DAS, as these were negative in correlation coefficient under DS condition (Table 4.6b).

Table 4.6b: Direct (Diagonal) and indirect effect of shoot traits on grain yield of 12 diverse genotypes of chickpea sampling at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Drought stressed				Optimally irrigated			
	↑SBM	SLA	LAI	Yld kgha^{-1}	SBM	SLA	LAI	Yld kgha^{-1}
24DAS								
SBM	**-1.858**	0.066	1.659	-0.133	**-0.453**	-0.002	0.309	-0.147
SLA	0.432	**-0.286**	0.134	0.281	0.116	**0.010**	0.052	0.178
LAI	-1.737	-0.022	**1.774**	0.015	-0.403	0.001	**0.347**	-0.055
37DAS								
SBM	**-2.571**	-0.010	2.627	0.046	**-1.663**	-0.053	1.754	0.038
SLA	-0.033	**-0.765**	1.027	0.230	-0.076	**-1.157**	1.510	0.277
LAI	-2.383	-0.277	**2.835**	0.175	-1.266	-0.758	**2.304**	0.280
48DAS								
SBM	**-2.351**	0.010	2.373	0.032	**-0.149**	0.061	0.007	-0.081
SLA	0.016	**-1.496**	1.766	0.286	-0.030	**0.302**	0.006	0.278
LAI	-1.845	-0.873	**3.024**	0.306	-0.125	0.204	**0.008**	0.087
58DAS								
SBM	**0.171**	-0.082	0.230	0.319	**0.337**	-0.023	-0.049	0.264
SLA	-0.057	**0.248**	0.090	0.281	-0.022	**0.358**	-0.053	0.283
LAI	0.130	0.073	**0.303**	0.506***	0.205	0.237	**-0.081**	0.361***
70DAS								
SBM	**0.462**	-0.051	-0.101	0.310	**-0.217**	-0.002	0.287	0.068
SLA	-0.065	**0.362**	-0.131	0.166	-0.001	**-0.361**	0.556	0.194
LAI	0.214	0.218	**-0.218**	0.214	-0.092	-0.295	**0.681**	0.294
80DAS								
SBM	**0.544**	0.081	-0.326	0.299	**0.504**	-0.069	-0.041	0.394***
SLA	0.056	**0.788**	-0.290	0.555***	-0.071	**0.490**	-0.285	0.135
LAI	0.270	0.347	**-0.658**	-0.042	0.060	0.401	**-0.348**	0.113

↑SBM= Shoot biomass (g m^{-2}); SLA= Specific leaf area; LAI=Leaf area index; Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

Under OI condition, this correlation was negative with SBM and LAI at 24 DAS. Generally these correlation coefficients became positive and larger with advance in growth stage. SBM after 58 DAS showed larger correlation coefficients particularly under DS condition though these were marginally short of significance. LAI at 58 DAS was closely and positively correlated with grain yield under both irrigation treatments. SLA at 80 DAS under DS condition was closely associated with the grain yield.

Under DS condition, LAI alone had a positive direct contribution to grain yield among the other shoot traits till 58 DAS and SBM and SLA had a clear negative direct contribution. But the contribution pattern of all these three components reversed from 58 DAS. Under OI condition, the direct positive contribution of SBM and SLA was highest at 80 DAS though such a a trend was set in at 58 DAS onwards.

4.1.2.2.3 Effect of canopy proportion and CTD on grain yield at different DAS in 2009-10

In 2009-10, the correlation coefficients of the canopy proportion at 66 and 70 DAS under DS, and 66, 70 and 81 DAS under OI condition were positive but nonsignificant. For the CTD, this was positive at all the samplings under both irrigation treatments and highly significant except at 81 DAS in 2009-10 (Table 4.6c). Under DS condition, the positive direct effect of CP on grain yield was highest at 70 DAS. For CTD, this was highest at 70 DAS, followed by at 66 DAS. Under OI condition, the positive direct contribution of canopy

proportion to grain yield was smaller. For CTD, this contribution was highest at 70 DAS with a significance level of p=<0.001. In addition, the CTD at 76 and 81 DAS also showed a significant correlation with grain yield at <0.01 and <0.001 levels, respectively. Though the direct contribution of CTD to grain yield is highly negative at 81 DAS, the large positive indirect contribution of 70 DAS had resulted in a positive association with grain yield at this stage.

In 2010-11, the correlation coefficients of the canopy proportion at 63 DAS under DS condition was large, positive and close to significance while under OI condition it was positive and significant. For CTD, this was positive at all the samplings under both irrigation treatments except for the 82 DAS sample under DS condition (Table 4.6d). Under DS condition, the positive direct contribution of canopy proportion on grain yield was highest at 63 DAS. For CTD, this was highest at 72 DAS, followed by 63 DAS. Under OI condition, the positive direct contribution of canopy proportion to grain yield was highest at 63 DAS with a significance of p=<0.05. For CTD, this was highest at 63 DAS, followed by 70 and 82 DAS with the significance level ranging from p=<0.01 to p=<0.001.

In both the years, under DS condition, the CTD of initial three samples have had highly significant correlations with the grain yield. And this significance had extended even up to the last sample under OI condition.

Table 4.6c: Direct (Diagonal) and indirect effect of canopy proportion and canopy temperature depression on grain yield of 12 diverse genotypes of chickpea at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 postrainy season

	Canopy proportion (%)					Canopy temperature depression (°C)				
	66-DAS	70-DAS	76-DAS	81-DAS	Yld kgha^{-1}	66-DAS	70-DAS	76-DAS	81-DAS	Yld kgha^{-1}
Drought stressed										
66-DAS	**0.208**	0.014	-0.002	-0.002	0.218	**0.361**	0.221	0.072	-0.032	0.622***
70-DAS	0.012	**0.246**	-0.004	-0.017	0.236	0.229	**0.347**	0.078	-0.064	0.591***
76-DAS	0.008	0.026	**-0.043**	-0.024	-0.034	0.162	0.169	**0.160**	-0.060	0.430**
81-DAS	0.005	0.046	-0.011	**-0.094**	-0.054	0.086	0.167	0.073	**-0.133**	0.193
Optimally irrigated										
66-DAS	**0.113**	0.000	-0.040	0.033	0.106	**0.120**	1.465	-0.022	-1.096	0.467**
70-DAS	0.008	**-0.004**	0.011	0.021	0.036	0.071	**2.489**	-0.034	-1.825	0.701***
76-DAS	0.014	0.000	**-0.316**	0.026	-0.275	0.059	1.889	**-0.044**	-1.421	0.483**
81-DAS	0.033	-0.001	-0.073	**0.112**	0.071	0.071	2.466	-0.034	**-1.843**	0.660***

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

Table 4.6d: Direct (Diagonal) and indirect effect of canopy proportion and canopy temperature depression on grain yield of 12 diverse genotypes of chickpea at different days after sowing (DAS) both under drought stressed and optimally irrigated conditions in a Vertisol during 2010-11 postrainy season

	Canopy proportion (%)					Canopy temperature depression (°C)				
	63-DAS	70-DAS	72-DAS	82-DAS	Yld kgha^{-1}	63-DAS	70-DAS	72-DAS	82-DAS	Yld kgha^{-1}
Drought stressed										
63-DAS	**0.304**	0.009	-0.003	0.001	0.312	**0.273**	0.075	0.253	-0.090	0.511***
70-DAS	0.022	**0.132**	-0.023	-0.024	0.107	0.181	**0.113**	0.340	-0.106	0.528***
72-DAS	0.005	0.019	**-0.159**	-0.029	-0.164	0.152	0.084	**0.454**	-0.142	0.549***
82-DAS	-0.003	0.026	-0.038	**-0.121**	-0.136	0.080	0.039	0.209	**-0.309**	0.019
Optimally irrigated										
63-DAS	**0.379**	-0.002	-0.017	0.013	0.372*	**0.520**	0.447	-0.601	0.171	0.537***
70-DAS	-0.026	**0.035**	-0.039	0.014	-0.015	0.475	**0.490**	-0.624	0.166	0.507**
72-DAS	0.032	0.007	**-0.197**	0.031	-0.127	0.447	0.437	**-0.699**	0.122	0.306
82-DAS	0.049	0.005	-0.062	**0.099**	0.091	0.345	0.315	-0.330	**0.258**	0.588***

Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

4.1.2.3 Crop phenology, morphological and analytical components

4.1.2.3.1 Effect of crop phenology on grain yield in 2009-10 and 2010-11

The correlation of crop phenology (days to 50% flowering and the maturity) with grain yield was negative across irrigation treatments and years except for days to maturity under OI condition in 2009-10 (Table 4.7a). Under DS condition, the days to 50% flowering had positive direct contribution to grain yield and the days to maturity had a high negative contribution to it, explaining the high negative correlation coefficient in both the years. Under OI condition, the days to 50% flowering had negative direct contribution to grain yield at p=<0.01 significance level in both the years. The days to maturity showed a positive direct contribution in 2009-10, and a high negative direct contribution to grain yield at a significance of p=<0.05.

Table 4.7a: Direct (Diagonal) and indirect effect of crop phenology on grain yield of 12 diverse genotypes of chickpea both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 and 2010-11 postrainy season

	2009-10			2010-11		
	↑DF	DM	Yld kgha^{-1}	DF	DM	Yld kgha^{-1}
Drought stressed						
DF	**0.038**	-0.273	-0.235	**0.194**	-0.436	-0.242
DM	0.031	**-0.333**	-0.301	0.162	**-0.520**	-0.358*
Optimally irrigated						
DF	**-0.456**	-0.011	-0.467**	**-0.336**	-0.108	-0.444**
DM	0.042	**0.120**	0.161	-0.159	**-0.227**	-0.386*

↑ DF= Days to 50% flowering; DM= Days to maturity; Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

4.1.2.3.2 Effect of shoot biomass and morphological components on grain yield in 2009-10 and 2010-11

Concerning the association with the final grain yield or their contribution to grain yield, the yield components shoot biomass at maturity, HI and pod number m^{-2} seemed to be important. The other three traits, seed number m^{-2}, seeds pod^{-1} and 100-seed weight have had minimum contribution or role in grain yield determination (Table 4.7b). There were indications of positive association of shoot biomass at maturity with grain yield irrespective of the irrigation treatment but it was highly significant only under optimal irrigation in 2010-11. HI had been very closely associated with grain yield in both irrigation regimes and years. Pod number m^{-2} was also positively correlated whereas it was significant under both irrigation levels only in 2010-11. Seed number m^{-2} was also positively correlated whereas it was only significant under DS condition in 2010-11. Seeds pod^{-1} was negatively correlated whereas it was only significant under DS condition in 2010-11. 100-seed weight was not generally correlated but for the indication of positive association under DS condition in 2009-10.

Under DS condition in both the years, shoot biomass at maturity had a large positive direct contribution to grain yield but this did not result in significant correlation mainly due to a large negative indirect contribution of HI. Higher shoot biomass production, in many of the later maturing genotypes, was not allowed to reflect in grain yield by the poor partitioning. In both the years under DS condition,

the path coefficient of HI showed a high direct positive and a highly significant contribution to grain yield at p=<0.001. This was possible due to the indirect contribution of pod and seed numbers per unit area. The seed number m^{-2} contributed negatively largely due to the negative contribution of seeds pod^{-1}. Seeds pod^{-1} had a positive direct contribution to grain yield which could not affect the correlation mostly due to negative indict contribution of seed number m^{-2} and seeds pod^{-1}. 100-seed weight had a small positive contribution that was largely suppressed by the negative indirect contribution by seeds pod^{-1}.

Also under OI condition, closely similar pattern of association of all the shoot traits to the final grain yield can be seen. But the major difference was the absence of major negative indirect contribution of HI to shoot biomass and therefore the shoot biomass association was significant with final grain yield. But the direct contribution of shoot biomass itself was low compared to the DS condition.

In summary, in both the years and irrigation treatment, the HI had a consistent direct positive contribution as well as a highly significant correlation with grain yield. In addition, the shoot biomass, pod number m^{-2} also often had a consistent positive direct contribution leading to a significant correlation with grain yield with some exception.

4.1.2.3.3 Effect of analytical components on grain yield in 2009-10 and 2010-11

In both the years and irrigation levels, the analytical component p had the closest association with grain yield explaining the highest levels of yield variation (Table 4.7c). Also this trait had provided the best positive direct contributions to the grain yield. The other two components provided a negative indirect contribution to grain yield through p.

In both the years and irrigation levels, the analytical component C had the close association with grain yield except under DS condition in 2010-11. Also C had provided a positive large direct contribution to the grain yield across irrigation environments and years. The component p tend to provide a major negative indirect contribution to grain yield under DS condition while Dr provided a major negative indirect contribution to grain yield under OI condition.

In both the years and irrigation levels, the analytical component Dr had a loosely negative, mostly nonsignificant, association with grain yield except under DS condition in 2010-11. But Dr had provided a positive large direct contribution to the grain yield across irrigation environments and years. The component p tends to provide a major negative indirect contribution negating the positive contribution of Dr to grain yield.

Table 4.7b: Direct (Diagonal) and indirect effect of morphological components on grain yield of 12 diverse genotypes of chickpea both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 and 2010-11 postrainy season

	2009-10							2010-11						
	↑SBM	HI	Pod no	Seed no	Seed pod^{-1}	100-sdwt	Yld kgha^{-1}	SBM	HI	Pod no	Seed no	Seed pod^{-1}	100-sdwt	Yld kgha^{-1}
Drought stressed														
SBM	**0.840**	-0.578	-0.062	0.024	0.011	0.010	0.244	**0.395**	-0.069	-0.075	0.045	0.007	-0.002	0.301
HI	-0.432	**1.124**	0.142	0.020	-0.156	0.000	0.698***	-0.029	**0.936**	0.052	-0.045	0.012	0.001	0.926***
Podno	-0.086	0.262	**0.611**	-0.643	0.105	-0.020	0.229	-0.182	0.297	**0.163**	-0.161	0.049	0.003	0.169
Seedno	-0.029	-0.032	0.551	**-0.713**	0.240	-0.023	-0.006	-0.101	0.239	0.149	**-0.176**	0.077	0.003	0.191
Seed/pod	0.025	-0.492	0.181	-0.480	**0.356**	-0.018	-0.429**	0.027	0.115	0.083	-0.140	**0.096**	0.002	0.184
100sdwt	0.285	-0.003	-0.440	0.575	-0.221	**0.028**	0.224	0.158	-0.131	-0.122	0.132	-0.061	**-0.004**	-0.028
Optimally irrigated														
SBM	**0.610**	-0.367	-0.071	0.039	-0.031	0.027	0.206	**0.503**	0.068	0.020	-0.014	-0.015	0.000	0.561***
HI	-0.214	**1.048**	0.244	-0.122	-0.106	-0.014	0.837***	0.040	**0.844**	0.045	-0.055	-0.012	0.002	0.865***
Podno	-0.143	0.848	**0.302**	-0.147	-0.131	-0.027	0.702***	0.089	0.338	**0.113**	-0.147	-0.006	0.015	0.402*
Seedno	-0.137	0.741	0.256	**-0.173**	-0.017	-0.059	0.612***	0.036	0.234	0.084	**-0.198**	0.073	0.024	0.255
Seed/pod	-0.076	-0.443	-0.157	0.011	**0.251**	-0.064	-0.477**	-0.063	-0.080	-0.006	-0.119	**0.122**	0.021	-0.125
100sdwt	0.159	-0.141	-0.079	0.100	-0.157	**0.102**	-0.016	0.001	-0.053	-0.058	0.168	-0.091	**-0.029**	-0.062

↑SBM= Shoot biomass at maturity; HI= Harvest index (%); Pod no= Pod number m^{-2}; Seed pod^{-1}= Seeds pod^{-1}; 100-sdwt= 100-seed weight (g); Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

Table 4.7c: Direct (Diagonal) and indirect effect of analytical components on grain yield of 12 diverse genotypes of chickpea both under drought stressed and optimally irrigated conditions in a Vertisol during 2009-10 and 2010-11 postrainy season

	2009-10				2010-11			
	↑C	Dr	p	Yld kgha^{-1}	C	Dr	p	Yld kgha^{-1}
Drought stressed								
C	**0.697**	0.123	-0.324	0.496**	**0.568**	-0.024	-0.372	0.172
Dr	0.129	**0.663**	-1.071	-0.279	-0.047	**0.289**	0.153	0.395*
p	-0.171	-0.538	**1.319**	0.611***	-0.218	0.046	**0.968**	0.795***
Optimally irrigated								
C	**0.373**	-0.045	0.160	0.487**	**0.565**	-0.200	0.261	0.626***
Dr	-0.048	**0.352**	-0.338	-0.035	-0.282	**0.401**	-0.322	-0.203
p	0.063	-0.126	**0.941**	0.877***	0.176	-0.154	**0.838**	0.860***

↑ C= crop growth rate; Dr = reproductive duration (°Cd); p= partitioning coefficient; Yld kgha^{-1}= Grain yield (kg ha^{-1}) at final maturity

4.1.3 Association between root length density and crop utilized soil moisture under both drought stressed and irrigated condition in 2009-10 and 2010-11

In both years under both irrigation treatments, the relationship between the roots (RLD and RDW) present in a soil zone and the amount of soil water utilized from that zone was found to be significantly positive in all the samplings and across crop growth stages except at the surface soil layers or the freshly descended rooting zones with few exceptions in the year 2009-10 (Fig. 4.1, 4.2, 4.3 and 4.4). The linear curves were drown only when significance in relationship existed between RLD and CUSM.

Under DS condition, the significant relationship between RLD and CUSM was found to be highest at the soil depth of 0-15 cm (at 35 DAS), 75-90 (at 50 DAS) and 60-75 (at 80 DAS) in 2009-10 and, 30-45 (at 35 DAS), 45-60 (at 45 and 55 DAS), 75-90 (at 65 DAS), 60-75 (at 75 DAS) and none (at 90 DAS) in 2010-11 (Fig. 4.1 and 4.2). None of the soil depths were shown a significant relationship between RLD and CUSM at 90 DAS in 2010-11, as most of the genotypes were attained maturity.

Under OI condition, the significant relationship between RLD and CUSM was found to be highest at the soil depth of 0-15 cm (at 35 DAS), 30-45 (at 50 DAS) and 90-105 (at 80 DAS) in 2009-10 and, 15-30 (at 35 DAS), 60-75 (at 45 DAS), 30-45 (55 DAS), 45-60 (at 65 DAS), 105-120 (at 75 DAS) and 75-90 (at 90 DAS) in 2010-11 (Fig. 4.3 and 4.4).

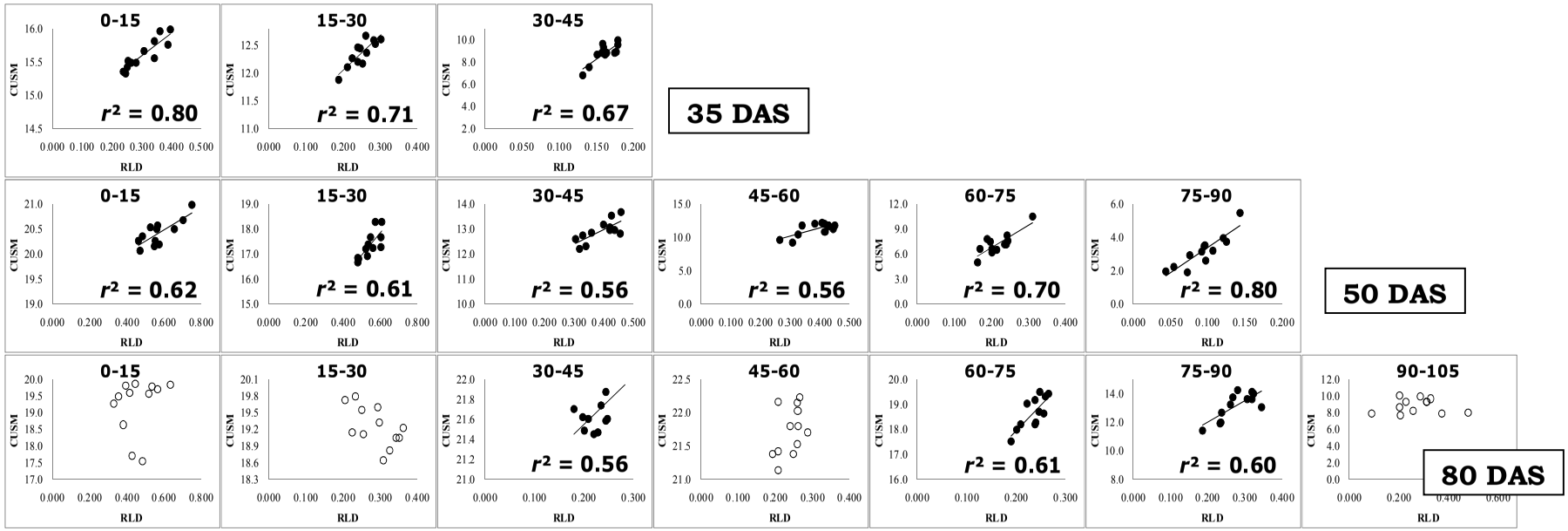

Fig. 4.1: Relationship between root length density (RLD) and crop utilized soil moisture (CUSM) at various soil depths at different days after sowing under drought stressed condition in 2009-10. Non-significant association of RLD with CUSM in figures were represented with open circles

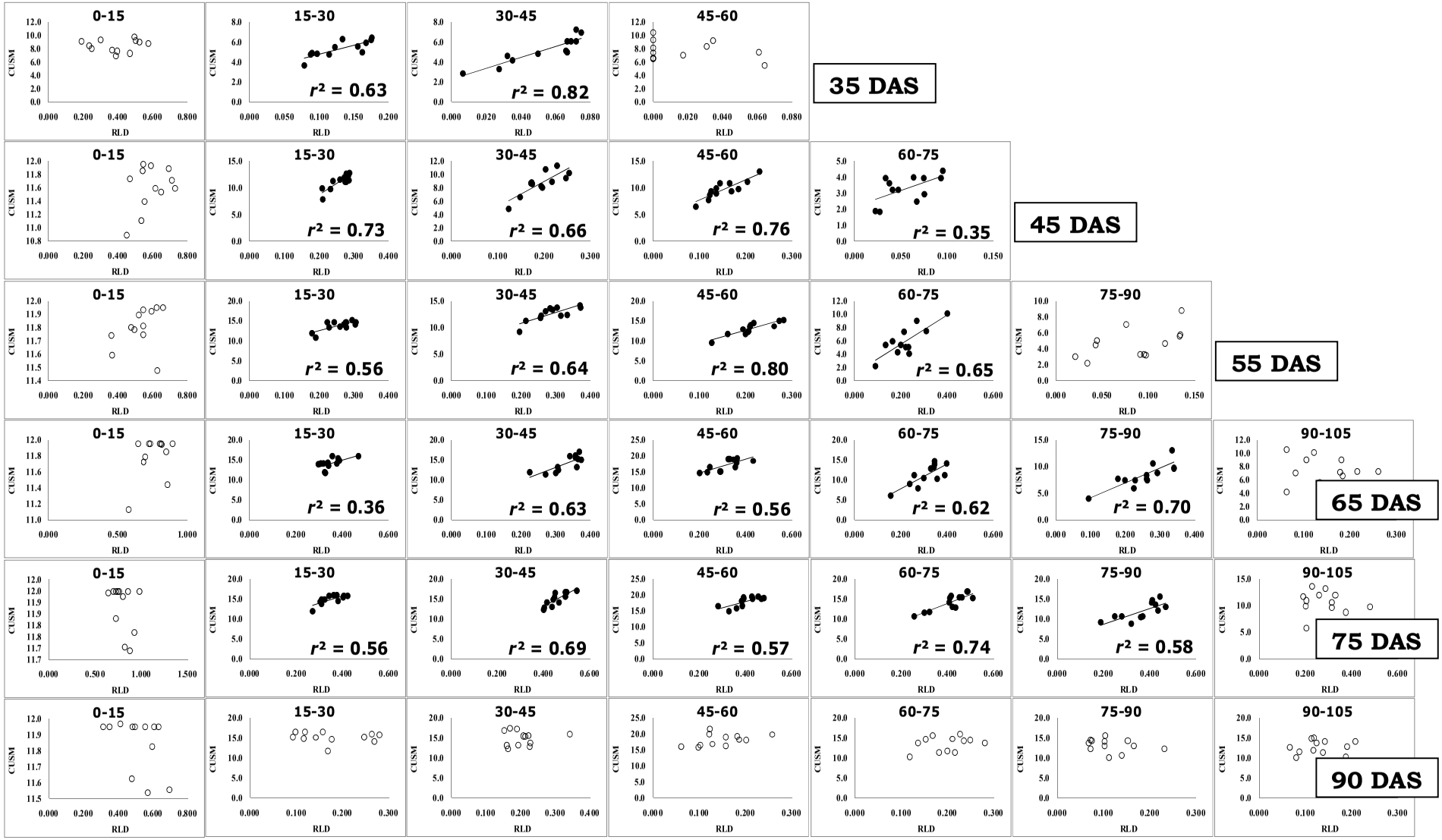

Fig. 4.2: Relationship between root length density (RLD) and crop utilized soil moisture (CUSM) at various soil depths at different days after sowing under drought stressed condition in 2010-11. Non-significant association of RLD with CUSM in figures were represented with open circles

