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Plant Biomass Productivity Under Abiotic Stresses in SAT Agriculture

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1. Introduction

1.1 Prevalence of abiotic stresses in SAT agriculture

The semi-arid tropics (SAT) include parts of 48 countries in the developing world: in most of India, locations in south east Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and a few locations in Latin America (Fig 1). Semi-arid tropical regions are characterized by unpredictable weather, long dry seasons, inconsistent rainfall, and soils that are poor in nutrients. Sorghum, millet, cowpea, chickpea, pigeonpea and groundnut are the vital crops that feed the poor people living in the SAT.

Environmental stresses represent the most limiting factors for agricultural productivity. Apart from biotic stresses caused by plant pathogens, there are a number of abiotic stresses such as extremes temperatures, drought, salinity and radiation which all have detrimental effects on plant growth and yield, especially when several occur together (Mittler 2006).

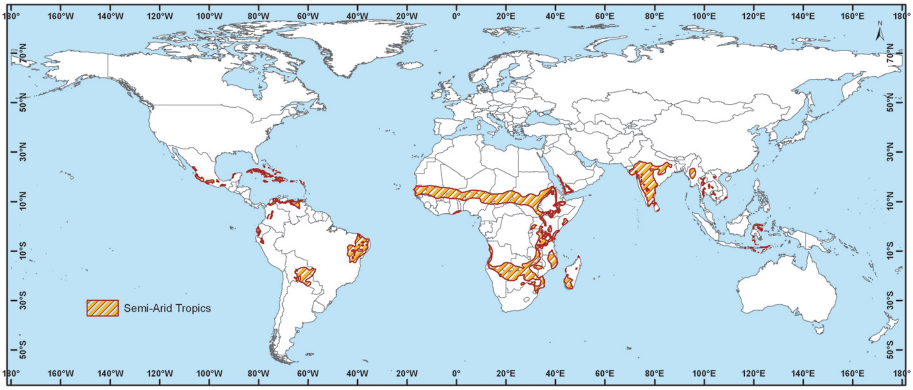

Fig. 1. Distribution of semi-arid tropical regions in the world (Source: http://www.fao.org/sd/EIdirect/climate/EIsp0002.htm)

Drought and soil salinity are the most prevailing abiotic stresses that curtail crop productivity in the SAT. Arable lands are lost every year due to desertification and salinization, as a result of sparse and seasonal rainfall and mismanagement of the natural resource base for agriculture (Evans, 1998). Expansion of irrigation does not seem feasible in many countries in Asia, the Middle East, and North Africa, where most of the available and easily accessible water resources have been already utilized. Furthermore, irrigated soils are affected by salinity with significant subsequent yield losses. Desertification may be aggravated by both extensive farming due to demographic pressure and the regional climatic changes. Hence, there is a need for the breeding programs to assign high priority for the development of crops with tolerance to both drought and salinity stress. The genetically complex control of these stresses in the plant genome may be facilitated through the manipulation of specific genes governing the component characteristics needed to achieve tolerance to salt or drought in plant crops.

1.2 Plant biomass productivity as affected by drought and salinity stress

Plant biomass is primarily a product of photosynthesis, a process needing carbon dioxide, water as bi-products and solar radiation as the energy source and mineral nutrients as basic blocks. In majority of the instances carbon dioxide and solar radiation never limit biomass production while abiotic stresses like water deficit and soil salinity very often do. Plant response to abiotic stress is one of the most active research topics in plant biology due to its practical implications in agriculture, since abiotic stresses (mainly drought and high soil salinity) are the major cause for the reduction in crop biomass and yield worldwide, especially in the SAT.