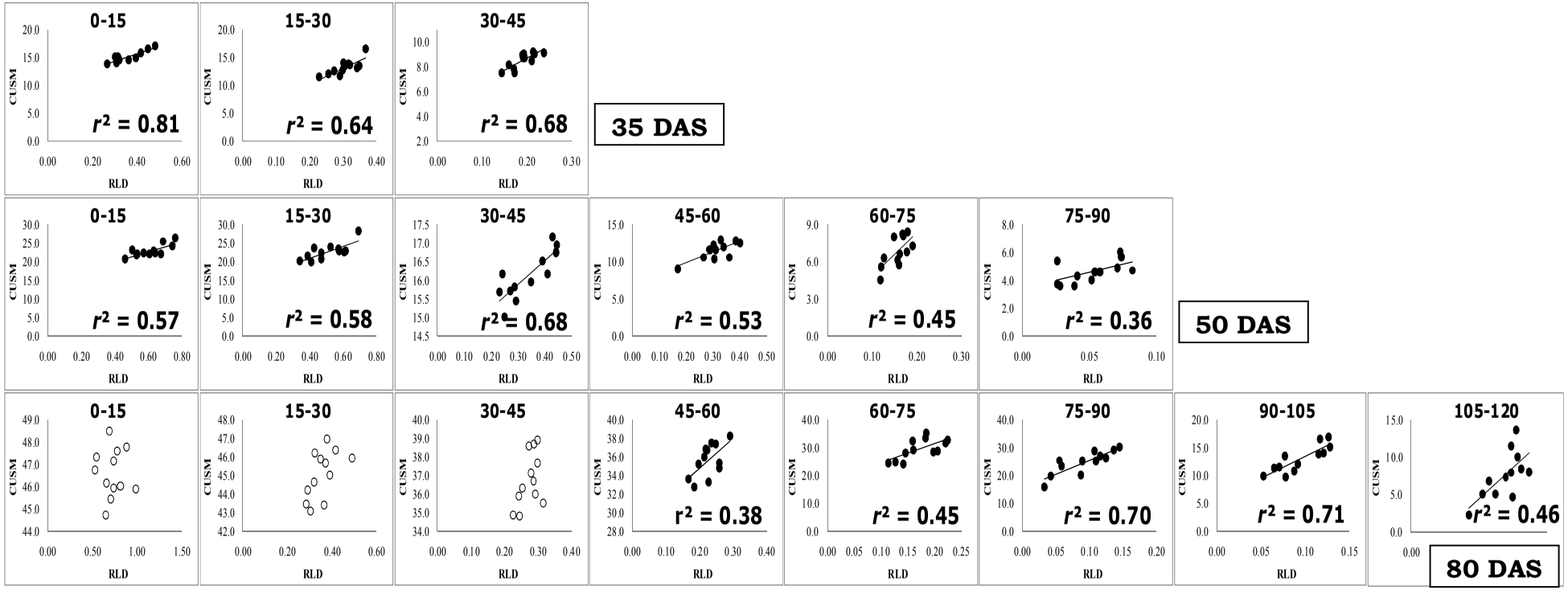

Fig. 4.3: Relationship between root length density (RLD) and crop utilized soil moisture (CUSM) at various soil depths at different days after sowing under optimally irrigated condition in 2009-10. Non-significant association of RLD with CUSM in figures were represented with open circles

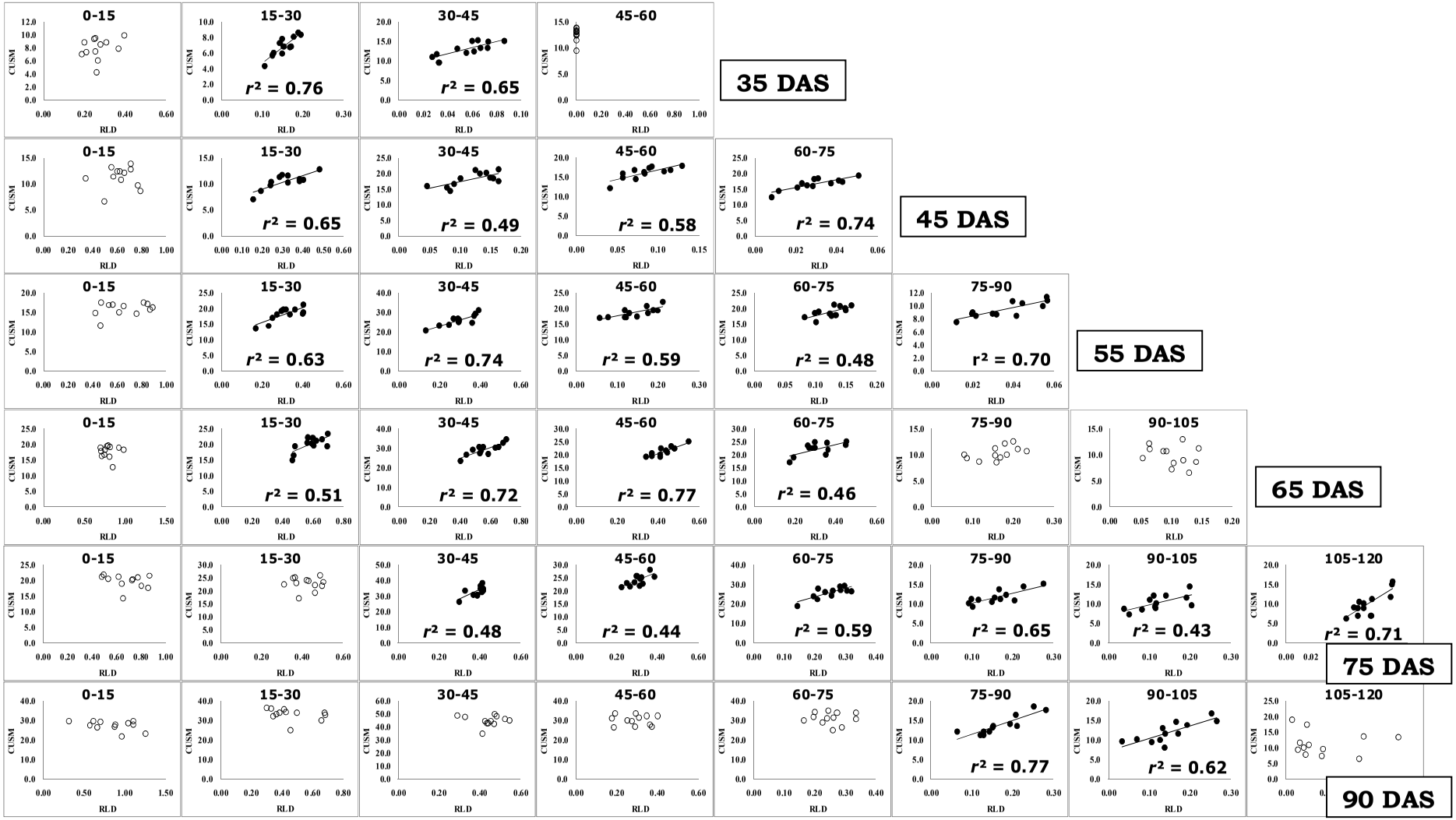

Fig. 4.4: Relationship between root length density (RLD) and crop utilized soil moisture (CUSM) at various soil depths at different days after sowing under optimally irrigated condition in 2010-11. Non-significant association of RLD with CUSM in figures were represented with open circles

4.1.4 Marker diversity among the studied genotypes

A total of 1926 markers which consist of 819 SNP, 1072 DArT and 35 SSR markers were used to understand the genetic diversity pattern across the 10 chickpea genotypes. Incase of SSR markers, the genotype ICC 4958 had the maximum per cent of missing was excluded for analysis.

4.1.4.1 SNP-based genetic diversity

Based on the 10 studied genotypes, only 169 polymorphic markers were identified from the total of 819 SNP markers and were used for genetic diversity analysis. The PIC value is a reflection of allele diversity and the informativeness of each marker. The PIC value ranged from 0.09 (CKaM1850) to 0.38 (AGL126, Ca1C18081, Ca1C33347, CAAB57TF, chs, CKaM0008, CKaM0043, CKaM1003, CKaM1276, CKaM1797, DR_564) with an average of 0.28. Gene diversity is defined as the probability that two randomly chosen alleles from the genotypes are different (Table 4.8). It varied from 0.10 (CKaM1850) to 0.50 (36 SNP markers), with an average of 0.36. The level of heterozygosity (%) was ranged from 0.00% (75 SNP markers) to 1.00 % (Ca1C18081, chs, CKaM0043), with an average of 0.31%. The major allele frequency was ranged from 0.50 (AGL126, Ca1C33347, CAAB57TF, DR_564, CKaM1276, CKaM1797, CKaM0008, CKaM1003, Ca1C18081, chs, CKaM0043) to 0.95 (CKaM1850), with an average of 0.73.

SNP makers were used to construct UPGMA dendrogram grouped all 10 genotypes into five groups at 0.2 similarity level using

the software's DARwin 5.0.156 and MEGA 6.06 (Fig. 4.5). The group 1 contains all the drought tolerant genotypes (ICC 3325, ICC 867, ICC 14799 and ICC 14778), one drought tolerant with large in root system genotype (ICC 4958) and, two small root system genotypes (ICC 283 and ICC 1882). The remaining three genotypes were occurred as separate group of which two are drought sensitive (ICC 3776 and ICC 7184) and the genotype ICC 8261 has the large root system.

4.1.4.2 DArT-based genetic diversity

A total of 377 out of 754 DArT markers were polymorphic and were used for genetic diversity analysis. The PIC value ranged from 0.16 (137 DArT markers) to 0.38 (cpPb-171426, cpPb-325979, cpPb-327746, cpPb-488707, cpPb-489724, cpPb-491012, cpPb-491384, cpPb-676765, cpPb-677314, cpPb-679660) with an average of 0.25 (Table 4.8). Gene diversity varied from 0.18 (137 DArT markers) to 0.50 (cpPb-171426, cpPb-325979, cpPb-327746, cpPb-488707, cpPb-489724, cpPb-491012, cpPb-491384, cpPb-676765, cpPb-677314, cpPb-679660), with an average of 0.30. The major allele frequency was ranged from 0.50 (cpPb-171426, cpPb-325979, cpPb-327746, cpPb-488707, cpPb-489724, cpPb-491012, cpPb-491384, cpPb-676765, cpPb-677314, cpPb-679660) to 0.90 (137 DArT markers), with an average of 0.79.

Table 4.8: Summary statistics of simple sequence repeat (SSR), single nucleotide polymorphism (SNP) and diversity array technology (DArT) polymorphic markers based on 10 diverse chickpea genotypes

Summary statistics	SNP	DArT	SSR
Total number of markers	169	377	35
Total number of alleles	338	754	219
Total number of alleles locus^{-1}	2.0 (2.0-2.0)	2.0 (2.0-2.0)	6.3 (2.0-11)
Gene diversity	0.36 (0.10-0.50)	0.30 (0.18-0.50)	0.77 (0.35-0.90)
Heterozygosity	0.31 (0.0-1.0)	0.0 (0.0-0.0)	0.04 (0.0-1.0)
PIC Value	0.28 (0.09-0.38)	0.25 (0.16-0.38)	0.74 (0.29-0.89)
Major allele frequency	0.73 (0.50-0.95)	0.79 (0.50-0.90)	0.31 (0.11-0.78)

PIC= Polymorphic information content

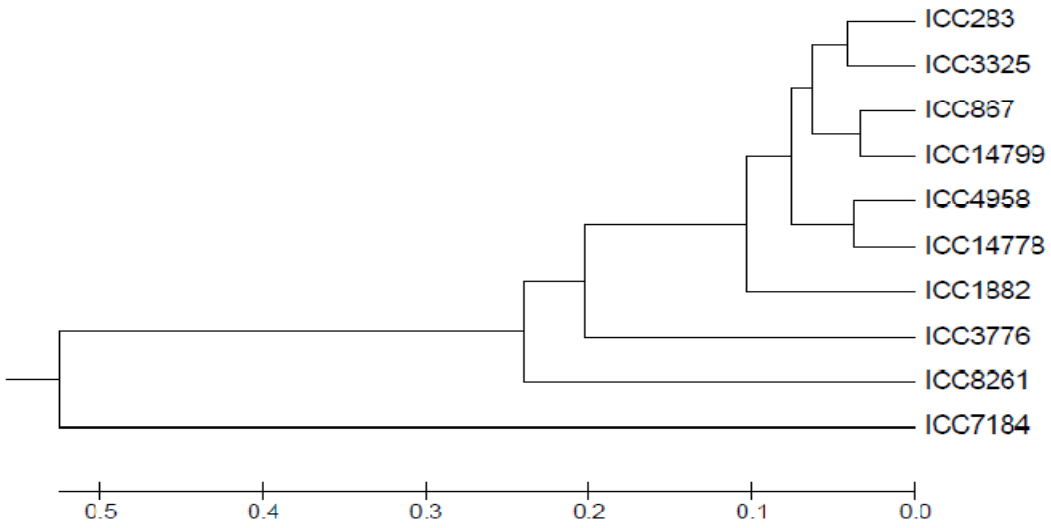

Fig. 4.5: Grouping of 10 genotypes based on the genotypic data of 169 SNP markers

Similarly DArT markers were also used for constructing Neighbor Joining dendrogram using the software NTSYSpc 2.02i. All 10 genotypes were grouped in to two major clusters (Fig. 4.6). The group1 consist of one drought tolerant with large root system genotype (ICC 4958) and two drought sensitive genotypes (ICC 3776

and ICC 7184). Group 2 consist of one large root system genotype (ICC 8261), two small root genotypes (ICC 283 and ICC 1882) and four drought tolerant genotypes (ICC 3325, ICC 14778, ICC 867 and ICC 14799).

4.1.4.3 SSR-based genetic diversity

A total of 35 polymorphic markers were used for genetic diversity analysis. The number of alleles per locus ranged from 2.0 (NCPGR19 and CaSTMS21) to 11 (TR2), with an average of 6.3 (Table 4.8). The PIC value ranged from 0.29 (CaSTMS21) to 0.89 (TA28 and TR2) with an average of 0.74. The level of heterozygosity (%) was ranged from 0.00% (30 SSR markers) to 1.00% (TR2), with an average of 0.31%. Gene diversity varied from 0.35 (CaSTMS21) to 0.90 (TA28 and TR2), with an average of 0.77. The major allele frequency was ranged from 0.11 (TA28) to 0.78 (CaSTMS21), with an average of 0.31.

Polymorphic SSR markers were utilized to construct dendrogram using the software NTSYSpc 2.02i. All nine genotypes were grouped in to two major clusters (Fig. 4.7). The group1 consists of one large root system genotype (IC 8261), two small root system genotypes (ICC 1882 and ICC 283) and three drought tolerant genotypes (ICC 867, ICC 3325 and ICC 14799). The group 2 consists of one drought tolerant genotype (ICC 14778) and two drought sensitive genotypes (ICC 3776 and ICC 7184).

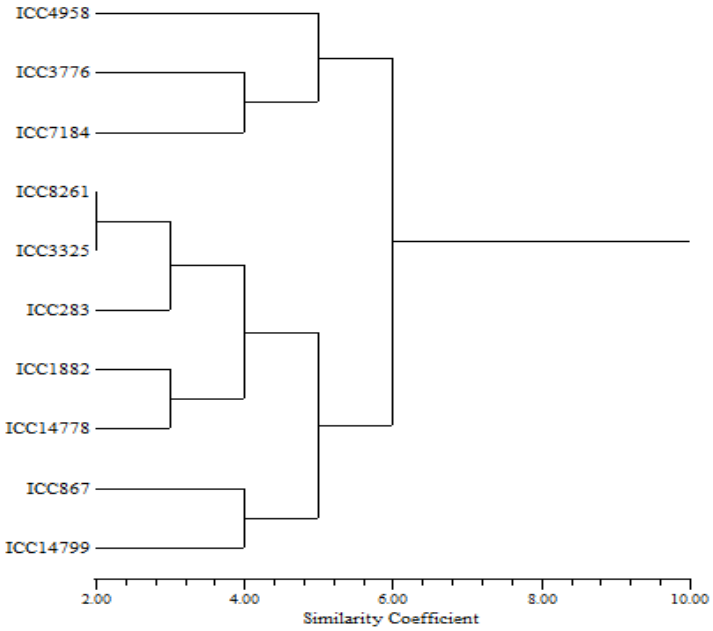

Fig. 4.6: Grouping of 10 chickpea genotypes based on the genotypic data of 377 DArT markers

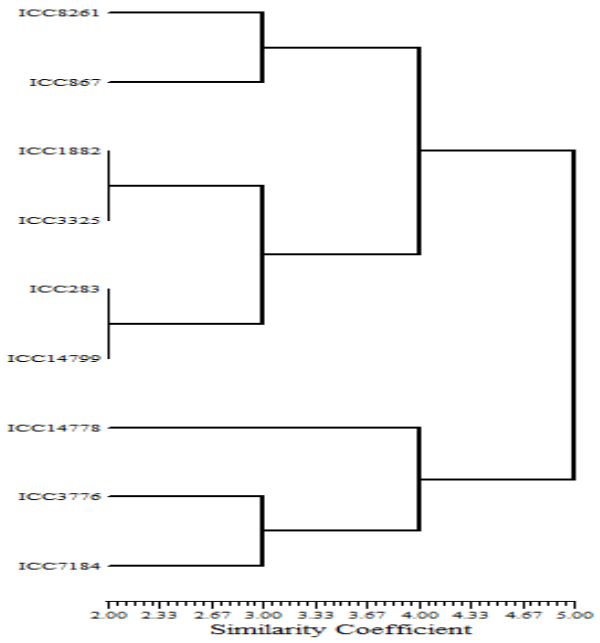

Fig. 4.7: Grouping of nine chickpea genotypes based on the genotypic data of 35 SSR markers

4.2 Experiment-2: Assessing the relationship of canopy temperature depression with grain yield and its associated molecular markers in chickpea under terminal drought stress

4.2.1Weather pattern of crop growing season

In all the three years, the rain received prior to the cropping season was >850 mm, well distributed and more than enough to ensure complete charging of the soil profile. Rains during cropping summed to 26 mm during 15 to 30 DAS in 2008-09, 44 mm during 9 to 19 DAS in 2009-10 and 12.6 mm during 19 to 22 DAS in 2010-11 delayed the onset of drought slightly but the terminal DS did built up (data not shown). There was another rain (39 mm) at 75 DAS during 2009-10, but at this stage under DS the early or medium maturing genotypes crossed the stage of responsiveness. Overall, the minimum temperatures were higher, particularly during the critical third and fourth week of December (flowering and early-podding season for the adapted germplasm), and maximum temperatures were lower during 2009-10 (Fig. 4.8). Relatively cooler minimum temperatures and maximum temperatures at vegetative period were observed in 2010-11. The cumulative evaporation was highest during 2008-09 cropping season that was getting lesser in subsequent years, except the reproductive period in 2010-11, influencing the vapor pressure deficit (VPD). VPD in 2008-09 was high and in 2009-10 it was moderate (Fig. 1). When the CT were recorded on 59, 62, 69, 73 and 76 DAS during 2010-11, the maximum temperatures remained close to 30°C. The minimum temperature, daily evaporation and the VPDs were to some

extent similar during these days but there were notable increase in all these parameters on 82 DAS (Table 4.9).

4.2.2 Changes in temporal soil moisture pattern

Largely, the pattern and the rate of soil moisture depletion remained the same among the three seasons but the soil moisture depletion was very rapid in 2010-11 season in the initial two weeks as a result of low relative humidity and a marginally high VPD (Fig.4.9). However, the rain that followed at 18-22 DAS minimized the soil moisture depletion. Also this year the soil moisture at harvest was slightly high. There was a large rain at 75 DAS in 2009-10 which raised the surface soil moisture to some extent but this has come back to normal dry condition within two weeks.

4.2.3 Crop phenology, grain yield and yield components

The overall trial means was 46 to 50 DAS for 50% flowering across years. The range varied from 31-66 to 35-69 DAS. Similarly, the overall trial mean for days to maturity was 91 to 97 DAS and the range varied from 79-113 to 84-118 DAS across years. Mean shoot biomass production across years ranged from 3388 to 3982 kg ha^{-1} and the range of genotypes varied approximately two times. Mean grain yield across years ranged from 1627 to 1757 kg ha^{-1} and the range of genotypes varied approximately three to four times. Mean HI across years ranged from 42.6 to 48.3% and the range of genotypes varied from 17.6 to 63.6%. The h^2 of the phenological traits and the HI was mostly above 0.9. The range of h^2 for shoot biomass was 0.5 to 0.9 and for grain yield was 0.5 to 0.8 across years (Table 4.10).

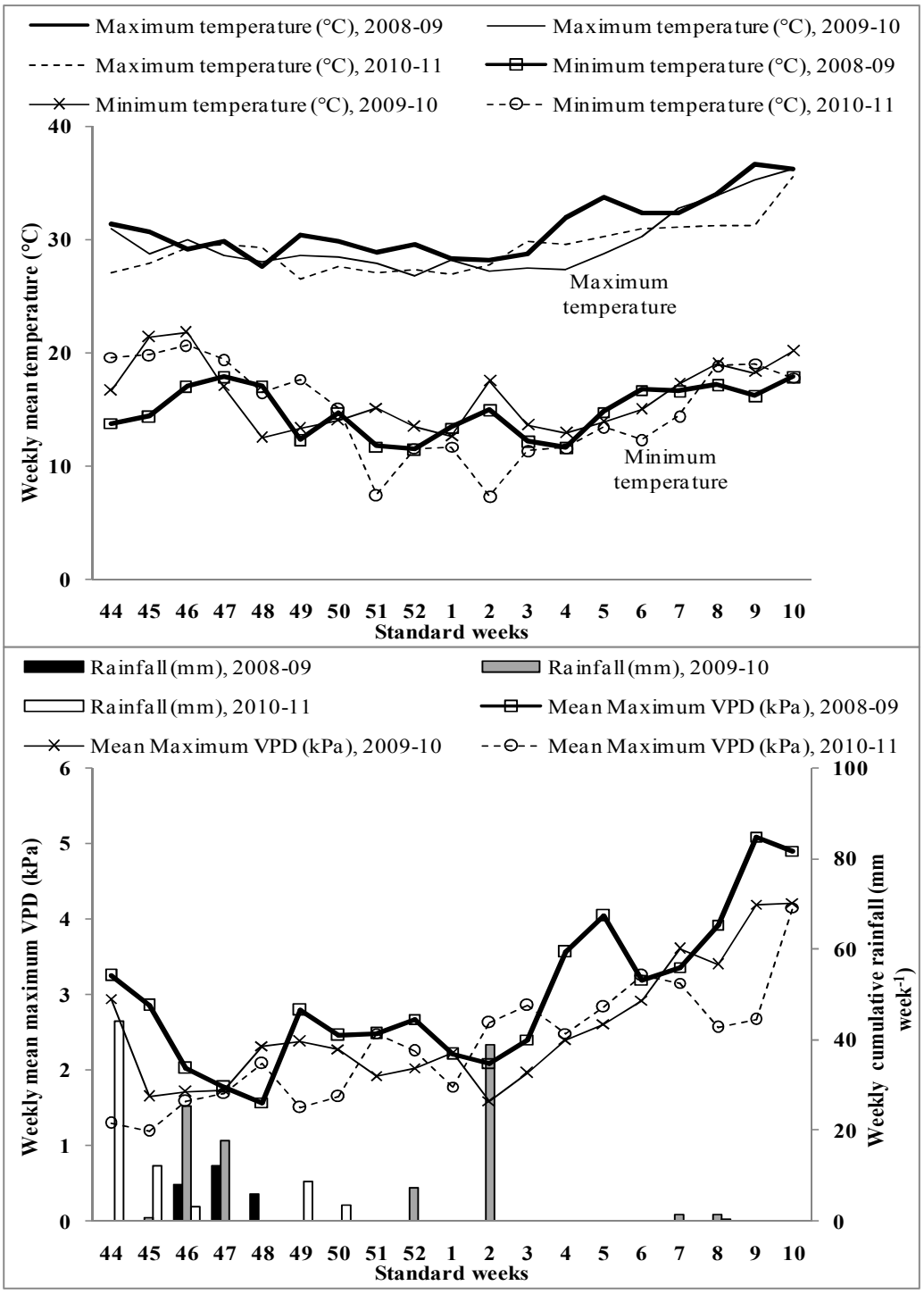

Fig. 4.8: Weather during the crop growing seasons (November to March) of 2008-09, 2009-10 and 2010-11

Table 4.9: Summary of weather condition at the canopy temperature depression (CTD) measuring days in the year 2010-11under drought stressed environment

CTD at	Cumulative rainfall (mm)	Mean temperature (°C)		Mean maximum VPD (kPa)	Total evaporation (mm)
		Max	Min		
59 DAS	0.0	28.8	11.3	2.42	3.8
62 DAS	0.0	30.3	10.7	2.93	5.3
69 DAS	0.0	30.3	13.6	2.67	5.3
73 DAS	0.0	29.4	13.8	2.77	5.4
76 DAS	0.0	29.8	11.5	2.57	5.3
82 DAS	0.0	31.7	13.4	3.42	6.0

Max= Maximum; Min= Minimum; VPD= Vapour pressure deficit

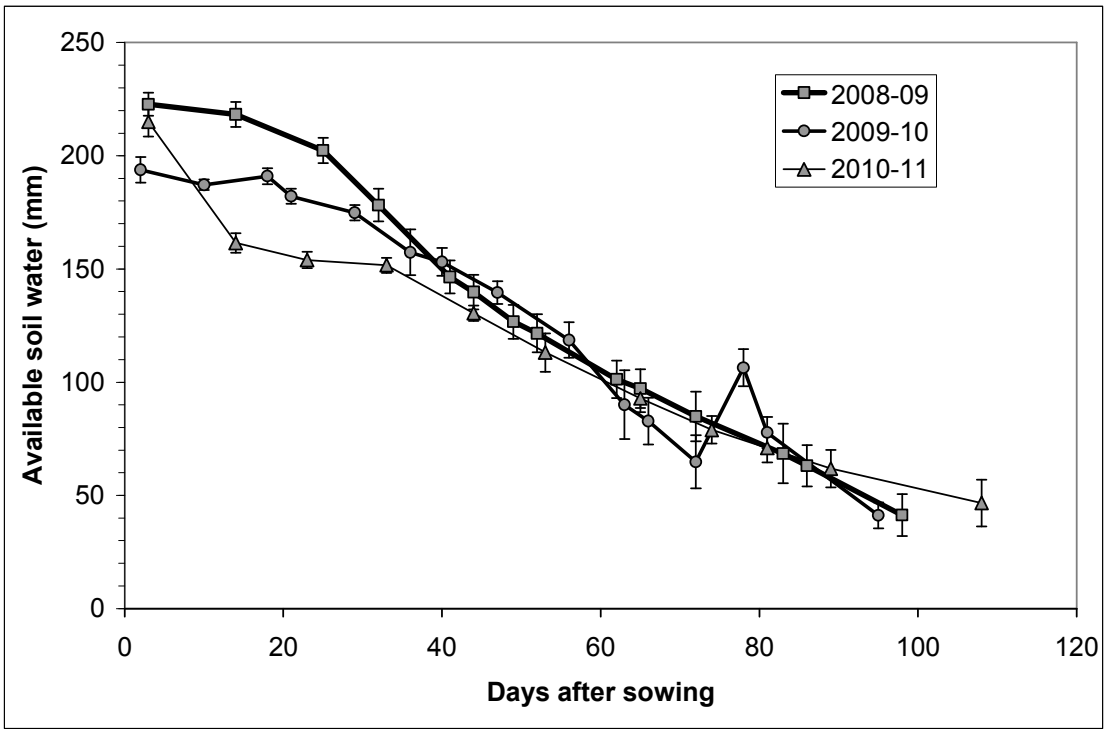

Fig. 4.9: Changes in available soil moisture up to a soil depth of 1.2 m across the crop growing seasons of 2008-09, 2009-10 and 2010-11. Vertical bars denotes standard error of differences (±)

A pooled analysis of three years data had shown that the genotype variation for shoot biomass, grain yield and HI were highly significant. The genotype × year interaction component was also significant but this

interaction component for the grain yield and the HI was five times less than the genotype component (Table 4.11).

Table 4.10: Trial means and analysis of variance of 84 genotypes, a subset of the minicore collection of chickpea germplasm, for phenology, shoot biomass at maturity, grain yield and harvest index in the field experiments during postrainy seasons of 2008-09, 2009-10 and 2010-11 under drought stressed environment

Season/ traits	Trial mean	Range of means	S.Ed	σ^2_g (F pr.)	Heritability (h^2)
2008-09					
Days to 50% flowering	49.7	35.0 – 68.7	1.77	64.3 (<.001)	0.96
Days to maturity	96.7	84.3 – 118.0	1.60	36.1 (<.001)	0.92
Shoot biomass (kg ha^{-1})	3388	2620 – 4359	400.0	1.89 (<.001)	0.86
Grain yield (kg ha^{-1})	1627	778 – 2336	212.0	3.71 (<.001)	0.48
Harvest index (%)	48.3	20.3 – 63.6	2.88	16.4 (<.001)	0.84
2009-10					
Days to 50% flowering	47.0	34.3 – 64.3	1.61	34.4 (<.001)	0.92
Days to maturity	92.3	79.3 – 113.7	2.38	29.1 (<.001)	0.90
Shoot biomass (kg ha^{-1})	3982	3030 – 5805	411.9	4.19 (<.001)	0.52
Grain yield (kg ha^{-1})	1660	686 – 2381	213.2	5.47 (<.001)	0.60
Harvest index (%)	42.6	17.6 – 58.4	2.29	46.4 (<.001)	0.94
2010-11					
Days to 50% flowering	46.2	31.3 – 66.3	2.20	25.4 (<.001)	0.88
Days to maturity	90.6	84.3 – 107.3	2.10	11.1 (<.001)	0.77
Shoot biomass (kg ha^{-1})	3953	2487 – 5006	340.2	3.66 (<.001)	0.47
Grain yield (kg ha^{-1})	1757	666 – 2462	186.2	10.6 (<.001)	0.76
Harvest index (%)	44.4	19.6 – 58.5	2.28	36.6 (<.001)	0.92

Table 4.11: Interaction of genotype with year for the grain yield and its components in the subset of the minicore collection of chickpea germplasm (n=84) during postrainy seasons of 2008-09, 2009-10 and 2010-11 under drought stressed environment

	Genotype	Genotype × Year
	Variance component (S.E.)	Variance component (S.E.)
Shoot biomass (kg ha^{-1})	63840 (24838)	174150 (27931)
Grain yield (kg ha^{-1})	94064 (16896)	17954 (4538)
Harvest index (%)	79.98 (13.67)	17.41 (2.28)

4.2.4 The extent of variation in CTD

Maximum temperatures recorded, on the days of CT measurements (59, 62, 69, 73, 76 DAS), were close to 30°C. At 82 DAS, it was 32°C (Table 4.9). There was a large range of variation among the genotypes for CTD, at all time of observations and the range was -4.9 at 62 DAS to -8.7 at 82 DAS. The genotypic variation among the genotypes was significantly different at a probability level of <0.001. The h^2 of the CTD at 76 DAS was relatively high (0.65) compared to 0.21, 0.48 and 0.49 at other DAS (Table 4.12).

The overall distribution of genotypes for their CTD was in general normal with a characteristic gap on the lower CTD wing (Fig. 4.10). As two thirds of the genotypes selected in this trial (n=58 out of 84) happened to be the drought tolerant ones, there were lower representation in the drought sensitive or lower CTD wing of the curve.

Table 4.12: Mean canopy temperature depression (CTD) measured at different days after sowing (DAS) for the 84 genotypes, a subset of the minicore collection of chickpea germplasm, during the postrainy season of 2010-11 under drought stressed environment

CTD at	Trial mean	Range of means	S.Ed	σ^2_g (F pr.)	Heritability (h^2)
59 DAS	-2.19	-5.68 – -0.10	0.91	1.80 (<0.001)	0.21
62 DAS	-2.38	-5.12 – -0.23	0.65	3.75 (<0.001)	0.48
69 DAS	-2.64	-5.83 – 0.53	0.87	3.73 (<0.001)	0.48
73 DAS	-4.94	-9.70 – -1.56	1.01	3.91 (<0.001)	0.49
76 DAS	-4.51	-8.46 – -1.90	0.64	6.52 (<0.001)	0.65
82 DAS	-5.08	-11.1 – -2.41	0.99	3.90 (<0.001)	0.49

4.2.5 CTD relationship with grain yield

The regressions between the CTD and grain yields were positive at all the measuring days, explaining 22, 40, 29, 21 and 9% of the grain yield variation at 59, 62, 69, 73, 76 DAS respectively. However, the measurement taken at 82 DAS was negative and explained a very minimal grain yield variation of 4% (Fig. 4.11). The closest association of CTD with grain yield was obtained with CTD measured at 62 DAS. At this stage, every one °C increase in CTD caused 293 kg increase in grain yield ha^{-1} (Fig. 4.11).

The CTD measured at 62 DAS in 2010-11 was regressed with 2008-09 and 2009-10 grain yields. The regression between grain yield and CTD were also positive and significant explaining 20 and 18% of the grain yield variation in the year 2008-09 and 2009-10 respectively (Fig. 4.12). The CTD of genotypes measured in a day correlated very well with the subsequent day measurements demonstrating that the CTD of the genotypes are largely genetic and repeatable. The correlation coefficients (r) of CTD 59 DAS verses 62 DAS, 62 DAS verses 69 DAS, 69 DAS verses 73 DAS, 73 DAS verses 76 DAS and 76 DAS verses 82 DAS were 0.86, 0.85, 0.81, 0.81 and 0.64, respectively (Fig. 4.13).

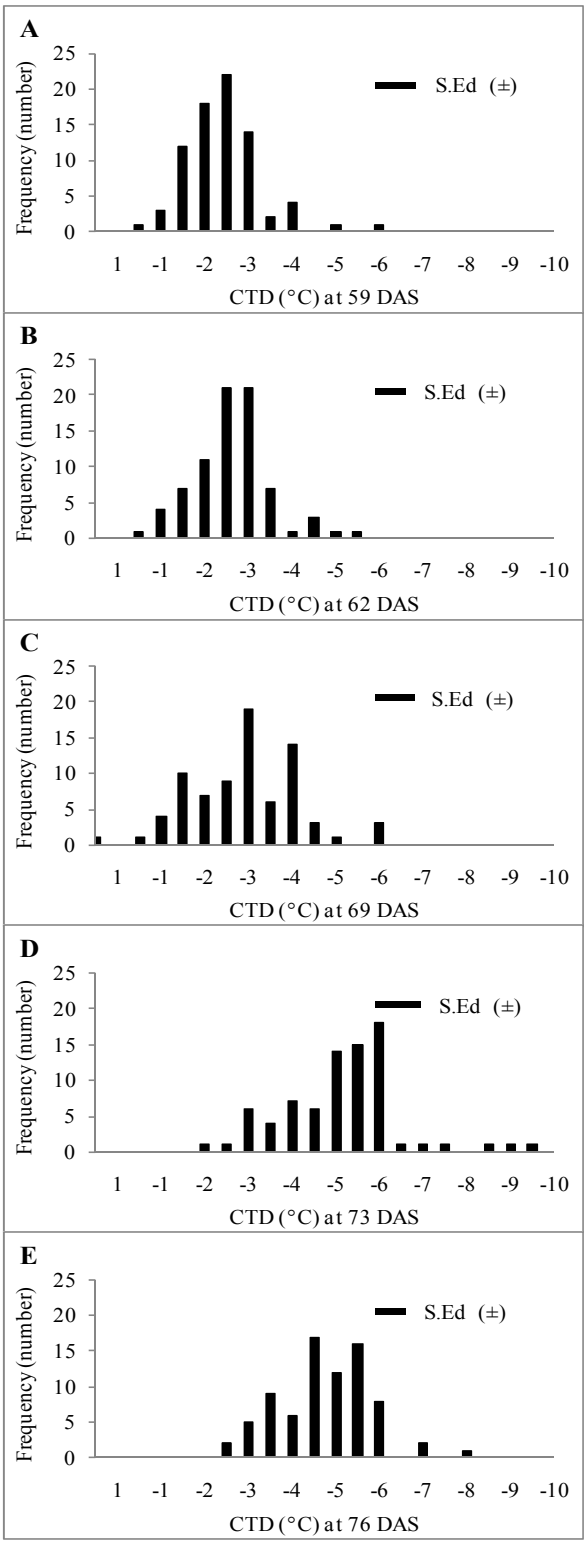

Fig.4.10: The distribution genotypes for the canopy temperature depression (CTD) at (A) 59 (B) 62 (C) 69 (D) 73 and (E) 76 DAS during crop reproductive stage in the subset of the minicore collection (n=84) during the postrainy season of 2010-11 under drought stressed environment

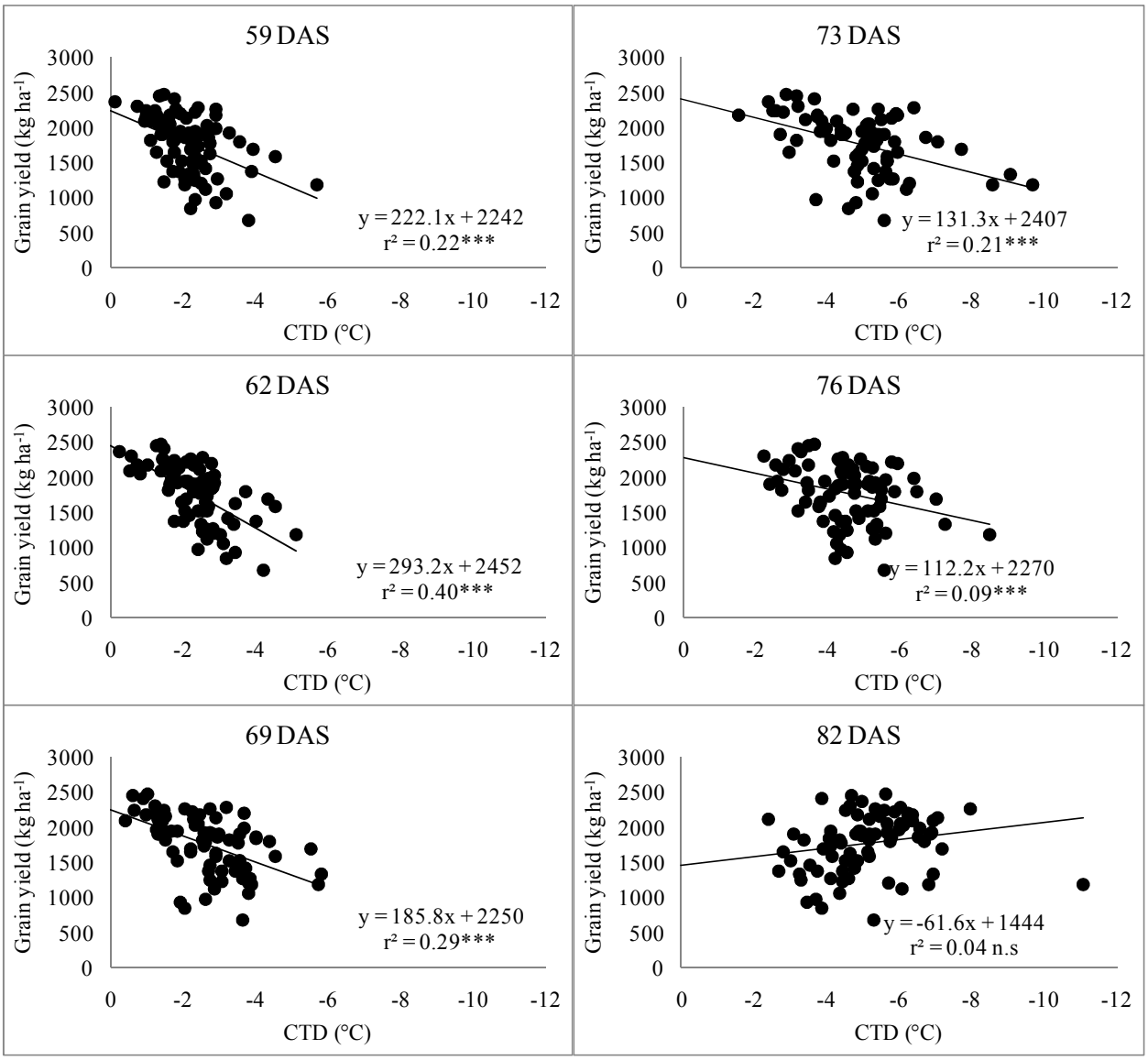

Fig. 4.11: The relationship between canopy temperature depression (CTD) at different days after sowing (DAS) during crop reproductive stage and the grain yield in the subset of the minicore collection (n=84) during the postrainy season of 2010-11 under drought stressed environment

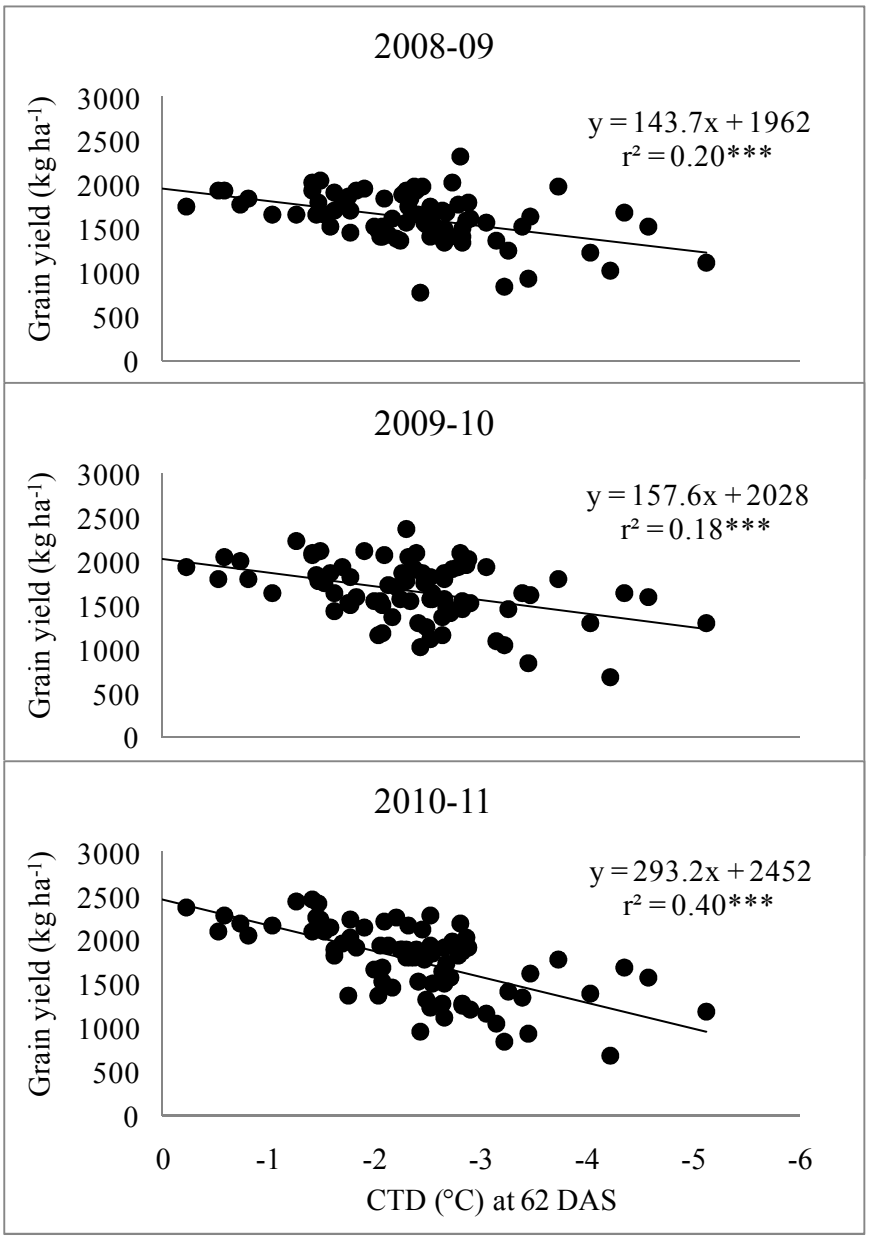

Fig. 4.12: The relationship between canopy temperature depression (CTD) measured at 62 days after sowing (DAS) in 2010-11 and the grain yield of the subset of the minicore collection (n=84) during postrainy seasons of 2008-09, 2009-10 and 2010-11 under drought stressed environment

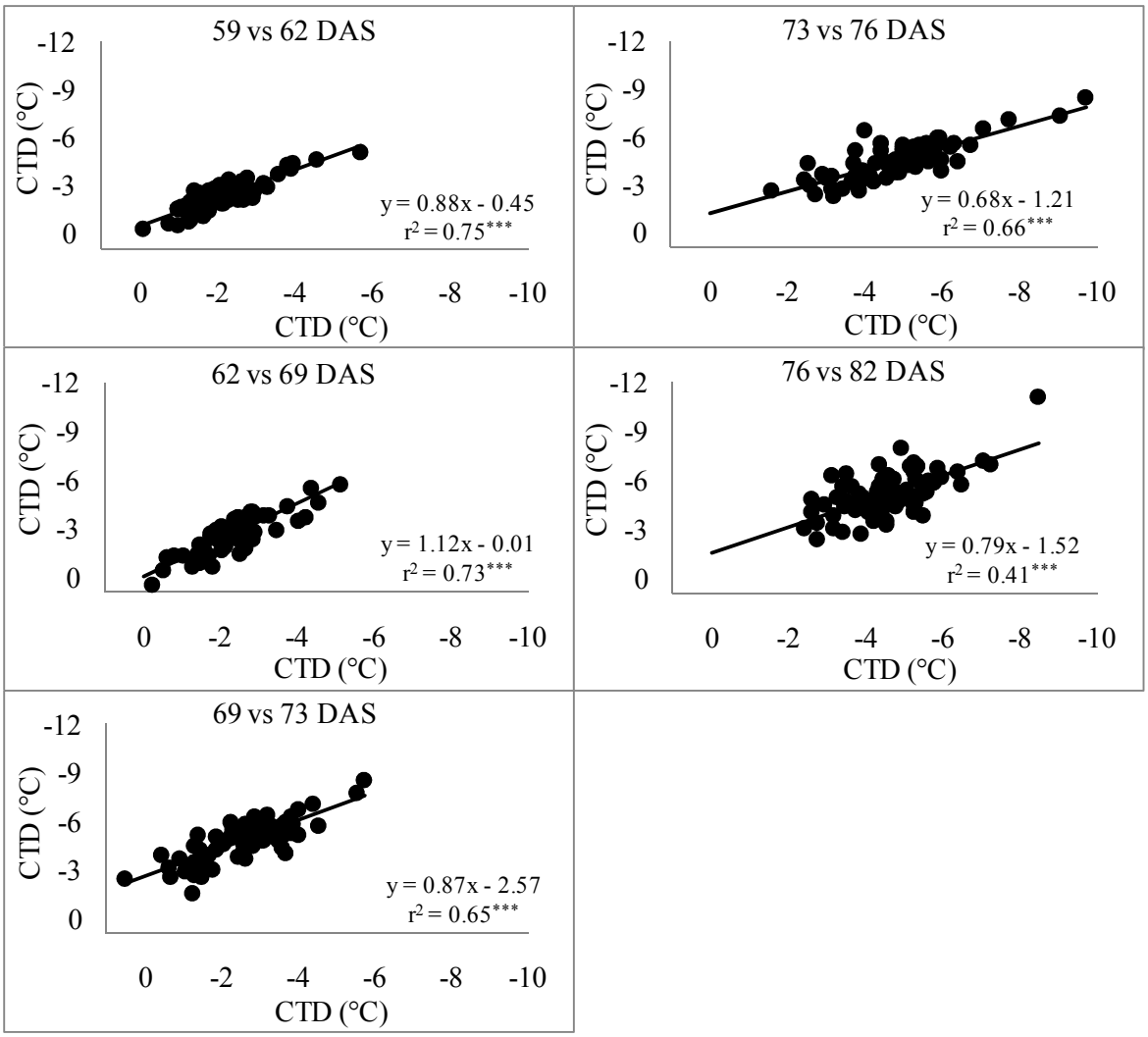

Fig. 4.13: The relationship of canopy temperature depression (CTD) recorded between two subsequent days of observation during crop reproductive stage in the subset of the minicore collection (n=84) during the postrainy season of 2010-11 under drought stressed environment. This is to show that the genotypes displayed considerable level of similarity across stages of observation

4.2.6 CTD categorization

As the closeness in association of CTD with the next subsequent measurement was deteriorating with every delay in sampling time leading to an insignificant relationship with grain yield, and the samples measured at 62, 69 and 73 DAS only explained the grain yield significantly with good level of h^2, these three sample means were used for clustering and to have representative groups of varying CTD. This analysis yielded five groups at 85% similarity level. Based on the extent of cluster group means of CTD these can be identified as: i. highest CTD (with CTD means at 62, 69 and 73 DAS as -1.2, -1.0 and -3.0), ii. high CTD (-1.9, -1.8 and -4.1), iii. moderately low CTD (-2.5, -2.8 and -5.2), iv. low CTD (-3.1, -3.9 and -5.8), and v. lowest CTD (-4.0, -5.2 and -8.8). The highest CTD, high CTD, moderately high CTD, low CTD and lowest CTD groups comprised of 13, 12, 42, 13 and 4 members, respectively. The extreme four groups except the moderately low CTD group is presented in table 4.13. The highest CTD entries not only had the highest grain yields in all the three years but also the highest shoot biomass (Table 4.13). Their previous drought reactions were either highly tolerant or tolerant (Krishnamurthy *et al.,* 2010). Similarly the high CTD group members were earlier ranked as mostly tolerant. There were 15 kabuli genotypes included in this trial but none of the kabuli merited grouping in the highest or the high CTD groups.