Plants are extremely sensitive to changes resulting from drought or salinity, and do not generally adapt quickly (Lane and Jarvis 2007). Plants also adapt very differently from one another, even from a plant living in the same area. When a group of different plant species was prompted by a variety of different stress signals, such as drought or cold, each plant responded uniquely. Hardly any of the responses were similar, even though the plants had become accustomed to exactly the same home environment (Mittler 2006). Abiotic stresses can come in many forms. The occurrence of many of these abiotic stresses is unpredictable, however, in agricultural management point of view, drought and soil salinity are relatively more predictable and common in occurrence demanding focused research. Therefore, the scope of this chapter is limited to drought and soil salinity.

2. Abiotic stresses and crop productivity

2.1 Drought

The agroclimatic and production-system environments of the SAT regions are very diverse. The inherent water constraints that limit crop production are variable. However, it is quite possible to broadly characterize and classify the drought patterns of a given environment using long-term water-balance modeling and geographic information system (GIS) tools (Chauhan et al., 2000). The assessment of the moisture-availability patterns of the target environments is critical for the development of best adapted crop genotypes to target environments and to identify iso-environments of drought patterns. As mentioned earlier, SAT environments are often characterized by a relatively short growing season in a generally dry semi-arid climate, with high average temperatures and potential evaporation rates. Soils are moderate to heavy, with low to moderate levels of available water content to the plants. In addition, the dry season at this location is generally rain-free, with a high mean air temperature and vapour-pressure deficits. This season provides an ideal screening environment to expose plants to controlled drought-stress treatments by regulating the timing and quantity of irrigation (Bidinger et al., 1987; Johansen et al., 1994).

Drought stress is a major limiting factor at the initial phase of plant growth and establishment. The usual effects of drought on the development of a plant are a lowered production of biomass and/or a change in the distribution of this biomass among the different organs. In addition, plant productivity under drought stress is strongly related to the processes of dry matter partitioning and temporal biomass distribution (Kage et al., 2004). Reduction of biomass due to water stress is common in both cereals and legumes, although genotypic variation does exist. In general, cereals biomass production is less affected by drought than legumes.

The types of drought occurrence is usually categorized as early, intermittent and terminal depending on the growth phase of the plant when the water deficit becomes acute. For example, long duration pigeonpea, a crop usually sown at the first onset of south Asian monsoon rains, experiences all the three types of drought.

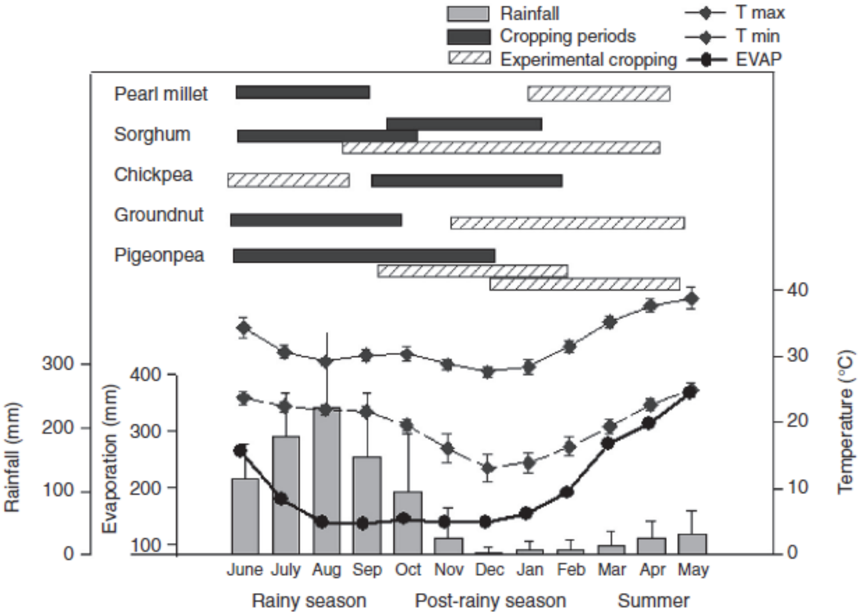

Fig. 2. Long-term average climate conditions (1974-2000) and cropping schedule at ICRISAT, Patancheru (17°N 78° E, msl 542M), India (Source: Serraj et al. 2003).