Table 4.13: CTD recorded at 62, 69 and 73 days after sowing (DAS), days to 50% flowering, days to maturity, shoot biomass(kg ha^{-1}) and harvest index (%) of 2010-11 with the grain yields recorded at 2008-09, 2009-10 and 2010-11 of the highest CTD, high CTD, low CTD and lowest (inconsistent) CTD cluster group members

Serial no.	Genotypes	CTD 62	CTD 69	CTD 73	Days to 50% flowering	Days to maturity	Shoot biomass (kg ha^{-1})	Harvest index (%)	Grain yield (kg ha^{-1}) 2008-09	2009-10	2010-11
Highest CTD											
1	ICC 637	-1.6	-1.3	-2.7	54	93	4307	44.0	1909	1651	1903
2	ICC 1422	-1.5	-1.5	-2.5	38	86	3865	57.7	2409	2111	2229
3	ICC 1098	-1.4	-1.0	-2.9	48	88	5006	49.2	2039	2093	2462
4	ICC 7441	-1.3	-0.6	-3.2	41	89	4445	54.8	1665	2234	2437
5	ICC 5434	-1.8	-0.6	-2.6	35	86	4422	50.4	1461	1510	2232
6	ICC 1180	-1.6	-1.5	-3.2	54	93	4998	35.9	1709	1432	1816
7	ICC 12947	-1.5	-1.3	-3.4	52	94	4398	48.0	1662	1761	2109
8	ICC 2969	-1.6	-1.5	-3.7	37	87	4145	52.1	1536	1859	2154
9	ICC 14778	-1.5	-0.9	-3.7	49	90	4738	50.9	1801	1781	2412
10	ICC 1083	-0.5	-0.4	-3.9	40	86	4031	51.9	1944	1808	2090
11	ICC 1923	-0.6	-1.2	-3.2	45	88	4475	51.1	1949	2049	2289
12	ICC 867	-0.2	0.5	-2.4	41	87	4664	51.0	1762	1933	2366
13	ICC 1164	-1.0	-1.3	-1.6	55	92	4315	50.3	1658	1631	2170
	Group Mean	-1.2	-1.0	-3.0	45	89	4447	49.8	1780	1835	2205
High CTD											
1	ICC 456	-2.5	-1.5	-3.8	49	90	3789	51.3	1543	1578	1942
2	ICC 11664	-2.1	-1.8	-4.2	56	94	4178	36.4	1405	1195	1517
3	ICC 14077	-2.0	-1.7	-3.9	43	88	3644	53.3	1406	1550	1945
4	ICC 1398	-1.4	-1.4	-4.3	37	85	3699	56.6	1943	2069	2091
5	ICC 13219	-1.7	-1.3	-4.4	41	85	3884	50.3	1816	1936	1951
6	ICC 1230	-2.3	-2.4	-3.8	40	87	3979	54.8	1764	2058	2177
7	ICC 2242	-2.4	-2.6	-3.7	66	105	4312	22.4	778	1032	962
8	ICC 9586	-2.3	-2.5	-4.1	53	92	3878	46.6	1855	1544	1805
9	ICC 2065	-2.6	-1.7	-3.0	56	95	4016	40.7	1707	1356	1640
10	ICC 3325	-2.1	-2.2	-2.8	45	89	3990	55.3	1849	2066	2205
11	ICC 6279	-0.7	-1.0	-6.0	36	85	3959	55.1	1768	2015	2179
12	ICC 10399	-0.8	-1.4	-5.1	40	86	3776	54.3	1849	1802	2048
	Group Mean	-1.9	-1.8	-4.1	47	90	3925	48.1	1640	1683	1872
Low CTD											
1	ICC 3218	-4.2	-3.7	-5.6	64	88	3046	22.5	1013	686	681
2	ICC 4814	-4.6	-4.5	-5.7	44	89	3741	42.1	1531	1604	1575
3	ICC 8058	-2.9	-3.8	-6.3	43	89	3093	38.5	1616	1522	1206
4	ICC 15868	-2.8	-4.0	-6.7	47	89	3732	49.8	1495	1542	1859
5	ICC 8318	-3.7	-4.4	-7.1	31	85	3426	52.1	1980	1803	1787
6	ICC 4958	-2.8	-3.7	-5.9	32	84	3747	58.5	2336	2108	2191
7	ICC 11879	-2.8	-3.8	-5.8	47	95	3686	34.5	1349	1517	1271
8	ICC 12028	-2.5	-3.6	-5.6	49	96	4335	30.4	1549	1257	1320
9	ICC 13283	-2.6	-3.6	-5.7	56	94	4760	31.8	1515	1578	1513
10	ICC 13461	-2.6	-3.6	-5.8	58	96	4414	28.8	1394	1153	1268
11	ICC 7184	-3.2	-3.7	-5.3	45	91	3918	36.2	1244	1459	1417
12	ICC 9402	-3.1	-3.8	-5.3	57	97	3999	25.9	1369	1099	1046
13	ICC 11944	-2.8	-4.0	-5.1	50	91	3987	45.3	1771	1935	1831
	Group Mean	-3.1	-3.9	-5.8	48	91	3837	38.2	1551	1482	1459
Lowest CTD											
1	ICC 4872	-3.0	-3.9	-9.7	34	87	2487	47.3	1580	1946	1169
2	ICC 9002	-5.1	-5.7	-8.6	47	88	3392	49.8	1709	1928	1187
3	ICC 12155	-4.3	-5.5	-7.7	43	86	3484	48.0	1678	1638	1682
4	ICC 13863	-3.4	-5.8	-9.1	39	86	2654	50.3	1528	1651	1336
	Group Mean	-4.0	-5.2	-8.8	48	87	3004	48.8	1624	1791	1344
	Environmental Mean	-2.4	-2.6	-4.9	46	91	3953	44.4	1627	1660	1757

4.2.7 Marker trait associations

Genotyping data generated earlier on this set (Varshney *et al.,* 2013b) coupled with phenotypic data was used for establishing marker trait associations. A total of 45 significant marker trait associations were identified for a total of 11 traits examined. For CTD trait studied at different DAS, maximum number of MTAs was observed in case of CTD at 69 DAS (10 MTAs). The p value for these MTAs ranged from 6.5×10^{-3} - 1.7×10^{-3} and phenotypic variation explained (PVE) ranged from 10.31 to 29.89 %. Among 10 markers associated with this trait eight were DArT loci (cpPb-677022, cpPb-491384, cpPb-676713, cpPb-350112, cpPb-682024, cpPb-678198, cpPb-675504 and cpPb-680058) and two SSR markers (NCPGR19, TA116). However, the maximum phenotypic variation was explained for CTD at 62 DAS (Table 4.14a). Interestingly, the MTAs for the CTD trait are located on CaLG01, CaLG04, CaLG05, CaLG06 and CaLG07 (Table 4.14b). Among four MTAs for CTD at 62DAS, three were SSR markers (TA113, TA116 and TA14) explaining > 20% PVE and while the DArT locus associated with this trait explained 10.29% PVE. CTD measured at 82 DAS had only one significant MTA with the SNP marker Ca_TOG898271_2_002_00001_Sep08. Nevertheless, CTD measured at 59 DAS, 73 DAS and 76 DAS had one, three and three significant MTAs, respectively.

Table 4.14a: Significant marker traits associations (MTAs) for canopy temperature depression (CTD) recorded at 59, 62, 69, 73, 76 and 82 days after sowing (DAS), days to 50% flowering, days to maturity, shoot biomass (kg ha^{-1}), grain yield (kg ha^{-1}) and harvest index (%) during the postrainy season of 2010-11 under drought stressed environment

Traits	Number of MTAs	Name of the marker associated with trait	P-value	Phenotypic variation explained (%)
CTD at 59DAS	1	CaSTMS21	4.2 × 10-3	10.3
CTD at 62DAS	4	TA113, TA116, TA14, cpPb-677022	6.5 × 10-3 - 1.7 × 10-3	10.3 - 29.9
CTD at 69DAS	10	cpPb-677022, cpPb-491384, cpPb-676713, cpPb-350112, cpPb-682024, cpPb-678198, cpPb-675504, NCPGR19, TA116, cpPb-680058	7.7 × 10-3 - 1.6 × 10-4	11.7 - 22.2
CTD at 73DAS	3	AGL111, NCPGR19, TA130	7.4 × 10-3 - 2.1 × 10-3	10.8 - 18.5
CTD at 76DAS	3	cpPb-677677, cpPb-490406, TA113	3.2 × 10-3 - 1.3 × 10-3	11.2 - 25.1
CTD at 82DAS	1	Ca_TOG898271_2_002_00001_Sep08	4.2 × 10-3	11.0
Days to 50% flowering	7	TAA58, Ca1C39501, TA14, cpPb-680739, cpPb-678696, cpPb-489416, cpPb-171342	7.96 × 10-18 - 1.1 × 10-3	10.3 - 62.7
Days to maturity	5	TA14, ASR_193_290, cpPb-675258, TR43, TA142	9.4 × 10-3 - 4.6 × 10-3	10.3 - 40.1
Shoot biomass (kg ha-^{1})	2	TA27, cpPb-678284	5.2 × 10-4 - 9.8 × 10-3	9.1 - 33.2
Grain yield (kg ha^{-1})	4	TA130, Ca1C39501, TA14, NCPGR4	8.2 × 10-4 - 2.9 × 10-3	14.7 - 42.3
Harvest index (%)	5	Ca1C39501, ASR_193_290, Ct6875951, Ca1C43515, Ca1C44194	9.9 × 10-3 - 1.4 × 10-3	9.5 - 13.8

Table 4.14b: Detailed information of marker trait association and the linkage group of the associated markers for canopy temperature depression (CTD) recorded at 59, 62, 69, 73, 76 and 82 days after sowing (DAS), days to 50% flowering, days to maturity, shoot biomass (kg ha^{-1}), grain yield (kg ha^{-1}) and harvest index (%) during the postrainy season of 2010-11 under drought stressed environment

Trait	Marker	Linkage group	P- value	Phenotypic variation explained (%)
CTD at 59DAS	CaSTMS21	LG1	0.0042	10.3
CTD at 62DAS	cpPb-677022	LG7	0.0065	10.3
CTD at 62DAS	TA113	LG1	0.0017	27.8
CTD at 62DAS	TA116	LG5	0.0040	22.5
CTD at 62DAS	TA14	LG6	0.0054	29.9
CTD at 69DAS	cpPb-350112	LG1	3.38E-04	19.4
CTD at 69DAS	cpPb-491384	LG5	2.39E-04	19.0
CTD at 69DAS	cpPb-675504	LG4	0.0027	14.3
CTD at 69DAS	cpPb-676713	LG6	2.85E-04	18.3
CTD at 69DAS	cpPb-677022	LG7	1.60E-04	19.4
CTD at 69DAS	cpPb-678198	Unlinked	8.38E-04	16.6
CTD at 69DAS	cpPb-680058	Unlinked	0.0077	11.7
CTD at 69DAS	cpPb-682024	Unlinked	6.41E-04	15.9
CTD at 69DAS	NCPGR19	LG7	0.0028	13.4
CTD at 69DAS	TA116	LG5	0.0061	22.2
CTD at 73DAS	AGL111	Unlinked	0.0021	11.5
CTD at 73DAS	NCPGR19	LG7	0.0054	10.8
CTD at 73DAS	TA130	LG4	0.0074	18.5
CTD at 76DAS	cpPb-490406	LG4	0.0030	11.2
CTD at 76DAS	cpPb-677677	Unlinked	0.0013	14.6
CTD at 76DAS	TA113	LG1	0.0032	25.1
CTD at 82DAS	Ca_TOG898271_2_002_00001_Sep08	Unlinked	0.0042	11.0
Days to 50% flowering	Ca1C39501	Unlinked	1.40E-04	18.9
Days to 50% flowering	cpPb-171342	LG1	0.0076	10.3
Days to 50% flowering	cpPb-489416	LG2	0.0057	10.4
Days to 50% flowering	cpPb-678696	Unlinked	0.0055	11.5
Days to 50% flowering	cpPb-680739	Unlinked	0.0051	10.9
Days to 50% flowering	TA14	LG6	0.0011	50.0
Days to 50% flowering	TAA58	LG7	7.96E-18	62.7
Days to maturity	ASR_193_290	Unlinked	0.0072	10.9
Days to maturity	cpPb-675258	LG6	0.0081	10.3
Days to maturity	TA14	LG6	0.0046	40.1
Days to maturity	TA142	LG3	0.0094	15.7
Days to maturity	TR43	LG1	0.0088	35.5
Shoot biomass (kg ha^{-1})	cpPb-678284	LG4	0.0098	9.1
Shoot biomass (kg ha^{-1})	TA27	LG2	5.29E-04	33.1
Grain yield (kg ha^{-1})	Ca1C39501	Unlinked	8.21E-04	14.7
Grain yield (kg ha^{-1})	NCPGR4	LG6	0.0050	16.6
Grain yield (kg ha^{-1})	TA130	LG4	3.43E-04	33.9
Grain yield (kg ha^{-1})	TA14	LG6	0.0029	42.3
Harvest index (%)	ASR_193_290	Unlinked	0.0014	14.9
Harvest index (%)	Ca1C39501	Unlinked	0.0014	13.8
Harvest index (%)	Ca1C43515	Unlinked	0.0099	9.1
Harvest index (%)	Ca1C44194	Unlinked	0.0099	9.1
Harvest index (%)	Ct6875951	Unlinked	0.0081	9.6

In addition to CTD trait, 7, 5, 5, 2 and 4 significant MTAs were also found for days to 50% flowering, days to maturity, HI, total shoot biomass and grain yield, respectively. The phenotypic variation explained by MTAs associated with days to 50% flowering ranged from 10.30 - 62.71%, while significant MTAs for days to maturity explained 10.28 - 40.08% PVE. Interestingly, among 5 markers that had significant MTAs 4 were SNP markers (Ca1C39501, Ct6875951, Ca1C43515 and Ca1C44194) and one was a gene-based SNP marker (ASR_193_290). Further, of four markers with significant association with grain yield, three were SSR markers (TA130, TA14 and NCPGR4) and one was SNP marker (Ca1C39501).

4.3 Experiment-3: Assessing the root anatomy of chickpea in comparison to other grain legumes and between types of chickpea to understand their drought adaptation

4.3.1 Experiment-3a

4.3.1.1 Root growth

Visual observations on the exposed trench wall had shown that the branching of the roots in pearl millet was profuse whereas branching was less and limited to the second order level in legumes (data not shown). Though the roots could be traced to depths more than 60 cm at 35 DAS the crop species did not differ in RDps. When the prolificacy of roots in the top 30 cm soil horizon is considered, it was the highest in pearl millet followed by chickpea. On the other hand, groundnut and pigeonpea had the least prolificacy of the root

system (data not shown). The differences in root distribution of chickpea and cowpea can be seen in Plate 7.

4.3.1.2 Root diameter

A wide range of root diameter at the proximal portion of the growing root tips, i.e. 10 cm above the root tip, was observed among the six crops studied (Fig. 4.14). Pearl millet had the thinnest roots (705 µm) followed by groundnut (728 µm) and pigeonpea (833 µm) (Fig. 4.15). The remaining crops produced relatively thicker roots with root diameter ranging from 975 to 1200 µm. These roots were relatively thick when compared to the reported soybean root thickness maintained in dry pots (Rieger and Litvin, 1999), likely due to very wet growing conditions provided by the Vertisol soil.

4.3.1.3 Cortex and endodermis

The cortex is made of parenchyma tissue and plays a critical role in regulation of the transport of water and other substances via the apoplast and symplast pathways. In dicotyledons, the cortex is shed when secondary growth begins while in monocotyledons, the cortex is maintained throughout the plant's life and the cells can develop secondary walls and lignify. The crops that are used in this study had the root cortex proportion in the range of 31% to 49% of the cross section area (Fig. 4.14 and 4.16). Pearl millet had the largest cortex area of about 50% of the whole root section. Soybean followed by pigeonpea presented smaller cortex than the other legumes. Pearl millet had revealed the presence of a clear endodermis layer in the center that surrounds the vascular cylinder. However in all the

Plate 7: The differences in rooting patterns of chickpea (two rows in the right) and cowpea (two rows on the left). Note the profuse surface rooting in chickpea on the surface soil horizon

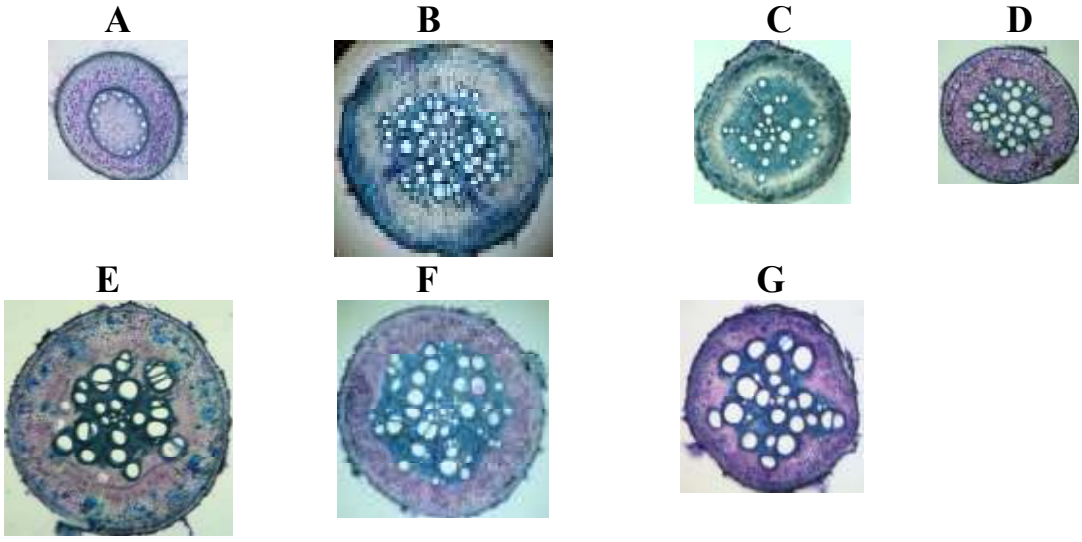

Fig. 4.14: Transverse sections of roots of six legume species in comparison to pearl millet. A= pearl millet (× 80), B= chickpea (× 120), C= pigeonpea (× 100), D= groundnut (× 100), E= cowpea (× 200), F= soybean (× 200) and G= common bean (× 300)

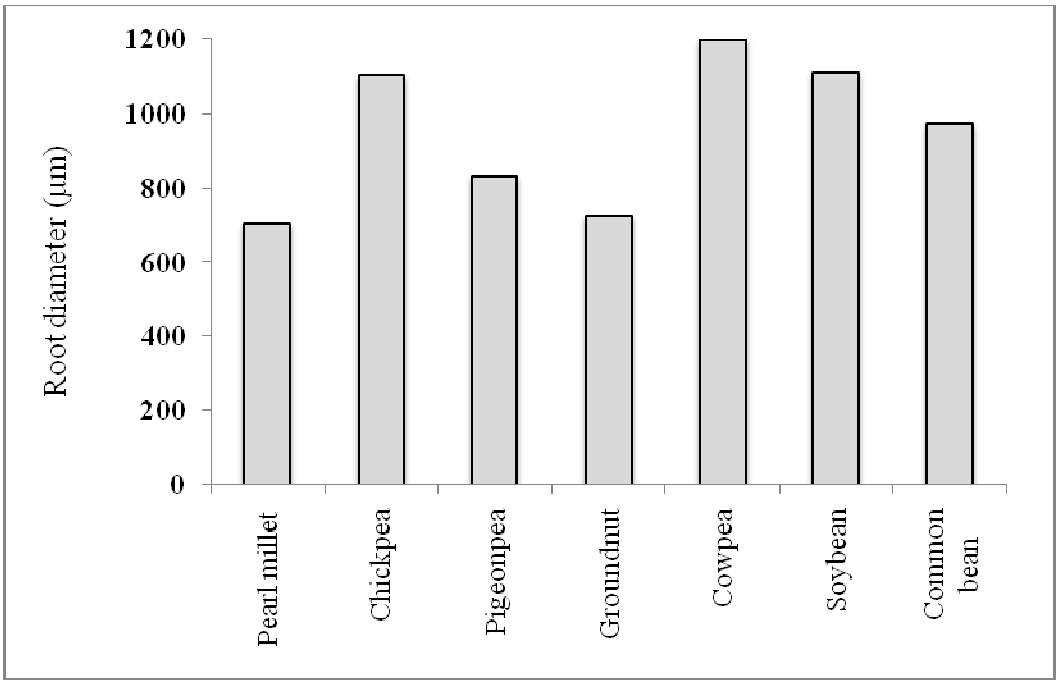

Fig. 4.15: The root diameter variation among the six legume species in comparison to pearl millet. The root diameter was measured on the portion of the roots used for cutting transverse sections to study the root anatomy

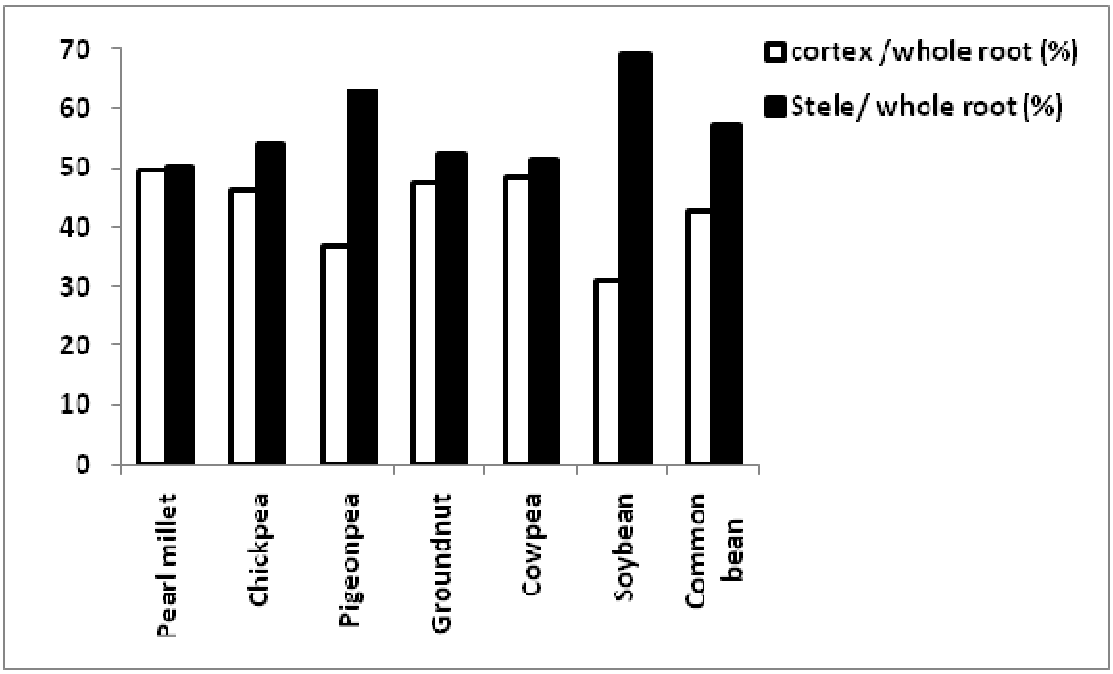

Fig. 4.16: The root cortex and stele ratio variation among six legume species in comparison to pearl millet

legumes both the endodermis and the pericycle layers were missing. The cortex was found intact in all legumes at this stage though loss of major cortex was reported as a consequence of secondary thickening (Vasquez, 2003).

4.3.1.4 Vascular tissue

The primary tetrarch arrangements of the vascular bundles, characteristic of the examined six legumes at the start of secondary thickening (chickpea: Fatima and Chaudhry, 2004; pigeonpea: Bisen and Sheldrake, 1981; groundnut: Tajima *et al.*, 2008; cowpea: Lawton, 1972; soybean: Kumudini, 2010; common bean: Jaramillo *et al.*, 1992), are lost due to secondary thickening in all the legumes. The whole inner core is fully occupied by the xylem vessels with medullary rays barely visible (Fig. 4.14). The centripetal pattern of maturation, reported in dicotyledons in the early stages of secondary thickening, is lost. The narrow xylem elements were seen interspersed with metaxylem vessels throughout the central xylem core. However, the crushing and loss of protoxylem as a consequence of secondary thickening in the stems of *Medicago sativa* is reported by Esau (1977). But, the symptoms of such crushing and loss of protoxylem is not seen in the roots of any of the legumes that were studied. The phloem is pushed more into the cortex towards the periphery of the central xylem-dominated core. The vascular cylinder of the root is very different from that in the stem. In stems, the xylem and the phloem are found in continuing rings, xylem occupying a more central position and the phloem on scattered patches well into the cortex. In

pearl millet, either one single xylem element or a few in a cluster surrounded by phloem cells are placed closely inside the pericycle and a large central medulla (Fig. 4.17). In many dicotyledons, secondary growth develops later where the cambium and the peridermis play an important role.

4.3.1.5 Xylem vessels

Among the crops studied, chickpea had the maximum number of large metaxylem vessels (32) as well as the small xylem vessels (44) but with the narrowest average diameter of these vessels (9.5 µm) (Table 4.15). Cowpea and common bean had the least number of total xylem vessels but their average diameter was moderate. If the total xylem passage (number of xylem vessels × average vessel diameter) of a single root is considered, pigeonpea (422 μm^2), groundnut (470 μm^2) and common bean (490 μm^2) ranked the least. Cowpea (681 μm^2) and chickpea (722 μm^2) ranked moderate and soybean was the top (882 μm^2) in terms of the xylem passage per root. However, pearl millet (166 μm^2) was way below in these terms.

4.3.1.6 Influence of growing environment on root anatomy

The roots of chickpea grown in a well managed hydroponics had shown large number of branches arising from the base of the tap root. These branches measured not more than 25 cm in length and showed less branching further (Data not shown). This morphological modification is likely due to less resistance to root elongation compared with soil grown plants. Roots grown in this environment had clearly shown the characteristic tetrarch pattern of xylem bundles

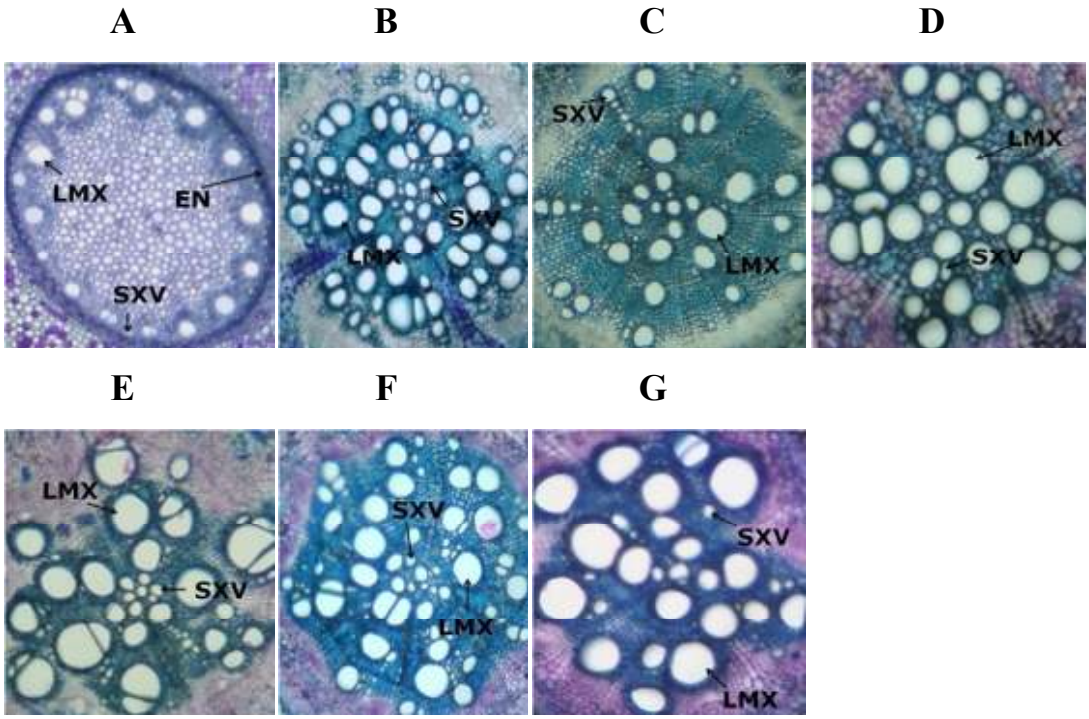

Fig. 4.17: Stelar portion of roots of B= chickpea (× 200), C= pigeonpea (× 300), D= groundnut (× 400), E= cowpea (× 400), F=soybean (× 400) and G= common bean (× 400) in comparison to A= pearl millet (× 200). LMX= large metaxylem; SXV= small xylem vessels; EN= endodermis

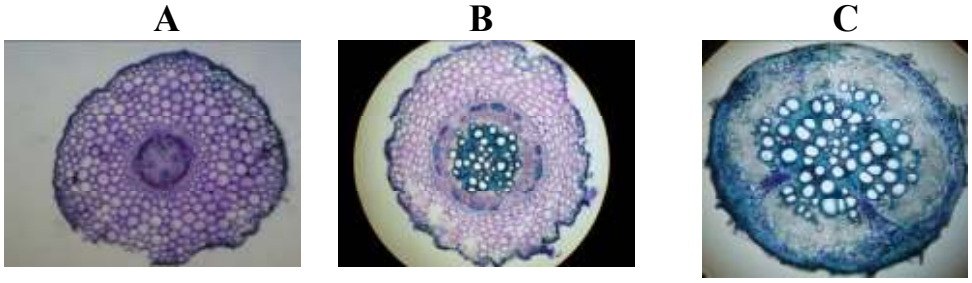

Fig. 4.18: Transverse sections of chickpea roots that were grown for 40 days in (A) hydroponics (× 100), (B) optimally irrigated Vertisol-filled pot (× 100) and (C) under receding soil moisture (× 120) in a Vertisol during rainy season 2010

Table 4.15: Xylem vessel characteristics of six grain legume species in comparison to pearl millet

Species	Number of small xylem vessels	Number of large metaxylem vessels	Total number of xylem vessels (small + large)	Range of vessel diameter (µm)	Average size of xylem vessels (µm)
Pearl millet	10	10	20	7 - 9	8.3
Chickpea	44	32	76	6 - 15	9.5
Pigeonpea	26	18	44	7 - 14	9.6
Groundnut	19	28	47	5 - 16	10.0
Cowpea	20	17	37	9 - 27	18.4
Soybean	40	23	63	10 - 22	14.0
Common bean	14	21	35	8 - 23	14.0

that alternated with strips of phloem bundles (Fig. 4.18). The stele size was very limited as well as in number of xylem vessels. All these stele characters indicated that either the secondary thickening was delayed or the roots will not thicken at all. However the cortex was proportionately thick with round, large and loosely packed parenchymatous cells indicating a very poor centripetal growth.

The chickpea roots grown in OI pots, did show all these characteristics of a hydroponics grown plant but the secondary thickening seemed to have progressed but by producing relatively fewer and narrower vessels (Fig. 4.18). Also the tetrarch formation of the xylem bundles were seen intact while newer large metaxylem vessels were added between the gaps of this tetrarch arms and below the phloem bundles. Also the round parenchyma cells seen in the hydroponics had turned hexagonal seemingly with the internal pressure of secondary thickening. A clear endodermis layer and cambium are intact.

In a field grown plant, with the advance in secondary thickening, all these early stage characteristics are lost with the enormous addition of xylem vessels in number and size (Fig. 4.18). However the cortical layer remained 6-7 layers thick irrespective of the stele growth or the growing environment. The cortical cells were centripetally compressed, relatively small and dense with no intercellular spaces. With increasing levels of water deficit the cells tend to be more compact and tightly packed.

4.3.2 Experiment-3b

The chickpea crop is sown and grown environment was different in the average temperature at Patancheru and Tel Hadya exhibits a shallow boat like pattern (Fig. 4.19).

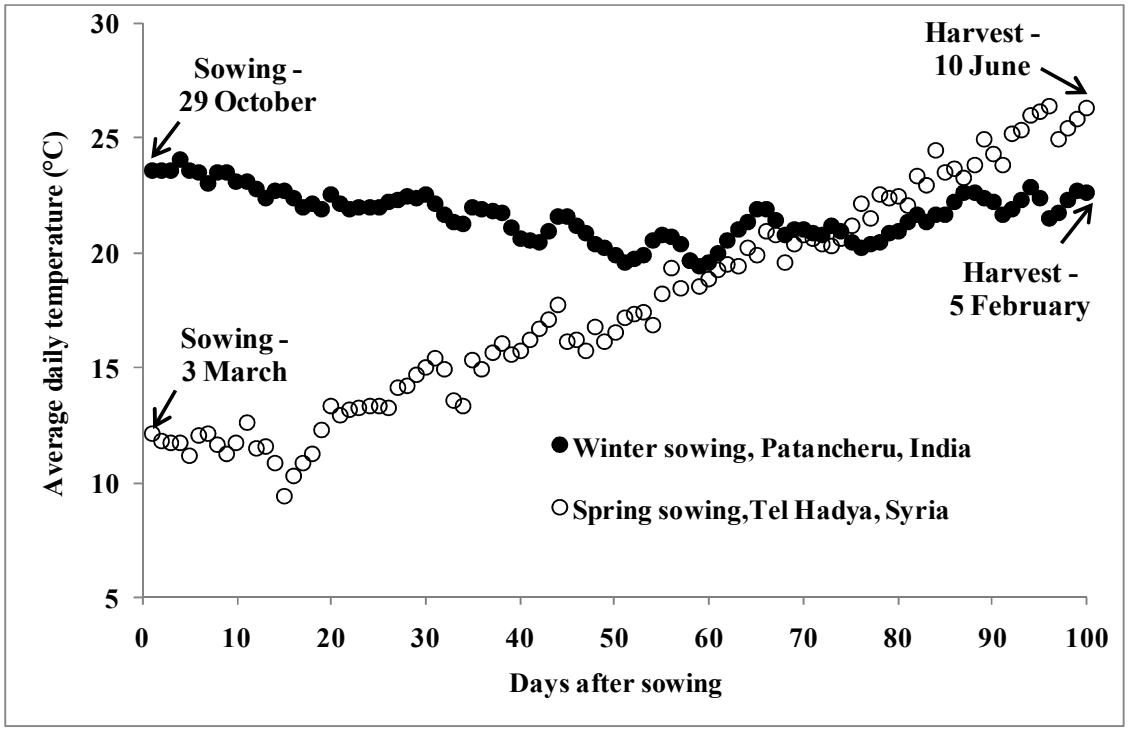

Fig 4.19: Long term (2004-2013) averages of daily temperatures (°C; average of maximum and minimum) at ICRISAT, Patancheru, India and at ICARDA, Tel Hadya, Syria during the crop growing season (winter-sown crop in Patancheru and spring-sown crop in Tel Hadya). The rain fed crop growing duration for Patancheru was adopted from Krishnamurthy et al. (2013a) and for Tel Hadya from Silim and Saxena (1993)

The thickness of the tap root varied heavily and it varied minimum at 20 cm soil depth across plants within a genotype. The stelar portion constitutes relatively more area than the cortex in both *desi* and kabuli genotypes except ICCV 10 and JG 11 as it was about to close in both cortex and stele area. However, the cortex was majorly reduced in kabuli compared to *desi* genotypes (Fig 4.20). Based on the three replicates of root transverse sections sampled for root anatomy it was noted that thexylem vessels in *desis* were fewer in number and narrower in diameter compared to the kabulis (data not shown). The wider metaxylem vessels were 21, 34 and 45 in *desi* genotypes ICCV 10, ICCC 37 and JG 11, respectively, compared to 57, 51 and 50 in the kabuli genotypes ICCV 2, JGK 1 and KAK 2 (Fig 4.20). Similarly the protoxylem vessels were 43, 31 and 70 in *desi* genotypes ICCV 10, ICCC 37 and JG 11, respectively, compared to 90, 90 and 85 in the kabuli genotypes ICCV 2, JGK 1 and KAK 2. Average metaxylem diameter (mean of three widest and three narrowest) of *desis* were 50.4, 75.5, and 71.2 µm for ICCV 10, ICCC 37 and JG 11 and of kabulis was 78.0, 78.5, and 76.0 µm for ICCV 2, JGK 1 and KAK 2, respectively.

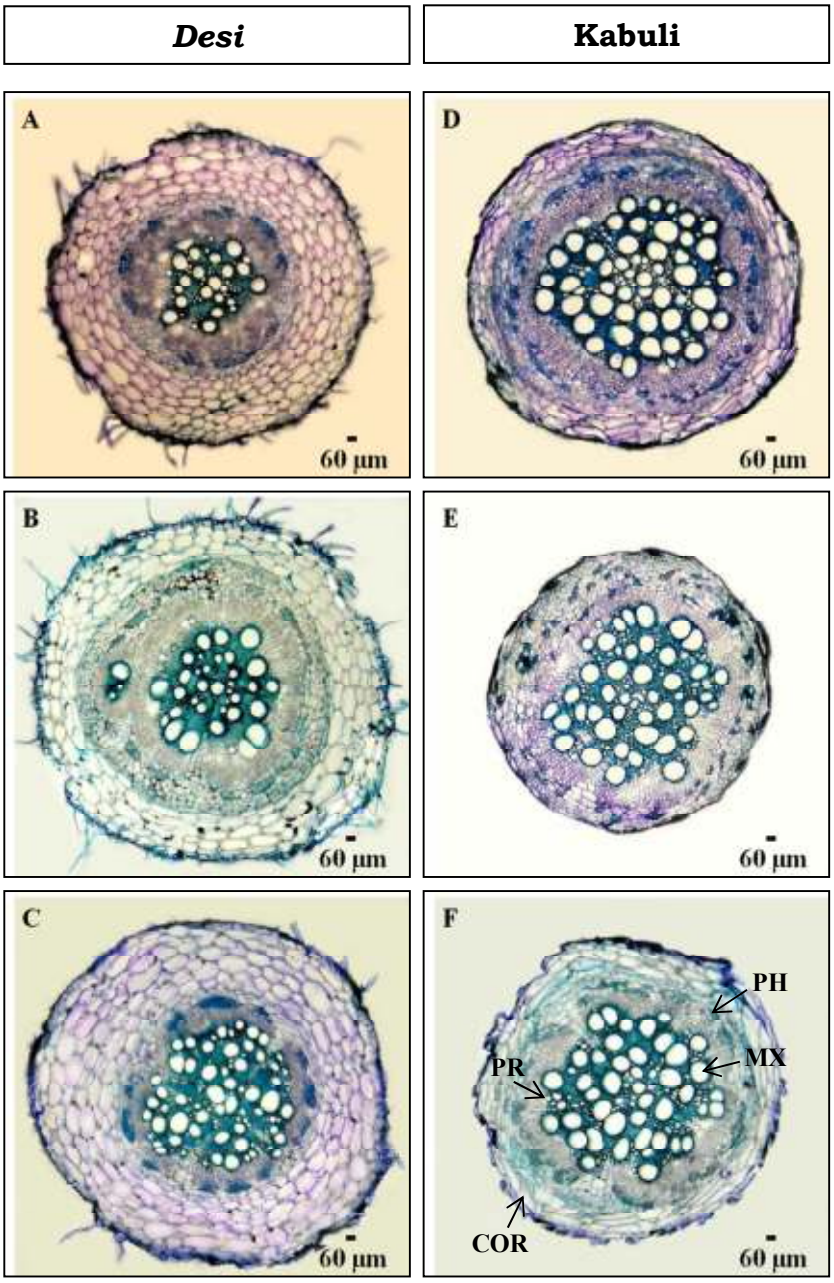

Fig. 4.20: Photomicrographs of transverse freehand root sections (× 100) of *desi*, A. ICCV 10, B. ICCC 37, and C. JG 11, and kabuli genotypes, D. ICCV 2, E. JGK 1, and F. KAK 2, stained with 50% toludine blue. COR= cortex; MX= metaxylem; PR= protoxylem; PH= phloem

5. DISCUSSION

5.1 Experiment-1: Assessment of various traits in chickpea for terminal drought tolerance

Chickpea is a major grain crop and therefore, the focus of drought resistance is on the ability to sustain greater biomass production and crop yield under a seasonally increasing water deficit, rather than the physiological aptitude for plant survival under extreme drought shock (Serraj and Sinclair, 2002). But the influence of G × E interactions on grain yield may make grain yield less reliable. But the current level of knowledge on the traits or combination of traits that explain the grain yield under water-limited environments is not adequately consistent and conclusive demanding a parallel verification of performance of both traits along with grain yield. Therefore in this study drought tolerance has been primarily measured as grain yield under DS. Apart from grain yield, few physiological characteristics such as shoot biomass production under DS and drought tolerance indices were also considered as alternative drought tolerance measures depending on the contextual relevance (Pinheiro *et al.,* 2005; Kobata *et al.,* 1996; Krishnamurthy *et al.,* 2010).

Physiological traits that might help in adaptation to water-limited environments are unlikely to be universal and some will be important in one region but detrimental in another (Richards, 2006). Likewise the strategies of water use for crop productivity may vary, mostly caused by the soil and environmental variations. For example,

a conservative soil water uptake can be risky under rapidly drying soils while this could remain as a life line to reproduction under slow drying soils. Though there are contradictions, on when the plant has to take more water for an enhanced drought avoidance (Passioura, 1972; Richards and Passioura, 1981a, b, 1989; Sinclair *et al.,* 1984; Johansen *et al.,* 1994; Krishnamurthy *et al.,* 1996; Rebetzke and Richards, 1999; Serraj *et al.,* 2003; Blum 2009; Zaman-Allah *et al.,* 2011a; Kashiwagi *et al.,* 2015), the amount of soil water extracted by a genotype at any given stage has been considered as an indication of successful drought avoidance strategy as high soil water use is known to directly reflect on T and shoot biomass production (Sinclair *et al.,* 1984; Blum, 2005, 2009).

In general, traits responsible for drought tolerance, and particularly drought avoidance, in any genotype are likely to be different from another as plants adapt to DS through different mechanisms and with the help of many different traits (Richards, 2006; Ludlow and Muchow, 1990; Saxena and Johansen, 1990a; Johansen *et al.,* 1997; Soltani *et al.,* 2000). Thus, a comprehensive coverage of all the traits and stages of crop growth, monitored as root traits (measured at 35, 50 and 80 DAS in 2009-10, and 45, 55, 65, 75 and 90 DAS in 2010-11), shoot traits (measured at 28, 51, 84 and 96 DAS in 2009-10, and 24, 37, 48, 58, 70, 80 and 101 DAS in 2010-11), yield components of both structural and analytical, and DTI and associated with the grain yield is expected to give us an indication of various possible trait combinations and their significant contribution

to drought tolerance. It had been observed that these trait combinations occasionally differ depending on the crop growth stage (Vadez *et al.,* 2014; Zaman-Allah *et al.,* 2011a; Krishnamurthy *et al.,* 2013a; Kashiwagi *et al.,* 2013, 2015). Many root traits have been seen to contribute to drought tolerance (avoidance) such as RDp, RLD, RDW, RSA, average root diameter, RV, root hair density under rainfed condition (Ludlow and Muchow, 1990; Saxena *et al.,* 1993; Krishnamurthy *et al.,* 2003; Kashiwagi *et al.,* 2005; Subbarao *et al.,* 1995; Turner *et al.,* 2001; Passioura, 2006). However, this study mainly focused on RLD and RDW that had been earlier known as major contributing traits compared to the other root parameters. Also some amount of information is generated on the RDp but the employed methodology was efficient enough to detect differences only in increments of 15 cm soil depth.

5.1.1 Contribution of roots traits to drought tolerance

5.1.1.1 Rooting depth

The genotypes varied for RDp, considerably, at the late vegetative stage or at the approach of flowering (35 DAS). The known early and strong rooting genotypes ICC 4958 and ICC 8261, the highly drought tolerant genotypes ICC 867 and ICC 14778 and the best adapted genotype ICCV 10 were able to reach, with substantial root presence, the maximum depth of 45-60 cm in 2010-11, a season when the crop was sown late by three weeks and the soil moisture receding was intense, indicating that the early gain in RDp has a relationship with drought tolerance. But such a differential genetic

performance displayed by these genotypes did not appear under irrigated condition. The RDp is seemingly is an opportunity driven expression as the phenotypic variation appeared only under DS (Kumar *et al.,* 2010).