At the early seedling stages of the crop, lack of water can adversely affect seedling growth and occasionally kill seedlings and reduce the plant population. Similar lack of water for a period of time at the later stages can affect leaf area expansion and subsequently the root and shoot growth causing intermittent set backs and relief. However at later stages once the rains cease the plants during their reproductive growth phases tend to rely on the constantly receding soil moisture leading to increasing levels of terminal drought stress affecting largely the reproductive plant parts. This may reduce the number of pod/spikelet bearing sites or the number of seeds formed in a pod/spike or the size of the developing seeds. On the other hand, pearl millet, sorghum, groundnut and pigeonpea sown in the rainy season experience intermittent drought while chickpea that is primariely grown postrainy experiences the terminal drought (Fig 2).

2.1.1 Cereals

Pearl millet

Most of the pearl millet, either as grain or fodder crop, is grown in the arid and semi-arid zones of south Asia and West Africa where the soils are prone to drought stress or soil salinity problems. The main target environment for the pearl millet drought work of ICRISAT and its partners in India is the pearl millet growing area of the north-western states of Rajasthan, Gujarat and Haryana, where postflowering stress, either alone or in combination with preflowering stress, is a very common feature of the environment (van Oosterom et al., 1996). The focus of pearl-millet research has thus been on terminal drought as it is also the most damaging to grain yield (Bidinger et al., 1987). As an example of the magnitude of yield loss under drought, pearl millet yields were reduced by 0-16% with the intermittent drought across years that was imposed as a preflowering stress (stressed from 12 days after emergence till flowering) whereas it was reduced by 55 to 67% with a post-flowering terminal drought stress (Bidinger et al. 1987). Pearl millet yields were reduced during the dry season compared to the rainy season by about 14 %. However the shoot biomass was reduced by 12% under normal photoperiod while it was not affected under extended photoperiod (van Oosterom et al. 2002).

Sorghum

Sorghum, a major grain and forage crop, is one of the most extensively adapted crops to the semi-arid tropics. The rainfall during the crop season could vary from 300 to 2000 mm. Terminal-drought stress is the most serious constraint to sorghum production worldwide. In sub-Saharan Africa, drought at both seedling establishment and grain-filling stages is also very common. In India, sorghum is grown during the rainy and the post-rainy seasons. The variable moisture environment during the rainy season can have a severe impact on biomass and grain yield, affecting both preflowering and postflowering stages. Characterizing drought in post-rainy season sorghum is simpler, compared with the intermittent drought experienced by rainy season crops. This is because much of the rainfall is received before the planting of the crop, which is therefore grown almost entirely on stored soil moisture and exposed mostly to progressively increasing (terminal) water deficits. Therefore, the factors governing crop growth and water use in the post-rainy season, i.e. radiation, temperature, vapour pressure and potential evaporation, are relatively stable and predictable, so that simulation modeling of both crop growth and the effects of various crop traits is quite feasible. In a set of NILs (Near Isogenic Lines) of sorghum the overall mean yield reduction due to preflowering drought stress was only 4% while that of the post flowering drought was 37% (Ejeta et al. 1999).

2.1.2 Legumes

Chickpea

Chickpeas (*Cicer arietinum* L.) sown at the end of the rainy season, usually experience terminal drought stress as a consequence of growing on receding soil moisture conditions with a scanty or no rainfall condition during the crop growing season. When such drought stress was not allowed to occur with an optimum irrigation regime the shoot biomass productivity was near 5 t ha^{-1} with a seed yield of 2t ha^{-1}. However, under the normal receding soil moisture condition, the shoot biomass productivity ranged across years from 1.8 to 3.8 and the seed yield from 0.7 to 1.6 t ha-1 (Krishnamurthy et al. 2010).

Chickpea breeding program at ICRISAT has placed high emphasis on development of early and extra early maturing varieties so that these can escape terminal drought. The early maturing crop, however, cannot accumulate enough total plant biomass due to reduced total photosynthetic period compared to the relatively longer duration varieties.

Terminal drought reduces both shoot biomass and yield in chickpea. For example the average shoot biomass reduction of 40 cultivated chickpea genotypes due to terminal drought was 44 to 61 % across two years whereas the grain yield reductions were 35 to 66% (Krishnamurthy et al. 1999). Similarly the average shoot biomass reduction of 216 (mini core) chickpea germplasm accessions due to terminal drought was 31 to 63 % across 3 years whereas the grain yield reductions were only 26 to 61% (Krishnamurthy et al. 2010). The relatively less reduction in grain yield under drought was due to an increased partitioning under the progressively built terminal drought stress.

Groundnut

Groundnut (*Arachis hypogaea* L.) is an important rainy-season crop in most of the production systems in the semi-arid tropical regions of south Asia and sub-Saharan Africa, where it is grown under varying agroecologies, either as a sole crop or intercropped with sorghum and pigeonpea. Groundnut yields are generally low and unstable under rain-fed conditions, due to unreliable rainfall patterns. Severity of drought stress depends on the stages of crop development and the duration of stress period (Wright and Nageswara Rao, 1994).

Improvement of transpiration efficiency (TE) is seen as a promising strategy to improve shoot biomass and pod yield productivity under episodes of intermittent drought. Efforts were made to identify simple and easily measurable traits that are closely associated with TE such as SCMR (Nageswara Rao et al., 2001; Sheshshayee et al., 2006), SLA (Nageswara Rao and Wright, 1994; Wright et al., 1994) and carbon isotope discrimination (Hubick et al., 1986; Farquhar et al., 1988; Wright et al., 1994). Recent works have demonstrated that root dry weight and SLA were important traits related to WUE under long term drought and considered useful as selection criteria for high WUE under long term drought (Songsri et al., 2009).

Groundnut pod yield productivity is more adversely affected by various seasonal droughts than the shoot biomass production. For example, in a field trial where the drought intensity and the timing is managed by withholding irrigation and providing a part by line source irrigation it was established that the drought occurring between emergence to peg initiation was rather beneficial, producing greater yields than the control. However the drought occurrence between the phases of start of flowering to start of seed growth had lead to a reduction of 13 to 49% in shoot biomass and 18 to 78% in pod yield. The drought stress from the start of seed growth to maturity (terminal drought) had caused a reduction of 16 to 73% for the shoot biomass and 24 to 95 % for the seed yield (Nageswara Rao et al. 1985).

Pigeonpea

Pigeonpea (*Cajanus cajan* (L.) Millspaugh) is a deep-rooted and drought-tolerant leguminous food crop grown in several countries, particularly in India and India accounts for about 80% of the total world pigeonpea production. It is grown mainly by resource poor farmers in

India south east Africa and, to a varying extent, throughout the tropics, usually under rain-fed conditions.

Pigeonpea can be exposed to intermittent drought stress during dry periods of the rainy season and to terminal-drought stress in the post-rainy season. Over the last two decades, shorter-duration pigeonpea (SDP) genotypes have been developed, with some genotypes capable of reaching maturity within 90 days (Nam et al., 1993). However, the developed short-duration genotypes are usually sensitive to intermittent drought. Considerable variation in tolerance to intermittent drought has been observed in short-duration pigeonpea lines and variation in sensitivity in relation to timing of drought stress has been established (Lopez et al. 1996). As in other crops, responses to intermittent drought stress have been shown to depend on the growth stage at which the stress occurs (Nageswara Rao et al. 1985). For example Nam et al. 1993 has shown that the drought incidences at flowering cause a large reduction in productivity than drought at preflowering stage or at pod fill stage. The shoot biomass reduction was 26 to 33% across years whereas the yield reduction was 30 to 48% (Nam et al. 1993).