At the flowering and early podding stages (45 and 55 DAS) the RDp differences that were observed in late vegetative stage, were not noticeable. The RDp of all the genotypes were almost the same though there were differences in deep zone RLD and RDW. Similar RDp progression without any genetic variation could be seen to occur at the mid- to late reproductive stages starting from 65 DAS. If there are any differences these were only in deep zone RLD and RDW. Two genotypes, ICC 7184 and ICC 3776, were the poor ones in the deep zone RLD or RDW distribution.

5.1.1.2 Root length density and root dry weight

At 35 DAS the genotypes varied for RLD and RDW considerably. RLD clearly had discriminated the drought tolerant genotypes from the sensitive ones indicating that most of the tolerant genotypes were early in root vigour and possessed larger root system. RDp and RLD have been found to be the relevant drought avoidance traits that confer grain yield advantage in chickpea under terminal DS environments (Subbarao *et al.*, 1995; Turner *et al.,* 2001; Kashiwagi *et al.,* 2006a; Kumar *et al.,* 2007). RDp is often emphasized to be an important trait as it is known to influence deeper soil water extraction to enhance reproduction and grain yield under DS (Saxena *et al.,* 1993; Krishnamurthy *et al.,* 2003; Kashiwagi *et al.,* 2005). However,

the two highly drought tolerant genotypes, ICC 14778 and ICC 867, and the best adapted genotype ICCV 10 have produced moderate to low RLD at this crop stage. Also the shoot biomass production and the soil moisture uptake have also been moderate for those genotypes. This conservative growth and soil water uptake had been restricted to the vegetative stage and these three genotypes were the top ones for the grain yield, shoot biomass at maturity and the root and shoot growth at the reproductive stages of crop growth. All the genotypes that yielded high under DS had been the ones that produced greater extent of RLD or RDW at deeper soil layers after 50 DAS or during the reproductive stage. However one single exception had been the genotype ICC 4958 that had shown to produce greater RDW or RLD very early and still yield high. Also the clarity with which the phenotypic variation has occurred was high under stress whereas such a differentiation had not occurred when OI either in terms of RDp or RLD. In several instances, though the RLD was high, it did not reflect in the RDW, likely due to the variation in their length to weight ratio (Krishnamurthy *et al.,* 1998) across genotypes that might appear in certain irrigation treatment or stage of growth or their combination. Also, the roots present at the deeper layer seem to contribute more to RL than to root weight (Follett *et al.,* 1974; Krishnamurthy *et al.,* 1996) as they tend to be finer compared to the whole root system. The RLD and RDW of the established genotypes, ICC 4958 and ICC 8261 were consistently high, and that of the drought sensitive genotypes (ICC 3776 and ICC 7184) were consistently low under both irrigation

treatments and years indicating the more constitutive nature of root traits (Silim and Saxena, 1993).

By flowering stage (45 DAS), the RLD and RDW of highly drought tolerant genotype ICC 867 started to become greater and comparable with other early strong root genotypes ICC 4958 and ICC 8261. However, the RLD and RDW of other highly tolerant genotype ICC 14778, had remained moderate. One of the small root genotype ICC 1882 also had started to produce moderate RLD and RDW at this stage indicating that enhanced root growth across genotypes could be growth stage specific. Chickpea is grown under receding soil moisture condition in highly cracking Vertisols. Under this growing environment a major part of the soil moisture available to the plant evaporates from the surface soil layers and therefore it is necessary to maximize T over evaporation and to gain a proportionate amount of shoot biomass productivity (Johansen *et al.,* 1994; Kashiwagi *et al.,* 2015). For example it had been estimated in wheat in Australia that up to 40% of the total available soil water was lost through soil evaporation (French and Schultz, 1984; Siddique *et al.,* 1990). Soil surface shading by the crop canopy is crucial for reducing this water loss. Reduced soil evaporation by a fast and vigorous growth of seedling was therefore a target in an Australian wheat breeding program (Rebetzke and Richards, 1999). Such seedling vigor is also desirable for chickpea. Chickpea is typically known to use significantly more water from the soil profile than the other legumes such as dry pea or lentil (Miller *et al.,* 2001), and a major part of this difference in

water use between dry pea and chickpea was due to the water used from below 60 cm soil depth and where chickpea roots were highly functional in terms of increased water extraction (Gan *et al.,* 2009). The genotypes ICC 3776 and ICC 7184 had produced the least RLD and RDW clearly among all the genotypes under DS condition. But this response was not the same under OI condition where some of the highly drought tolerant produced low RLD and RDW similar to the sensitive ones, suggesting that when soil moisture is favorable, the plants tend to produce less roots and manage to extract adequate amount of water (Wang *et al.,* 2012).

At 50 and 55 DAS, a stage when all the genotypes entered into the reproductive phase, the strong root genotypes, ICC 4958 and ICC 8261, had maintained the high RLD and RDW status. At this stage most drought tolerant and particularly ICC 14799 and ICC 867 did exhibit a turn around in root growth. But still the drought sensitive (ICC 3776 and ICC 7184) and weak root genotypes (ICC 283 and ICC 1882) had produced low RLD and RDW. These responses clearly explained the drought reactions through the differences in root growth. The deep and profuse root system is considered to be essential for increased soil water extraction from the deeper layers and to maximize soil water-use for T, high stomatal conductance and greater CO_2 fixation per unit land area resulting in a higher plant production (Hinckley *et al.,* 1983; Blum, 2009; Kirkegaard *et al.,* 2007). Under OI condition also, the root growth in terms of RLD and RDW of the genotypes ICC 867, ICC 14778, ICCV 10 and Annigeri

became moderate to high at this stage indicating that these traits are also governed by the exponential phase of growth.

At the mid- to late reproductive stages starting from 65 DAS, a clear cut reversal in root growth, particularly at deeper zones, was noticeable. Also this deeper zone performance has influenced the overall RLD or RDW. The importance of enhanced stored soil water use during grain filling development is considered to be as twice as valuable for yield formation compared to the water captured at the younger stages of crop growth (Wasson *et al.,* 2014). The genotypes ICC 3325, ICC 14799 and ICC 283 were some good examples of a stronger root system particularly at reproductive stage. A reversal from poor to moderate levels of root growth was also observed in the drought tolerant genotypes ICC 1882 and ICC 283 that had very low RLD and RDW in the initial stages and become moderate at this stage. As observed at 45 DAS, the genotypes ICC 3776 and ICC 7184 had remained poor in root growth compared to the other drought tolerant genotypes emphasizing the constitutive nature of root growth.

At around 75-80 DAS, the genotypic distribution for their RLD and RDW had seen a large change. The highly drought tolerant genotype ICC 14778, that ranked low to moderate at previous stages in RLD and RDW, had turned to be the largest in root system. Also, the genotype ICC 3325 produced highest RLD and RDW at this stage. The genotypes, ICC 4958 and Annigeri, that were found to be strong in their root system at the early growth stages, become the poor ones at this stage due to the root senescence and death as these were early

in phenology. The genotypes ICC 14778 and ICC 3325 had achieved a strong root at this stage as these reached close to stage of physiological maturity. Also, the early stage poor rooting genotypes ICC 1882 and ICC 283 produced high to moderate RLD and RDW. Thus, in terms of root growth, the whole set of genotypes can be categorized as early strong rooting (ICC 4958 and ICC 8261), late strong rooting (ICC 867, ICC 3325, ICC 14799, ICC 14778 and ICCV 10), late moderate rooting (ICC 1882, ICC 283 and Annigeri) and poor rooting (ICC 3776 and ICC 7184) and the root growth to a major extent explained their drought grain yields.

5.1.1.3 Contribution of root length density and root dry weight to soil water uptake

Root traits explained the variation in crop utilized soil moisture very closely at any given soil depth or stage of crop growth under both the irrigation environments with a few exceptions. Such exceptions were the surface soil or the ultimate soil depth of root presence, at any given stage of crop growth. Also the sample measured immediately before the maturity or in the last stage of crop growth happened to be an exception as the root verses crop utilized soil moisture relations did not exist. The surface soil looses water rapidly through direct evaporation, independent of absorption by roots (Johansen *et al.,* 1994). But at the ultimate soil depth the presence of roots can be seen but that takes some more time and soil water absorption for the soil water loss to be noticeable (Krishnamurthy *et al.,* 1999). As the crop approaches maturity root senescence and decay starts leading to a

poor utilization of soil water by plants (Krishnamurthy *et al.,* 1996). The relationships of the crop utilized soil moisture and the RLD was so close that either one of these parameters can be adequate to explain drought tolerance variation in chickpea (Sinclair *et al.,* 1984; Blum, 2005, 2009).

5.1.1.4 Contribution of root length density and root dry weight to grain yield

Both the root proliferation and RDW across various depths and growing stages have been monitored with a single purpose of understanding their contribution to the grain yield under DS. At the early vegetative stage (35 DAS) when the stored soil water is plenty even under DS condition, the path coefficients of RLD and RDW as their to grain yield at maturity was limited to the roots of soil depths 30-45 cm as the most active soil water uptake at this stage is expected from this soil layer. But under OI condition in 2010-11, when this treatment had already received the first irrigation, the uptake at the 15-30 cm soil depth and its association with grain yield was apparent. The contribution of roots from 0-15 cm soil depth to grain yield at this stage was not consistent across year and the path coefficients were largely negative in both irrigation treatments and years. This inconsistency could have happened due to the rapid soil moisture loss through evaporation depending on the vapor pressure deficit variations (French and Schultz, 1984; Siddique *et al.,* 1990), as it has direct contact with dry air. Moreover, chickpea plant only has partial access to the soil water from this layer but a major quantity can be

expected to be utilized in the very early growth stage (Kashiwagi *et al.,* 2006a, 2015). Therefore, at this stage, under DS condition roots from the soil depth 30-45 cm and under OI condition soil depth15-30 cm were seen to be critical for the enhanced drought tolerance (Kashiwagi *et al.,* 2006a).

At 45 DAS, a sample taken only in 2010-11, the effects that were seen at 35 DAS was further intensified. The roots up to 60 cm soil depth have shown positive contribution to grain yield but the level of significance was relatively high at the initial two depths. This positive contribution was limited up to 45 cm soil depth under OI condition. The path coefficients of root present at 60-75 had a negative effect on grain yield. This indicates that the presence of roots can vary but as these roots proliferated to this depth recently these had created no big variation in soil moisture yet.

At the early podding stage (50 and 55 DAS), the significant association of root traits with grain yield was apparent by correlations. There was clear shift from the previous soil depth to subsequently deeper soil depths for a clear and positive contribution. This shift of significant relationship was clearly seen by soil water uptake as to be driven by the gradual decline of stored soil moisture to a further wet zone as the soil moisture was constantly receding. At this stage the major contribution of root trait to grain yield comes from the roots present between 30-75 cm soil depths in 2009-10 and 0-60 cm soil depth in 2010-11. Roots from 75-90 cm soil depth had a consistently

poor to the grain yield largely due to a recent arrival and had not influenced the soil water uptake.

At the mid- to late reproductive stages (65 DAS), roots from soil depth 0-15 cm started to show a negative contribution on grain yield as most of the genotypes that added weight or grew dense at this stage are late in duration and this late growth of roots and shoots are more affected by the terminal DS leading poor harvest indices (Kashiwagi *et al.,* 2015). At this stage the most significant contribution of root trait to grain yield mainly comes from 30-90 cm soil depths and these associations were significant at p=<0.001 level in 2010-11. The drying soil surface seems to reduce the shallow root production and enhance the deeper root production by redirecting the photoassimilates to the primary roots which grew deeper in to the soil and result in increased RLD and RDW (Blum and Ritchie, 1984; Asseng *et al.,* 1998; Wasson *et al.,* 2014; Kashiwagi *et al.,* 2015). Therefore, the roots from the soil water available zones exhibit a significant contribution to grain yield and this contribution had gradually shifted towards the deeper soil layer with the age of the plant or as a consequence of soil water depletion from the top layer. Also there are genetic variations with clear interactions with the age of the plant determining the peak growth of roots. This was from the early stages in ICC 4958 and ICC 8261 but such a peak growth was after 65 DAS in all the drought tolerant and the well adapted controls. Thus, this contribution of roots had been critical to support the yield formation by sustaining T and stomatal conductance as seen in various crops measured through CT

difference under DS condition (Blum *et al.,* 1982; Kobata *et al.,* 1996; Sanguineti *et al.,* 1999; Araus *et al.,* 2002; Pinheiro *et al.,* 2005; Izanloo *et al.,* 2008; Blum, 2009). In addition both by direct experiments and modeling exercises in wheat and in empirical studies with different crops the value and contribution of deep root to grain yield under DS in the field had been demonstrated well (Wasson *et al.,* 2012). RDp, RLD and RDW have been found to contribute positively to the yield in various crops (Saxena, 1984; Cortes and Sinclair, 1986; Ludlow and Muchow, 1990; Saxena and Johansen, 1990b; White and Castillo, 1989; Wright *et al.,* 1991; Reader *et al.,* 1992; Champoux *et al.,* 1995; Johansen *et al.,* 1997; Asseng *et al.,* 1998; Krishnamurthy *et al.,* 1999, 2003; Turner *et al.,* 2001; Kamoshita *et al.,* 2002; Li *et al.,* 2005; Manschadi *et al.,* 2006; Hammer *et al.,* 2009; Kell, 2011; Lilley and Kirkegaard, 2011; Zaman-Allah *et al.,* 2011a; Wasson *et al.,* 2012; Comas *et al.,* 2013; Lynch, 2013). In the current study, under OI condition, this contribution was noticeable from 15-90 cm soil depths as the irrigation given at 30 DAS has kept the surface roots growing and fit for soil water utilization for an appropriate contribution to grain yield.

At 80 and 75 DAS the roots present in the initial two soil depths were completely inactive in terms of contribution to grain yield and a massive significant contribution was provided by the roots of 75-105 in 2009-10 and 45-90 in 2010-11. Most of drought tolerance genotypes had a strong root presence up to 105 cm soil depth, to have a complete access of soil moisture at this stage. But such an access

was achieved much earlier, particularly in the early maturing genotypes ICC 4958 and Annigeri. However, the weak root genotypes had failed to have a complete access of soil moisture as these produced a very low root prolificacy even at this stage indicating that the plants that have shallow root system have limited access to water uptake ensuring the lowest yield under rainfed condition (Wasson *et al.,* 2012). Under OI condition, this contribution had been seen to come from the roots present at 60-120 soil depths in 2009-10 and from 15-120 cm soil depths in 2010-11. Interestingly the roots present at 15-30 soil depth had been found to contribute to grain yield. As the contribution of roots was the highest at 65 DAS, a supplementary irrigation at this stage can be highly benefecial.

At 90 DAS, under DS condition, root present at 105-120 cm soil depth had a significant contribution to grain yield. At this stage, the root strength could be beneficial mainly to the late maturing genotypes as their roots can be expected to be active and have the possibility to access soil moisture from deeper layers than the early maturing genotypes as their root system started sloughing and become less functional (Ali *et al.,* 2002b). Under OI condition, the contribution of root present at 60-75 cm soil depths to grain yield was highly significant. This indicated that the supplementary irrigation had a greatly helped the plants to exploit relatively upper soil zones.

Largely, no major differences were noticeable due to genotypes in the soil water left unutilized at crop maturity under the rainfed receding soil water conditions (Serraj *et al.,* 2004b; Wang *et al.,* 2012).

The major reason for this lack of heterogeneity is the direct soil water evaporation assisted by the soil cracking. Heavier clayey Vertisols are prone to cracking when dry and expand when wet. Such a cracking provide access to rapid soil drying in a rapidly warming atmosphere at the approach of crop maturity. But this effect was not found when the crop had been grown under favorable soil moisture condition (Wang *et al.,* 2012).

In case of the roots, the downward growth has been considered as a result of two shared and divergent mechanisms as gravitropism and the hydrotropism (Takahashi *et al.,* 2009). In rice, a gene for deeper rooting (DRO1) has been identified on the chromosome 9 (Uga *et al.,* 2013). It could permit strong gravitropism on roots through negative regulation of auxin at the root tips, and which could alter the direction of root growth toward greater depth.

5.1.2 Shoot traits contribution to drought tolerance

At 28 DAS in 2009-10 and 24 DAS in 2010-11, the treatment differences are not expected as the differential irrigation was not started. If any such differences had still existed, that needs to be treated as sampling error at this stage. Genotypes ICC 4958, ICC 8261 and Annigeri have been the best shoot biomass producers at this stage similar to the root production at 35 DAS that confirmed the early growth vigor. The genotype with superior root system may not render drought tolerance unless it produces matching shoot production in order to provide sufficient hydraulic demand or xylem capacity to make this deeper root system functional (Wasson *et al.,*

2012). The early growth vigor seems to be influenced by early phenology as seen in ICC 4958 and Annigeri except in ICC 8261 as it was relatively late in phenology (Silim and Saxena, 1993). A longer vegetative period results in a larger vegetative frame and increased capture of photosynthetically active radiation (PAR), which in turn results in increased total biomass production (Singh *et al.,* 1997).

LAI had exhibited a similar pattern of genetic variation as that of shoot biomass. At this stage, the shoot biomass production and LAI of most of the drought tolerant (ICC 14778, ICC 14799 and ICC 3325) and drought sensitive (ICC 3776 and ICC 7184) genotypes were similar. The genotype ICC 14778 was low in both root and shoot production at the vegetative stage but still become a highly drought tolerant genotype apparently by the advantage of other putative traits such as higher HI and p. Genotypes with early growth vigor showed a smaller SLA compared to other genotypes. SLA largely remained similar among the drought tolerant genotypes, except in ICC 867, compared to the drought sensitive one ICC 3776 at this stage. The genotypic performance in shoot traits was about the same at the late vegetative stage (37 DAS in 2010-11). The genotypes ICC 4958 and Annigeri entered early in to the reproductive stage and as consequence in to the mid exponential growth phase and produced reproductive parts. These early genotypes are also considered to be the best adapted to peninsular India (Saxena, 1987; Kumar and Abbo, 2001; Gaur *et al.,* 2008). Among the shoot traits monitored up to late vegetative stage, the LAI largely differentiated the drought tolerant

genotypes from that of the drought sensitive genotypes the maximum compared to the shoot biomass or SLA.

At mid flowering to mid podfilling stage (51 DAS in 2009-10, and 48 and 58 DAS in 2010-11), genotypes ICC 4958, ICC 8261, Annigeri and ICCV 10 maintained their shoot biomass production high as monitored at the vegetative phase across years. Increased shoot biomass production up to flowering, sustained water use and T in to the reproductive growth stage is crucial for reproductive success (Merah, 2001; Kato *et al.,* 2008) and such a pattern of growth and soil water use of all these genotypes except ICC 8261. An effective means of achieving reproductive success under DS is soil moisture capture by deep root system where deep soil moisture is available (Kirkegaard *et al.,* 2007). Thus, this advantage of increased shoot biomass production in the four genotypes ICC 4958, ICC 8261, Annigeri and ICCV 10 was likely to be favored by the high root growth and enhanced water use of these genotypes in this study. Rest of the genotypes included highly tolerant, tolerant, weak root and sensitive genotypes that had no clear differentiation in shoot biomass production at this stage. The development of differences in shoot growth between the two drought response group genotypes seems to be interlinked with their root growth as the root growth was also found to be very low at this stage. Reductions in water availability or extraction through roots result in reduced shoot turgor which can reduce shoot growth and development (Morison *et al.,* 2008). Among the different components of shoot biomass, leaf dry biomass

contributed 60-70% of the total shoot biomass across genotypes resulting to the significant linear relationship between LAI and shoot biomass production. SLA did not differentiate the genotypes at this stage clearly except that of ICC 867 having consistently high SLA and LAI. LAI increases exponentially up to the early podfilling stage and decreased beyond that due to increasing sensecence of leaves due to shading and competition between plants for light and other resources, especially, when plant encounters DS or high temperatures. Increasing LAI is one of the ways to increase the capture of solar radiation within the canopy and production of dry matter. Hence, dry matter produced decreases with a decrease of LAI (Dalirie *et al.,* 2010). In this study, the contribution of LAI to drought tolerance was significantly highest at the podfilling stage under both DS and OI condition in 2010-11. In addition, the grain yield was found to be increased when LAI and shoot biomass increased (Winter and Ohlrogge, 1993; Dalirie *et al.,* 2010)

At late podfilling to close to maturity stage (84 DAS in 2009-10, and 70 and 80 DAS in 2010-11), almost all the genotypes have produced moderate to high shoot biomass except the drought sensitive genotypes. The drought sensitive genotypes produced comparatively very low shoot biomass particularly in 2010-11. Higher shoot biomass production under DS condition enhance the yield, suggesting it can also be used as a direct selection criterion for drought tolerance (Lu *et al.,* 1998; Kibret, 2012; Serraj *et al.,* 2004b; Krishnamurthy *et al.,* 1999, 2013b). The exponential increase in mean

LAI observed in the previous stages become decreased at this stage as most of the genotypes approaching maturity and exhibited a negative contribution to grain yield. SLA had a relatively good differentiation of genotypes mainly in 2010-11 with the significant positive contribution to the drought tolerance. Though the contribution of SLA to drought tolerance was positive at all crop stages, the level of expression was the highest at this stage suggesting the preferable time of measurement of SLA was appropriate at the podfilling stages (Nigam and Aruna, 2008).

The genotypes selected for this study consist of eight drought tolerant, two drought sensitive and two best adapted genotypes, and therefore, can be considered as a skewed group of genotypes producing largely greater shoot biomass. Therefore, a close correlation of any trait with either the shoot biomass production can be difficult to notice as most of the genotypes were the top performers lacking normal distribution. Similarly lack of significance in relationships related with shoot biomass also needs to be treated with caution as the shoot biomass variation can be marginal.

5.1.2.1 Contribution of CTD to drought tolerance

CTD is a crop response to drying soils and environment. Though recent in its application and usage, it had been well accepted as a reliable selection tool to assess the continuance of stomatal conductance and canopy transpiration. Under DS conditions best differentiation (widest range) in CTD, large number of genotypes exhibiting highly negative CTDs (warmer canopies) as an indication of

suffering the consequences of water deficit and a close association of CTD with with drought yields are desirable at the time of sampling for the best estimate of drought yields or drought tolerance (Zaman-Allah *et al.,* 2011b; Belko *et al.,* 2012; Rebetzke *et al.,* 2013). In this study, the best association of CTD with grain yield has been seen to occur at both 66 and 70 DAS in 2009-10 and at 63, 70 and 72 DAS in 2010-11. Most of these indicators were less effective at 76 DAS in 2009-10 and 82 DAS in 2010-11. In wheat, CTD has been found to be associated with not only the grain yield but also with shoot biomass and HI at the reproductive stage (Rebetzke *et al.,* 2013). The best adapted genotypes Annigeri and ICCV 10 maintained a CTD close to the mean at all the stages of samplings except for an insignificant increase at 82 DAS in 2010-11. It was apparent that an active root growth continued for a longer period at this stage enabling soil water absorption in these genotypes. Prolific and deep root systems seem to play a major role in keeping the canopy cooler for longer time by active water extraction (Kashiwagi *et al.,* 2008a; Lopes and Reynolds, 2010; Rebetzke *et al.,* 2013). The CTD of ICC 4958 was clearly lower than the mean from 70 DAS in 2009-10 and 72 DAS in 2010-11. This early large rooting genotype was the shortest in duration and escaping the major part of the terminal DS (Saxena, 1987; Gaur *et al.,* 2008; Kumar and Abbo, 2001). The relatively advanced state of growth and the likely root and shoot senescence at the approach of maturity have lead to the lower CTD or warmer canopy. But this was an artifact delayed observation as far as ICC 4958 is concerned. However, ICC

4958 displayed other characteristics for a successful drought tolerant genotype.