2.2 Salinity

In the semi-arid agricultural areas of the world, soil salinization is closely linked to the extensive use of artificial irrigation, which in combination with extended dry seasons, very quickly turns formerly productive areas practically into deserts. In the future, this effect will even increase due to the high demand of water from other non agriculture sectors (i.e. industry, overpopulated cities), whereas the possibilities to increase any crop's productivity through irrigation will necessarily decrease. Apart from irrigated areas, salinity is a major management problem in many unirrigated rainfed areas.

Dryland salinity ranges from a slightly saline soil condition which reduces crop growth to extensive areas where cultivation is almost impossible. This constraint has been a threat to the land and water resources in several parts of the world including the SAT, although the seriousness of the problem well realized in recent years. All the crops are affected by salinity while they vary in their degree of response as some of them being tolerant while others are sensitive.

2.2.1 Cereals

Pearl millet

Soil salinity is a major problem for pearl millet [Pennisetum glaucum (L.) R. Br.] production in the arid and semi-arid zones of south Asia and West-Africa (Blummel et al. 2003). Pearl millet also remains as a potential crop to grow in the rice fallows of saline areas in south Asia, where typical increases of salinity levels during post-rainy season prevent crop production. Compared to other crop species, Pearl millet and its wild relatives are rated to be fairly tolerant to salinity (Maas and Hoffman 1977; Shannon 1984; Krishnamurthy et al. 2007) and provide an option while selecting crops that can be more profitably grown in saline soils.

Lack of a single reproducible screening protocol and lack of knowledge on trait(s) that confer yield under salinity is a great limitation to breeding tolerant varieties. Field screening under salinity stress may not be effective because of the extent of variability in salinity experienced within a single field and among plots even at shorter distances (Richards and Dennet 1980). Pearl millet seems to be sensitive at germination stage in ECe of 16 dS m^{-1} and beyond but this sensitivity is to some extent compensated by the tillering capability (Dua 1989). However, it seems that salinity response estimated at germination stage does not correlate well with plant performance at later stages (Munns and James 2003; Krishnamurthy et al. 2007).

Na+ exclusion and grain K/Na ratios were suggested to be reliable traits for selection. However, their usefulness as selection criteria (Munns and James 2003; Poustini and Siosemardeh 2004) could not be emphasized when five cultivars in pearl millet used for this association study (Ashraf and McNeilly 1987) where as leaf Na+ contents or the K+/Na+ and the Ca++/Na+ ratios assessed with 100 ICRISAT breeding lines were found to explain the biomass productivity at flowering time (Krishnamurthy 2007). Therefore this relationship of Na-based ratios needs to be evaluated with a wider range of genotypes and in association with the grain yield. Overall, it seems that although various aspects have been related to tolerance, the variation in whole plant reaction to salinity has been suggested to provide the best means of initial isolation of salinity tolerant genotypes (Shannon 1984; Ashraf and McNeilly 1987).

Large genotypic variation was reported to exist in pearl millet for salinity response in terms of whole plant response (Ashraf and McNeilly 1987; 1992; Dua 1989). Moreover, availability of high levels of tolerance in other species of Pennisetum (Ashraf and McNeilly 1987; 1992; Muscolo et al. 2003) and within the *P. glaucum* (Dua 1989) offers a scope for understanding the traits related to tolerance and to integrate these tolerant crop species/genotypes into appropriate management programs to improve the productivity of the saline soils. A total shoot biomass productivity ranging from 9 to 12 t ha^{-1} and a grain yield from 3.1 to 4.9 t ha^{-1} recorded in normal Alfisol fields at Patancheru, India (van Oostrom et al. 2002) got reduced to an average of 3.3 t shoot biomass and 1.1 t ha^{-1} grain yield of 15 germplasm accessions when grown in a 10 dS m^{-1} saline vertisols at Gangavathi, Karnataka, India (Kulkarni et al. 2006).