The differentiation in CTD, the relative raking of the genotypes for the CTD and the contribution of CTD to grain yield under OI condition, did follow a similar pattern but the overall mean remained high (or the canopy was fairly cooler) compared to the DS condition. Also, all these parameters indicated 70 DAS in 2009-10 and 63 DAS in 2010-11 to be the most suitable time for estimating grain yield through CTD. In wheat, while screening for heat tolerance, 10 days after anthesis was found to be the critical time for the best discrimination of genotypes through their CTD differences (Gowda *et al.,* 2011b). Since the maturity was delayed by 15 to 20 days, OI environment seems to provide an extended period of time for sampling CTD when the periods proximal (before and after) to irrigation were avoided.

5.1.3 Contribution of crop phenology, grain yield and harvest index to drought tolerance

The days to 50% flowering ranged from 38 to 52 days in 2009-10 and 33 to 52 in 2010-11. The delayed sowing in 2010-11, induced early flowering, mainly under DS, in genotypes ICC 4958, ICC 283, ICC 7184 and Annigeri compared to 2009-10. However, it delayed the flowering by four days in genotype ICC 8261 suggesting that the phenology of this genotype was not much influenced by DS. This response may be linked to their early, strong and profuse root system, that might have helped to reduce the effects of DS by enhaced water

supply. The locally adapted genotypes (Annigeri and ICCV 10), small root genotypes (ICC 283 and ICC 1882), and large root producing genotype (ICC 4958) were early in duration and the highly drought tolerant genotypes (ICC 867, ICC 3325, ICC 14778 and ICC 14799) were comparatively late in duration. Genotypes that are early in duration are considered to fit the available season and the quantity of available soil water better in this region (Saxena, 1987; Gaur *et al.,* 2008; Kumar and Abbo, 2001). But the growing duration of highly tolerant genotypes were slightly longer than the early ones, and are capable of yielding more using the extended growing opportunities when available (Johansen *et al.,* 1997; Bolanos and Edmeades, 1996; Krishnamurthy *et al.,* 2010). Overall, the late sowing caused early flowering and maturity in most of the genotypes. On the contrary, the crop phenology had been delayed under OI condition. Crop phenology was associated with the grain yield negatively under DS condition.

The increased shoot biomass production at maturity is also considered to be a key factor for the drought tolerance (Krishnamurthy *et al.,* 1999, 2013a, b; Serraj and Sinclair, 2002; Richards *et al.,* 2002). All the highly drought tolerant and tolerant genotypes with a large root system have produced high shoot biomass than the drought sensitive genotypes in this study, validating the importance of this trait. Moreover, the contribution of shoot biomass to grain yield was highly positive in both the years. Maintenance of higher shoot biomass production under DS was through maintenance

of greater C or greater T (Passioura, 1994; Kashiwagi *et al.,* 2006a, 2013).

Optimal irrigation resulted in a two-fold increase in grain yield compared to DS yield in one year. Contrastingly, in another year, the differences in grain yield production between the two irrigation treatments were minimal. But this was due to detrimental effect of rainfall immediately following an irrigation application causing excessive vegetative growth leading to poor HI and grain yield (Kush, 1995). With a few exceptions, the highly drought tolerant genotypes (ICC 867, ICC 14778 and ICC 3325), best adapted genotypes (Annigeri and ICCV 10) and large rooting genotype (IC 4958) have produced consistently higher grain yield under DS condition. The drought sensitive genotypes (ICC 3776 and ICC 7184) have produced poor grain yield across the years and that of ICC 283 and ICC 8261 was also poor in 2010-11. In general, the highly drought tolerant genotype ICC 867 and the best adapted genotypes Annigeri and ICCV 10 produced high grain yields. The HI explained 78 and 89% of yield variation in 2009-10 and 2010-11, respectively, as often observed in chickpea (Silim and Saxena, 1993; Krishnamurthy *et al.,* 1999). Across treatment and years, the mean HI had been close to 45% but the excessive water application under OI condition the year 2009-10 had reduced this mean to a mere 27%. This reduction had occurred due to excessive vegetative growth (Krishnamurthy *et al.,* 2013a). The HI had clearly differentiated the drought sensitive (ICC 3776 and ICC 7184) and the kabuli genotype (ICC 8261) from the rest of the drought

tolerant genotypes in both the years and irrigation treatments. A highly significant contribution of this trait to grain yield (at p=<0.001), was apparent indicating the importance and consistency of this trait in contribution to drought tolerance. Results of large numbers of work in the past have shown this trait to be highly associated with the grain yield under DS (Viola, 2012; Fischer and Edmeades, 2010; Krishnamurthy *et al.,* 1999, 2010, 2013a, b; Rehman, 2009; Ribaut *et al.,* 2009).

5.1.4 Contribution of yield components to drought tolerance

5.1.4.1 Morphological yield components

Year 2010-11 had seen an increase in pod number m^{-2} most likely as a consequence of late sowing and pod formation at a relatively warmer temperature. Irrigation also enhanced the pod number production and the increase was substantial in 2010-11. The contribution of pod number m^{-2} to grain yield was positive in both the year and irrigation treatments and the correlation pod number with the grain yield was highly significant (p=<0.001) under OI condition. Few of the highly tolerant and tolerant genotypes possessed the best pod number m^{-2} but the drought sensitive genotypes had the least. Pod number per plant was considered to be one of the key traits for DS (Silim and Saxena, 1993; Krishnamurthy *et al.,* 2013a), salinity (Krishnamurthy *et al.,* 2011b) and heat tolerances (Krishnamurthy *et al.,* 2011c; Viola, 2012), that can be used in selection for breeding programs. The seed number m^{-2} followed similar pattern as that of the pod number m^{-2}, with minor exceptions. However, this contribution

was not consistent across years mostly to the influence of seeds pod^{-1} under DS condition. However, the contribution level of this trait to drought tolerance was high when the crop received optimal irrigation. The seed number pod^{-1} of the genotypes ICC 4958 and ICC 8261 was low similar to the pod number m^{-2} and seed number m^{-2} likely due to the negative interaction of seed size (100-seed weight). Such a low pod number in some drought tolerant cultivars was adequately compensated by hundred seed weight, producing similar grain yield as that of the small seeded genotypes that produce large number of pods (Saxena and Sheldrake, 1976). Genotypic distribution for 100-seed weight followed directly inverse pattern as that for the pod number m^{-2} and seed number m^{-2} distribution, with minor exceptions. Hundred seed weight of genotypes ICC 4958 and ICC 8261 was higher in both irrigation treatments and years. However, large seeded types produced more economic yields than the small seeded types (Eser *et al.,* 1991). Largely, among the genotypes ICC 14778 performed consistently greater for the morphological yield components pod number m^{-2}, seed number m^{-2}, seed number pod^{-1} than the mean across irrigation treatments and years. And this ability in establishing superior pod number and seed number per pod had helped it to be a superior genotype for the best grain yields under terminal DS and yield stability (Acosta-Gallegosa and Adams, 1991; Silim and Saxena, 1993; Loss and Siddique, 1997; Rehman, 2009; Krishnamurthy *et al.,* 2013a).

5.1.4.2 Analytical yield components

DS had reduced both Dv and Dr, but the Dr to a much greater extent. It indicates that these growing degree days are vulnerable to soil moisture changes (Krishnamurthy *et al.,* 2013a). When water is not a limitation for T, canopy and plant temperatures are known to be cooler and close to 25°C deviating heavily from the ambient temperatures. Cooler temperatures and shorter photoperiods are known to encourage suppression of reproductive growth (Roberts *et al.,* 1985). Conversely, soil water deficit and increasing temperatures would hasten the reproductive processes but with a reduced ultimate plant productivity. Selective reduction in reproductive growth phase is commonly observed not only in response to DS (Krishnamurthy *et al.,* 2013a) but also in response to salinity or heat (Krishnamurthy *et al.,* 2010, 2011b, c). Contribution of Dr to grain yield was negative in all the environments except under DS condition in 2010-11 as a consequence of terminal DS. Optimal irrigation increased the C and the genetic variation was narrow among the studied genotypes. However, it had a significant contribution to grain yield in both the irrigation treatment and years. Among the studied genotypes, large root genotypes (ICC 4958 and ICC 8261) had a high C and, the small root genotypes (ICC 1882 and ICC 283) and drought sensitive genotypes (ICC 3776 and ICC 7184) had the least C. The CGR had been suggested to be considered as a trait for water harvesting since the total water use, viz. total T, is strongly correlated with the plant growth (Udayakumar *et al.,* 1998; Condon *et al.,* 2002). In comparison

with the small root producing genotypes and drought sensitive genotypes, the large root producing genotypes seems to have advantage of greater water extraction which reflects to the increase in total T results in greater C under DS environments (Kashiwagi *et al.,* 2015).

The analytical component p is one of the key components of HI (Jogloy *et al.,* 2011; Krishnamurthy *et al.,* 1999) besides Dr. Therefore, any effort to keep a higher HI needs to aim for a greater p to compensate for the loss in Dr under DS and to keep the yield gap reduced. The realization of the importance of p and the approach of selection for p or HI is not new (Adams, 1982; Duncan *et al.,* 1978; Scully and Wallace, 1990; Jogloy *et al.,* 2011). The association of p with grain yield was the closest irrespective of the irrigation environment and the year. Also the direct contribution of p to grain yield had remained the highest leading to a high total contribution despite the large indirect contribution of C and Dr. Measurement of p is simple and any yield evaluation field trial is sufficient to record the required parameters. It is well realized that many interacting traits contribute to drought tolerance with their importance shifting with the level of stress intensity (Tardieu, 2012). The advantage of p, as a complex resultant state of various processes, is that it could be improved through many of the traits operating simultaneously. Surprisingly, this trait possesses the best h^2 surpassing even the estimates for the phenological observations (Krishnamurthy *et al.,* 2013a). Reduction in p was found to be high under OI condition than

under DS. Under OI condition, this reduction was too high particularly in 2009-10 when the grain yields were relatively minimal than in 2010-11. The range of genetic variation for p was found to be high. The p of the highly drought tolerant genotype ICC 14778 and the widely-adapted genotype ICCV 10 were the highest and highly consistent explaining their superior grain yields particularly under DS condition. The remaining highly drought tolerant genotypes have also had a greater p in one year. Both the drought sensitive genotypes (ICC 3776 and ICC 7184) and the kabuli genotype (ICC 8261) had a lowest p. When the component p was regressed with the grain yield, it explained 76 to 82% of the grain yield variation. This shows the constitutive nature of this trait meriting consideration in drought tolerance breeding.

5.1.5 Various trait combinations employed in different studied genotypes for their drought tolerance

When the grain yields across years under DS were grouped into four groups ICCV 10 occupied the topmost group (with about 2100 kg ha^{-1}) and the genotypes ICC 4958, ICC 867, ICC 14778 and Annigeri (ranging 1880 - 2080 in yield kg ha^{-1}) occupied the next order high yield group. Genotypes ICC 3325, ICC 14799, ICC 1882 and ICC 283 yielded moderate (with a yield range of 1540 - 1790 kg ha^{-1}) and genotypes ICC 8261, ICC 3776 and ICC 7184 yielded poor (with a yield range of 1080 - 1680 kg ha^{-1}). By the total shoot biomass productivity under DS similar four groups were noticeable but the genotype ICC 8261 produced the highest shoot biomass (with more

than 4200 kg ha^{-1}) and genotypes ICC 867, ICC 14778, ICC 3776 and ICCV 10 (ranging 3700 - 4230 kg ha^{-1}) occupied the next order highest group. Genotypes ICC 4958, ICC 3325, ICC 14799, ICC 1882, ICC 7184 and Annigeri produced moderate shoot biomass (with a biomass range of 3340 - 3910 kg ha^{-1}) and genotype ICC 283 produced the least shoot biomass (with a range of 3200 - 3400 kg ha^{-1}).

ICC 4958: This genotype was the earliest to flower and mature finishing its life cycle at least 10 days before other genotypes. Under DS, its shoot biomass production was moderate but the grain yield was high. The advantages this genotype possessed are the early strong root growth as both RDp and root proliferation, enhanced soil water use at early vegetative stage, the top early growth vigor, longer Dr, moderate C, the highest HI and p. The large seed size and the seedling size (twice compared to Annigeri) provided the early advantage of larger root system. The soil moisture use and mining depths were almost comparable to that of other medium duration drought tolerant genotypes but the shoot biomass produced was only moderate as a result of the two inversely interacting growth determinants such as the reduction in growth duration and increase in growth vigor. However the early flowering permitted two critical opportunities, longer Dr and a rapid rate of partitioning. Both the fast declining available soil moisture and the approach of high temperature regimes set a ceiling to the length of the growth duration in this environment. Early flowering ensured the possibility of an extended Dr as well left enough soil water for less restrained seed filling. Therefore ICC 4958

is a genotype that responds partly as drought escape and partly drought tolerant; remains stable across years but cannot use extended growing periods for achieving the top yield slot. Genotype ICC 4958 is a released variety for the central Indian environment as GW 5/7. It is well known for its drought tolerance, partly through the escape mechanism with short duration and partly through an early developed strong root system (Saxena *et al.,* 1993; Silim and Saxena, 1993; Kashiwagi *et al.,* 2005). It is also known for its high early growth vigor, large compound leaf and seed size (Saxena *et al.,* 1993). It has also been categorized as a drought tolerant genotype, describing to perform well under acute DS environments and not that well under OI regimes (Johansen *et al.,* 1994).

ICC 8261: This genotype was a medium duration one but it was one of the latest to flower among the genotypes that were used in this trial. However this late flowering did not reduce the Dr leading to exposure to an intense stress levels at the end. Under DS, its shoot biomass production was the highest but the grain yield was low particularly under late sown 2010-11. The advantages this genotype possessed are the early strong root growth as root proliferation that very often did not reflect in the soil water uptake either in the early or late stages. It displayed moderate early growth vigor, longer Dr, high C, the poorest HI and p. The larger seed size and the seedling size provided the early advantage of larger root system. The soil moisture use and mining depths were moderate but the shoot biomass produced was the highest as a result of the growth duration and

increase in growth vigor. The drought adaptation of kabulis to constantly receding soil moisture environments were only moderate as their adaptation is more tuned to higher rain fall regions that reflect in the warmer CTs, broader and more xylem vessels (Purushothaman *et al.,* 2013; Purushothaman and Krishnamurthy, 2014). Kabulis in general also require a longer and warmer Dr to match their longer seed filling requirements compared to *desis* and in the absence of such long periods the HI or partitioning to grains gets limited seriously affecting the grain yield.

ICC 867: This genotype was medium in flowering and maturity. Under DS, its shoot biomass production was consistently high reflecting its moderately high growth duration and the grain yield was highest and only next to ICCV 10. It had produced moderate shoot biomass throughout its early growth and maintained a high proportion of leaves. This also maintained the largest SLA at all the growth stages. This genotype exhibited a poor root growth at 35 DAS but had medium root growth till 55 DAS and strong root growth from 65 DAS with soil moisture extraction closely matching the root system. The advantages this genotype possessed are shorter Dr, moderate C, high HI and p. This was a perfect example of a drought tolerant genotype that utilized the whole season that the soil water could permit, a conservative early root and shoot growth leading to a rapid growth and later stages with the best C and the partitioning rates converting most of the shoot biomass into grain yield. Genotype ICC 867 is a germplasm accession from India alternatively known as P

690 or Larkapura 1. It has been listed as one of the highly drought tolerant genotype from the minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010) and known for its highest CT difference indicating an ability to keep its canopy relatively cooler than the other genotypes (Purushothaman and Krishnamurthy, 2014).

ICC 3325: This genotype was medium in flowering and maturity and matured 2-3 days later than ICC 867. Under DS, its shoot biomass production and grain yield were moderate to high. It had produced moderate shoot biomass throughout its early growth and maintained a high proportion of leaves. This also maintained the largest SLA at all the growth stages. This genotype exhibited a poor root growth at 35 DAS but had relatively greater root presence at the deepest soil zone of this growth stage (45-60 cm). Later it recorded a medium root growth till 55 DAS and strong root growth from 65 DAS onwards with soil moisture extraction closely matching the root system. Throughout the growth period it had greater LAI and SLA. This genotype also possessed shorter Dr, moderate to high C, high HI and p. This genotype is characterized with a slow early growth (both root and shoot) and a rapid growth at later stages leading to a moderate C and high partitioning rates converting most of the shoot biomass into grain yield. Genotype ICC 3325 is a germplasm accession from Cyprus alternatively known as P 3971. It has been listed as one of the drought tolerant genotypes from the minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010) and known for its high CT difference indicating an ability to keep its

canopy relatively cooler than the other genotypes (Purushothaman and Krishnamurthy, 2014).

ICC 14778: This genotype was medium in flowering and maturity and was the latest among the tested genotypes. It flowered at 52 DAS and matured between 93-96 DAS. Under DS, its shoot biomass production and grain yield was close to the highest. It had produced a poor root and shoot biomass at its early vegetative growth phase whereas at the reproductive phase (at and beyond 65 DAS) root and shoot growth was high and the soil moisture uptake matched closely the root growth pattern. It maintained a high proportion of leaves through all the stages of growth. This genotype had a relatively long Dv but a short Dr. The C was moderate to high and the p was the highest. Genotype ICC 14778 is a germplasm accession from India alternatively known as RSB 156-1. It has been listed as one out of the five highly drought tolerant genotypes from the minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010). Genotype ICC 14778 has been known for its consistent high p close to one and this genotype has also been known to be the best in maintaining a cooler CT (Kashiwagi *et al.,* 2008a; Zaman-Allah *et al.,* 2011b; Purushothaman and Krishnamurthy, 2014), known to extract maximum soil water (Zaman-Allah *et al.,* 2011a).

ICC 14799: This genotype was medium in flowering and maturity and was one of the latest among the tested genotypes. It flowered at 51 DAS and matured between 92-94 DAS. Under DS, its shoot biomass production and grain yield was moderate. It had

produced above-average root and a moderate shoot biomass across its growth and the soil water uptake at the late vegetative growth was high. It maintained a high proportion of leaves at all the stages of sampling and maintained a high SLA at all growth stages. This genotype had a relatively long Dv but a short Dr very similar to ICC 14778. The C and the p were moderate. Genotype ICC 14799 is a germplasm accession from India alternatively known as RSB 172. It has been listed as one of the drought tolerant accessions from the minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010). Genotype ICC 14799 has been known to be the best in maintaining a cooler CT (Kashiwagi *et al.,* 2008a; Zaman-Allah *et al.,* 2011b; Purushothaman and Krishnamurthy, 2014) and also known to extract maximum soil water (Zaman-Allah et al., 2011a).

ICC 1882: This genotype was early to medium in flowering and maturity and was the next early genotype after ICC 4958 and Annigeri. It flowered at 43-45 DAS and matured between 89-93 DAS. Under DS, its shoot biomass production and grain yield were moderate. It had produced a poor root and shoot biomass at its early vegetative growth phase (35 DAS) whereas at the reproductive phase (at and beyond 65 DAS) root and shoot growth was moderate and the soil moisture uptake matched closely the root growth pattern. It maintained a high proportion of leaves through all the stages of growth. This genotype had a relatively moderate Dv and a moderate Dr. The C was low to moderate and the p was moderate to high. Genotype ICC 1882 is a germplasm accession from India alternatively

known as P 1506-4. It has been identified as one of the weak rooting genotype at the late vegetative stage of crop growth (Kashiwagi *et al.,* 2005) and used as one of the weak rooting parents in developing mapping populations leading to the identifications QTLs associated with root system as well as other DS related traits. This genotype has been categorized as one of the drought tolerant accession of the minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010). This genotype is also known for its high $\Delta^{13}C$ and high yields through high HI (Krishnamurthy *et al.,* 2013b). Genotype ICC 1882 has been known for its consistent and highest CTD or for its cooler canopy maintenance under DS (Purushothaman and Krishnamurthy, 2014).

ICC 283: This genotype was early to medium in flowering and maturity and was the next early genotype after ICC 4958 and Annigeri and also earlier than ICC 1882. Under DS, it flowered at 41-45 DAS and matured between 86-87 DAS. Under DS, its shoot biomass production was the lowest and grain yield was low to moderate. It had produced a poor root and shoot biomass at its early stages of growth till 70 DAS whereas later, at the reproductive phase, the root and shoot growth was above average and the soil moisture uptake matched closely the root growth pattern. This genotype had a relatively moderate Dv and a low Dr. The C was low to moderate and the p was moderate to high. Genotype ICC 283 is a germplasm accession from India alternatively known as P 223-1. It has been identified as one of the weak rooting genotype at the late vegetative

stage of crop growth (Kashiwagi *et al.,* 2005) and used as one of the weak rooting parents in developing mapping populations leading to the identifications QTLs associated with root system as well as other DS related traits. This genotype has been categorized as one of the drought tolerant accession of the minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010). This genotype is also known for its high $\Delta^{13}C$ and high yields through high HI (Krishnamurthy *et al.,* 2013b). Genotype ICC 283 has been known for its consistent and high CTD or for its cooler canopy maintenance, only next to ICC 1882, under DS (Purushothaman and Krishnamurthy, 2014).

ICC 3776: This genotype was a medium duration one and was a late one among the genotypes tested. It flowered around 47-49 DAS and matured 94-98 DAS under stress. Under DS, its shoot biomass production was moderate to high but the grain yield was low to moderate. It was consistently shallow in RDp as well as moderately weak in RLD and RDW and the shoot production across the whole crop growth period that reflected in the poor soil water uptake. This genotype possessed a longer Dv close to the most of the successful high yielding genotypes, and particularly the four drought tolerant genotypes, but the Dr was exceptionally long. But when an opportunity was provided for extending the Dr this genotype did not use that. This genotype had a moderate C but a poor HI and p under both DS and OI conditions. Genotype ICC 3776 is a germplasm accession from Iran and alternatively known as P 4394. This genotype has been categorized as one of the drought sensitive accessions of the

minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010). Genotype ICC 3776 has been known for its consistent and low CTD, or for its warmer canopy maintenance, under DS (Kashiwagi *et al.,* 2008a; Purushothaman and Krishnamurthy, 2014).

ICC 7184: This genotype was a medium duration one and was a late one among the genotypes tested. It flowered around 44-50 DAS and matured 91-100 DAS under stress. Under DS, its shoot biomass production was low to moderate and the grain yield was the lowest. The RDp of this genotype was shallow in one year but the RLD, RDW shoot weights were average in the initial stages but grew poor at later stages. It was also poor in soil water uptake across all the stages. This genotype possessed a long Dv close to the most of the successful high yielding genotypes and also the longest Dr that was even more than ICC 3776 in 2009-10. But when an opportunity was available for extending the Dr under irrigation this genotype did not extend it reproductive growth. This genotype had a poor C, a poor HI and p under both DS and OI conditions. Genotype ICC 7184 is a germplasm accession from Turkey and alternatively known as NEC 1554. This genotype has been categorized as one of the highly drought sensitive accessions of the minicore collection of chickpea germplasm (Krishnamurthy *et al.,* 2010). Genotype ICC 7184 has been known for its consistent and lowest CTD, or for its warmest canopy maintenance, under DS (Kashiwagi *et al.,* 2008a; Purushothaman and Krishnamurthy, 2014).

Annigeri: This genotype was the next earliest to flower and mature after ICC 4958 finishing its life cycle at least 7 days before other genotypes. Under DS, it flowered around 35-41 days and matured around 82-87 DAS. Under DS, its shoot biomass production was moderate but the grain yield was high. The advantages this genotype possessed are the early moderate root growth as both RDp and root proliferation, enhanced soil water use at early vegetative stage, moderate early growth vigor, shortest Dr when sown early and longest Dr when sown late, moderate C, the highest HI and a high p. The moderately large seeds produced moderately large seedlings. The root and the shoot growth was moderately high using moderately high soil water. This genotype had a minimum Dv as well as minimum Dr. But when sown late this had reduced the Dv extensively but increased the Dr. How this pleotropic effect is useful in bringing the yield stability needs to understood yet. The early flowering when sown late permitted two critical opportunities, longer Dr and a rapid rate of partitioning as in ICC 4958. Thus Annigeri responds partly as drought escape and partly as a drought tolerant genotype; remains stable across years but can use extended growing periods provided by irrigation for achieving the top grain yields. Genotype Annigeri is a long-standing released variety for the peninsular Indian environment until recently. It is well known for its drought tolerance (Krishnamurthy *et al.,* 2010) and it has been rated as one of the few stable varieties that have the ability to perform well both under DS and sumptuous soil water conditions (Johansen *et al.,* 1994).

ICCV 10: This genotype was moderate in flowering and maturity among the genotypes included. It flowered around 44-47 and matured around 90-93 DAS under DS. Under DS, its shoot biomass production was moderate but the grain yield was the highest. The advantages of this genotype are the moderate root and shoot growth at the early stages and the (after 50 days growth) above-average root and shoot growth at later stages along with the best RDp. This genotype turned into one of the highest user of soil water as early as 65 DAS maintaining this early advantage till maturity. It was also a low SLA genotype under DS. Under both moisture environments ICCV 10 possessed a moderate C but the highest p. It had a moderate Dv and Dr and these durations enhanced proportionately, when irrigated. This genotype had exhibited a high level of stability in yield under DS as well as under irrigated environments. Similar observations were also made earlier (Johansen *et al.,* 1994). ICCV 10 is a released variety for the central and southern zones of India as Bharati in1992 and as Barichhola 2 in Bangladesh (Gowda *et al.,* 1995).

5.1.6 Marker diversity among the studied genotypes

There was a high level of diversity found in the polymorphic SNP, DArT and SSR markers for the studied genotypes. The gene diversity and PIC value were comparatively high in SSR markers. SNP markers had a high heterozygosity and DArT had a high major allele frequency. All the three different types of markers have discriminated the drought sensitive genotypes from the tolerant ones and the discrimination resolution was found to be comparatively high in SNPs.

5.2 Experiment-2: Assessing the relationship of canopy temperature depression with grain yield and its associated molecular markers in chickpea under terminal drought stress

In the present study the CT was measured at six stages between 59 and 82 DAS or early pod set to the start of maturity of early duration genotypes. The best linear regression between grain yield and CTD was observed with the CTD sampled at 62 DAS. This was about 15 days after 50% flowering and the early pod-filling stage of majority of the genotypes. Such an association was also demonstrated to occur at anthesis, and closely after, in bread wheat grown under dryland condition (Blum *et al.,* 1989; Royo *et al.,* 2002; Balota *et al.,* 2007). In wheat, while screening for heat tolerance, 10 days after anthesis was found to be the critical time for the best separation of genotypes through their CTD differences (Gowda *et al.,* 2011b). This difference in genetic discrimination stage is likely to be related to the difference in maximum LA development between the determinate wheat developing its maximum LA close to anthesis and the indeterminate chickpea at early pod fill stage or at the cessation of flowering. In addition, greater level of association of CTD with grain yield were also found to occur at 69, 73 and 76 DAS but with a diminishing level of Pearson's fit (r^2) (Fig. 4) with each delay in sampling time. This is likely due to the increasing diversification of growth stage with the delays in sampling time as some of the early duration genotypes approached physiological maturity and their root system started sloughing and become less functional (Ali *et al.,* 2002b). The slope values of the CTD at 62 DAS indicated a 293 kg

increase in grain yield with every one °C decrease in CTD. However the best h^2 was observed for the CTD sampled at 76 DAS. Although the ambient temperature remained close to 30°C across the days of sampling (except 82 DAS), every delay in sampling time increased the range of CTD from -5° to -8° reflecting the increasing build up of DS and the failure of resilience in canopy water status occurring in increasing numbers of genotypes. Notwithstanding the controversies (Berger *et al.,* 2010) that a cool or a warm canopy contributes to maximum grain yield, this study reveals that under DS a cooler canopy at the early pod-filling stage of crop growth is important to realize the best drought yields in chickpea.

CTD is used as an index to determine the crop water status in many crops, as CT is heavily influenced by the air temperature compared to other environmental factors such as light intensity, wind speed and VPD (Wen-zhong *et al.,* 2007). Dehydration avoidance is considered to be an adaptive strategy whereby plants decrease T (Blum, 2009) and eventually decrease the CTD. Genotypes that are capable of regulating their stomatal activity seem to transpire less in response to high VPD under water limited conditions. This overall process makes the canopy warmer. At vegetative stage, drought tolerant genotypes had warmer CT than the sensitive genotypes in chickpea (Zaman-Allah *et al.,* 2011b), cowpea (Belko *et al.,* 2012) and wheat (Rebetzke *et al.,* 2013) due to lower leaf porosity or more closed stomata. Also at this stage the ambient air temperature regimes are relatively cooler and the resultant CTD is within the comfort zone for

plant metabolism. However, this pattern is not the same at reproductive stage because, increased grain yield, shoot biomass and HI rely upon and were associated with reduced CT in wheat cultivars (Rebetzke *et al.,* 2013). It is revealing that, cooler CT contributes to drought yield at reproductive stage and this phenomenon may be hard to achieve without the help of an adequately active, deep and prolific root system (Lopes and Reynolds, 2010; Rebetzke *et al.,* 2013). However, few genotypes in this study had a good grain yield with a moderate CTD value seemingly due to their balanced T.

Plot wise CT measurement using portable IR FlexCam® S seems highly advanced and reliable for screening drought tolerant genotypes in field condition in comparison to leaf based CT measurement using commercial infrared thermometers (Berger *et al.,* 2010; Wang *et al.,* 2013) as the thermal camera captures the whole crop canopies of many plants in a plot helping to minimize the sampling error compared to spot measurements (Kashiwagi *et al.,* 2008a). Other additional advantages are simultaneous measurement of the crop canopy area by the camera and the associated software that helps to quantify the range and mean CT and to remove the background (soil) temperature. The water requirement of a smaller canopy can be expected to be small and still resulting in a cooler canopy. This necessitates a simultaneous measurement of canopy size for validating the worth of a cool canopy. Such crop canopy area measurements as proportions of ground area made in this study ranged from 0.86 to 0.99 and also the incorporation of canopy area as

an additional variable to explain grain yield did not improve the closeness of fit and therefore the CTD alone was considered to explain yield in this study. Additional advantage of this method is the possibility of imaging a large number of plots in a field trial in one go allowing comparison of differences in CT among genotypes as demonstrated in rice (Jones *et al.,* 2009). This high throughput imaging technique is suitable for comparing genotypes in a large-scale without any error due to changing environmental conditions between measurements (Berger *et al.,* 2010) with the limitation of increased size of the ground plot for each genotype in response to the infrared camera height (Sepulcre-Cantó *et al.,* 2007).

In an earlier study, the whole minicore chickpea germplasm was characterized for drought reaction using a drought index that heavily depends on the grain yield performance under terminal DS (Krishnamurthy *et al.,* 2010). Four out of five genotypes that were grouped as highly drought tolerant accessions previously displayed highest CTD here confirming that their drought tolerance strategy is maintenance of an able root system for supply of enough water. Similarly, majority of the accessions categorized as drought tolerant previously also grouped themselves into high CTD group here while the sensitive ones as low CTD ones. Also entries like ICC 4958, the best rooting and yielding genotype, displayed a low CTD due to its earliness in maturity (Table 5). Two low CTD genotypes ICC 4958 and ICC 8318 flowered early and matured at 84 DAS. Massive root and leaf senescence is known to start 15 days before the maturity of the

crop and therefore these genotypes were already approaching the start of maturity loosing resilience in CTD. Adaptation to both DS and salinity involves some common physiological and biochemical adjustments. Large number of highest and high CTD genotypes (11 out of 23) such as ICC 456, - 867, - 1098, - 1164, - 1180, - 1230, - 1398, - 3325, - 5434, - 7441 and ICC 14778 were also the DS and salinity tolerant ones (Krishnamurthy *et al.,* 2010, 2011b). Though the mechanisms of tolerance to heat are expected to vary from DS and salinity, six of these genotypes, i.e. ICC 456, - 1164, - 3325, - 5434, - 7441 and ICC 14778, were also tolerant across all the three abiotic stresses.

Along with CTD, both phenological and yield component traits were included for MTA with a purpose to detect the nature of association of these markers (direct or indirect through other traits) with CTD. Significant MTAs (n=45) were established in this work. It is well established through earlier works that flowering time and yield potential of the genotypes influence the grain yields under DS (Krishnamurthy *et al.,* 2010). Similarly CTD in this study was also established to be closely associated with the grain yields under DS. Therefore the marker trait association of CTD could also be due to direct effect of flowering time or the yield. CTD is explained by more number of markers that were located in many different linkage groups, indicating that it was controlled by many genes. Also the Gaussian distribution of the CTD means (Fig. 3), in close pattern to the grain yield, supported the polygenic control of CTD as observed in

wheat (Rebetzke *et al.,* 2013). In this study, only two markers were associated with multiple traits. For example, TA14 (LG6) associated with CTD at 62DAS, was also associated with days to 50% flowering, days to maturity and grain yield. Similarly TA130 (LG4) associated with CTD at 73 DAS was also associated with grain yield. Therefore, these markers associated with more than one trait, are most likely due to pleiotropic effect of the same gene(s) (Diab *et al.,* 2008). Except TA 14 and TA130, the remaining markers were unique in association with CTDs at various stages. However, there were almost no common markers that continue to exhibit their association across all stages of pod filling. CTD is the end result of many different direct plant processes such as root structure and function, LA, leaf porosity, stomatal frequency, stomatal conductance, senescence and sink strength and the importance of their contribution changing with the stage of the plant. Therefore these markers are still expected to be indirect in explaining the CTD through other traits. CTD recorded at 69 DAS exhibited MTAs with highest probability and the CTD recorded at 76 DAS resulted in the best h^2 value giving high level of direct relevance to the 13 markers that were associated with CTD in these two stages. CTD is a consistent and reliable trait, which is highly linked to WUE and yield potential through stomatal conductance, leaf porosity and indirectly reflects the instantaneous T at the whole crop level (Reynolds *et al.,* 1994; Fischer *et al.,* 1998; Condon *et al.,* 1990, 2007; Rebetzke *et al.,* 2013). It was also found to explain a significant proportion of yield variation under heat stress (Bennett *et al.,* 2012).

Therefore, markers specific for CTD trait seems to have a greater advantage to screen for drought response of genotypes. However, it is still necessary to validate the robustness of these markers for their association with CTD.

5.3 Experiment-3: Assessing the root anatomy of chickpea in comparison to other grain legumes and between types of chickpea to understand their drought adaptation

5.3.1 Experiment-3a

Majority of the pulses are grown under water-limited environments but with varying intensities of DS and periods of exposure. Chickpeas are usually grown under progressively receding soil moisture conditions whereas the other pulses also experience intermittent DS that gets relieved with subsequent rains or irrigation. Based on the results of root anatomy of the crops, efforts were made to understand differences among legumes for their strategy for drought adaptation. One of the most functional aspects related with root anatomy is water and nutrient transport capacity, because it is highly influenced by the number and size of the water conducting elements (Esau, 1965; Steudle and Peterson, 1998). Roots, the primary organs for the absorption of water and minerals, ironically offer the greatest resistance to liquid water flow in the soil-plant inter-phase simply to regulate the absorption process with possibly minimum energy (Rieger and Litvin, 1999).

Pearl millet had been included in this study as a representative of dry land cereals and to provide for the comparison of legumes with

cereals. Roots of pearl millet branch into higher orders and are thin and have a definite but less number of narrow xylem vessels arranged in a single layer below the endodermis (Fig. 2 and 5), with a low range in xylem vessel diameter. This fine root development and limitation in xylem vessel number is likely to be a compensation for a large RLD of finer roots that are known to be produced in cereal crops as in wheat (Gregory and Eastham, 1996). Cereals are known to produce greater RLD than the legumes (Hamblin and Tennant, 1987; Brown *et al.,* 1989; Petrie and Hall, 1992). The presence of highly suberized exodermis, a definite cortex, a pericycle and the endodermis are clearly meant for better regulation and resistance that ensured very effective but a conservative absorption of soil moisture making the plants more suited to lighter soils with minimum water holding capacity as well as longer periods of water deficit. Thinner roots, wider xylem vessels and a thin cortex were positively related to the hydraulic conductivity (Rieger and Litvin, 1999) while maintaining the minimum water potential gradient in the soil-plant-atmosphere continuum.

Chickpea had relatively thicker roots compared to pearl millet or groundnut and pigeonpea among legumes. It also had large number of thinner vessels with a range of sizes compared to common bean, cowpea or soybean that had broader vessels. It can be expected that in heavier soils such as Vertisols with finer soil particles the lateral movement of water is relatively restricted and therefore finer vessels coupled with dense RLs can lead to better absorption of the available soil water. Therefore chickpea seems more suitable to dense heavier

soils while common bean, cowpea and soybean are better adapted to coarse soils and rapid absorption of available soil water than chickpea.

Groundnut had the thinnest roots along with very slender vessels though the number of vessels was about similar to cowpea or common bean. Groundnuts are also seemed to be well adapted to conservative use of soil moisture and are also known for producing less prolific root system and thus poorly equipped with a rapid absorption of soil water. In groundnuts the leaves are better equipped for a prolonged DS that can be seen as temporary wilting and drooping of leaves. All the plants are capable of complete recovery when watered.

Pigeonpea seem to be one of the special legumes that had fewer and the narrowest xylem vessels. The stele contained large number of xylem fibres mimicking the stems where these cells are certainly needed for providing mechanical strength to the tall plants. Large number of xylem fibres with thickened walls, similar to the ones seen in pigeonpea (Bisen and Sheldrake, 1981), were also seen in soybean. On the contrary, such fibres were very few in groundnut (Fig.5). Pigeonpeas are relatively longer duration crops with a very low C in the early vegetative growth (Sheldrake and Narayanan, 1979). Therefore this conservative approach of soil water absorption can be appropriate match for the slow growth of this crop.

Common bean, soybean and cowpea had the moderate number of broad vessels. The root thickness of these roots was also the

highest indicating that these roots are capable absorbing more amount of water as and when available and explains their good adaptation to rainy seasons. Even within these three legumes, common bean had the thinnest cortex with more uniformly broader xylem vessels indicating that this crop is well adapted to soils with better water regimes and can be highly productive with regular irrigations.

Root water uptake of the whole plant is a function of both hydraulic conductivity and water potential gradient across the root or the whole plant (Rieger and Motisi, 1990). Considering the low root prolificacy and narrowest xylem vessels in groundnut, this crop is expected to develop a high gradient of water potential across the soil-plant continuum for the necessary water uptake whereas chickpea, with a thicker roots and large number of xylem vessels, may not need such a wide gradient of water potential for the necessary water uptake. But both these crops are adapted to water-limited environments with a different strategy.

Crop plants are better equipped with appropriate type of anatomy, largely constitutive in nature, to cope with the surrounding (soil moisture) environment (Rieger and Litvin, 1999). However environment also seems to play a major role in modifying the anatomical features. In response to the changing water regime of the growing environment major changes do occur in selective growth of component tissues. During the secondary thickening, very little change seems to occur in the volume of cortical layer and the phloem

bundles whereas the number and size of the xylem vessels and other xylem components seem to increase with water scarcity. In situations of severe DS further increase in vessel number and size seems likely. Also these root growth changes are structural and once secondary thickening is completed then no more changes are possible even when alternate moisture environments are provided. This could be more harmful to crops where the rooting front descends with the receding soil moisture. Development of permanent conducting tissues that can support less volume passage can act as a bottleneck when better soil moisture conditions are provided. For example chickpeas grown in lighter soils with drier soil environment till flowering never yields high even if very comfortable moisture regimes are provided at later crop growth stages. While most economical limited life saving irrigations are tested, vegetative stage irrigation is found invariably inevitable most likely due to this cause. It may be the reason why new axillary roots are initiated when late crop growth stage irrigations are practiced or rainfall is experienced.

5.3.2 Experiment-3b

At Patanceru, the crop is sown when the weather is warm, this weather gradually cools down as the crop reaches flowering and warms up again gradually as the crop matures. This average temperature progression exhibits a shallow boat like pattern (Fig 1). But at Tel Hadya, the crop is planted when it is too cool and flowers at similar temperature as that of Patancheru and matures when the weather is the warmest depicting a linear rise of temperature throughout the crop growth. It is well known that cooler temperatures delay the developmental stages in chickpea (Summerfield *et al.,* 1990) as a consequence of requiring greater number of calendar days to aggregate the required growing degree days. Whereas the time in calendar days influence the amount of biomass accumulated during that period. Cooler temperatures also encourage more vegetative growth, both roots and shoots, and therefore kabulis under the Mediterranean take longer to flower (70 d; Silim and Saxena, 1993) with a potentially heavier root and shoot growth before entering into the reproductive phase.

Roots are in direct contact with the soil and the shoot and therefore the water conducting xylem vessels in roots are expected to give a clue on their capacity in water uptake influencing the ability to tolerate DS. The thickness of the tap root varied heavily and it varied minimum at 20 cm soil depth across plants within a genotype. Nevertheless, it was difficult to characterize the genotypes for root thickness that was ranging heavily (data not shown). The transverse

sections of the tap root from a soil depth of 20 cm revealed that the cortex is mostly getting narrowed down with the advancing of secondary thickening of the vascular tissue. Such a reduction or loss in cortical tissue was greater in kabulis than in *desis* (Fig 5). The cortex was intact and prominent in *desis* and particularly in genotypes ICCV 10 and JG 11. Based on the three replicates of root transverse sections sampled for root anatomy it was noted that the xylem vessels in *desis* were fewer in number and narrower in diameter compared to the kabulis. Though existence of conclusive differences cannot be drawn on the basis of root diameters and cortical thickness between *desis* and kabulis, it is clearly noticeable that the kabulis possessed greater number of wider xylem vessels. Conduit number and diameter had been shown to be the two principal determinants of water flow, closely following the estimates of Hagen-Poiseuille equation that envisages conductance per tube to be proportional to the capillary diameter raised to the fourth power (Zimmerman, 1983; Gibson *et al.,* 1984). The resistance to the longitudinal flow of water through the seminal roots of a wheat plant was shown to depend on the number of seminal axes and on the diameters of their main xylem vessels (Richards and Passioura, 1981a). A breeding program, with limited success, was also carried out in wheat to moderate water uptake through selection of narrower vessels (Richards and Passioura, 1989). It had also been shown that the legume genera are typical in their number and width of xylem vessels explaining their adaptation to certain moisture environments, water requirements/uptake and the

nature of drought tolerance (Purushothaman *et al.,* 2013). Also it had been demonstrated that the vascular bundle development during secondary root thickening was heavily sensitive to water deficits and the number and width of xylem vessels increase to decrease the resistance in water flow as an adaptive strategy towards DS. On this basis of such predictions, *desis* seem to moderate their water flow or uptake and are conservative in their water requirement adapting well to the receding soil moisture environments than the kabulis that have access to more water during the major part of their early growth (Berger *et al.,* 2004).

6. SUMMARY AND CONCLUSIONS

Experiment-1

Out of twelve genotypes selected for this study most were dominant for a few alleles or traits that were frequently documented to be one of the critical functions for drought tolerance enhancement. Among the selected genotypes, only two of them were drought sensitive and this selection process lead to a population that was skewed more for drought tolerance. Traits related to root, shoot, soil moisture, physiological and analytical yield components were measured across various growth stages and the relationship of these traits with grain yield was tested through correlations, regressions and path analysis. Path coefficients helped to analyze the extent of direct or indirect nature of trait contribution to grain yield fully explaining the correlation values. Among the root traits, RLD and the roots present at the deeper layers, particularly at the reproductive phase of crop growth, were closely associated with grain yield and was considered to be the major contributing factors to drought tolerance. Roots at all the soil depths were associated closely with the total soil water uptake of the plants except at the surface layer and the ultimate rooting depths at any given stage. This close relationship provides confidence for use of one of either the rooting extent or the soil water uptake to assess the extent of drought tolerance. Among the shoot traits LAI at flowering stage, SLA and CTD at reproductive stage were found to be the major contributing traits to drought tolerance. Interestingly, higher SLA or drought tolerant leaf expansion was seen

to contribute positively to the grain yield in chickpea. CTD a functional plant process that was found to be associated closely with grain yield, can also act as a proxy for the estimation of drought tolerance. Among the yield traits HI, pod number m^{-2} and p explained the yield closely and consistently. It was possible to rank these traits in the order of their importance as well as consistency, robustness, stability and heritability as p > CTD > RLD > RDW > RDp > pod number m^{-2}> LAI or C. Crop duration to fit soil water availability and the shoot biomass at maturity are the two important parameters that are very relevant and are known to influence drought response. But in this study as the genotypic selection was skewed more towards earliness and high shoot biomass production such relationship of the duration and shoot biomass with grain yield might not have appeared. Measurement of most of the suggested contributory traits is simple except for the root related traits and amenable for high throughput evaluation of thousands of germplasm or breeding lines. Future drought tolerance breeding programs need to consider incorporating these traits for better drought tolerance and yield stability.

Experiment-2

CTD is a putative plant function that offers to be used as a proxy for plant water extraction under a constantly changing soil-plant-atmosphere continuum. CTD measured at the mid-reproductive stage explained a major proportion of the grain yield variation under terminal drought stress proving its worth as a proxy for grain yield. This association tended to become sparse with further delays in

measurement. A cooler canopy temperature at mid reproductive stage can be used as a selection criterion as it ensured greater grain yield under drought stress. The genotypic differentiation was also found to be high when the ambient temperatures were above 32°C which occurred at the mid-reproductive stage in this study. Moreover, this differentiation became less with the drop in ambient temperature. For the best discrimination on CTD, it is ideal to subject the germplasm lines of closer phenology and a synchronized flowering as test material. Alternatively, such CTD assessments can also be done separately on groups of genotypes or germplasm nested on the basis of phenology such as early, moderate and late for better and clearer differentiation of the genotypes for drought tolerance. There were large number of molecular markers that explained a major proportion of the phenotypic variation in CTD, two of them through phenology and yield. But majority of these molecular markers were specific to each sampling time indicating that this function is an integration of many plant responses related to phenology, reproductive success and soil water acquisition ability. More work is required to validate the markers identified and to ascertain the pathways of marker association with CTD.

Experiment-3

Knowledge of additional constitutive traits that explain drought tolerance is desirable. Morphology and anatomy of roots, as organs of first contact with drying soil, are expected to reveal useful information on strategies of drought adaptation. Such adaptation may also vary

across legumes and among types within one species. Among the six legumes studied, the root portion 10 cm above the root tip was the thinnest in both groundnut and pigeonpea and was closely similar to pearl millet. The presence of thinner roots and thinner cortex that offers less root resistance to hydraulic conductance in groundnut makes this crop more adapted either to regularly irrigated environment or to a very dry environment. The early growth of pigeonpea is conservative and the presence of very few thin xylem vessels in pigeonpea explains a low passage of water and consequently the growth. Chickpea and cowpea had a thicker cortex along with a moderately high xylem passage per root indicating that these are capable of absorbing water moderately and are well equipped for regular drought stress episodes. Soybeans with thin cortex and the common beans with their broad and fewer vessels are well suited for locations with optimum water supply. Legumes, as demonstrated under various moisture level grown plants in chickpea, are capable of regulating the necessary tissue development for appropriate hydraulic conductance during secondary thickening of the root system depending on the soil moisture status. Therefore roots with large number of thinner xylem vessels and a thicker cortex are likely drought tolerance traits for a conservative water use.

Between the kabuli and *desi* types of chickpea, kabuli genotypes possessed larger stelar portion and a relatively narrow cortex than desis. Compared to *desis*, kabulis possessed greater number of wider xylem vessels suggesting that kabulis originate from better soil water

environments than desis and are equipped to use more water and offer less resistance to water flow. Though the anatomy of roots and xylem vessels offered to be of good traits to measure drought adaptation in chickpea this needs to be confirmed yet in a large range of germplasm or breeding lines before being recommended for use as selection criteria in breeding programs. Also rapid measurement techniques need to be designed to improve the high throughput nature of these measurements.

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List of Publications Relevant to the Study

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