Sorghum

Sorghum is characterized to be moderately tolerant to salinity (Maas, 1985; Igartua et al., 1995) with a large genotypic variation reported. It is considered relatively more salt tolerant than maize, the cereal crop ranking first in productivity globally (Maas, 1985). Therefore, sorghum has a good potential for salt affected areas (Ayers & Westcott, 1985; Igartua et al., 1994).

There are limited successes in enhancing crop yields under salinity stress as available knowledge of the mechanisms of salt tolerance has not been converted into useful selection criteria to evaluate a wide range of genotypes within and across species. Attempts have been made to evaluate salt tolerance at germination and emergence stages in grain sorghum (Igartua et al., 1994; Krishnamurthy et al. 2007), and large genotypic differences were reported, but this early evaluation appears to have little relation with overall performance under saline conditions (Munns et al., 2002; Krishnamurthy et al. 2007). Though Na+ exclusion and grain K+/Na+ ratios have been suggested to be reliable traits for selecting salt tolerant crops (Munns & James, 2003; Munns et al., 2002; Poustini & Siosemardeh, 2004; Netondo et al., 2004; Krishnamurthy et al. 2007), the value of that trait has not been used in a large scale. Therefore, there is a need to identify traits associated with salinity tolerance, and simple, high throughput, repeatable screening methods to evaluate large number of genotypes. In fact, the variation in whole-plant biomass responses to salinity was considered to provide the best means of initial selection of salinity tolerant genotypes (Shannon, 1984; Ashraf & McNeilly, 1987), prior to the evaluation on the basis of specific traits.

Some of the known salt tolerant genotypes (n=29) of sorghum have been reported to yield in the range of 1.5 to 4.2 t ha^{-1} in naturally occurring saline soils with an average ECe of 10 dS m^{-1} at the Agricultural Research Station, Gangavathi, Karnataka, India (Reddy et al. 2010). However the grain yield range was much superior (4.7 to 6.0 t ha^{-1}) for the hybrids that were tested along the germplasm lines under similar saline field conditions.

2.2.2 Legumes

Chickpea

Chickpea (*Cicer arietinum* L.) is sensitive to salinity (Flowers et al. 2010). The decline in the area sown to chickpea in traditional chickpea-growing areas of northern India and the Indo-Gangetic Plain (Gowda et al. 2009) is partly due to increased soil salinity and increased use of brackish water for irrigation. If this decline is to be reversed, then resistance of existing chickpea varieties to salinity needs to be improved. Since management options are often too expensive for small-holder farmers to adopt, breeding and selection of salinity-resistant varieties remains a more practical and immediate option.

Until recently, little genetic variation for salinity resistance had been observed in chickpea (Saxena 1984; Dua 1992; Johansen et al. 1990). However, recently a large range of variation (Vadez et al. 2007; Krishnamurthy et al. 2011) was found to exist in seed yield of 265 chickpea genotypes grown in artificially-salinized soils watered to field capacity with 80 mM sodium chloride. Further, it was found that the seed yield under salinity in chickpea was closely associated with time to flowering and to the seed yield under non-saline conditions.

Several reports have shown that the resistance to salinity in chickpea is related to the resistance of reproduction (Mamo et al., 1996; Katerji et al., 2001). Salinity resistance indeed had been shown to be associated with the capacity to maintain a large number of filled pods, rather than to the capacity to grow under salt stress (Vadez et al., 2007), indicating that salt stress may have a deleterious effect on flower/pod production and retention. Yet, reproductive success may have been conditioned by the late-sown conditions in which the previous work was carried out (Vadez et al., 2007) and needs to be validated with sowing at the normal sowing time.

As salinity is likely to be an increasing problem in a warming and drying world, especially for relatively sensitive crops such as chickpea, it is important to make sources of resistance available to the breeding community by systematically screening a representative set of germplasm. To date, only the mini-core collection of chickpea germplasm has been evaluated for salinity resistance (Vadez et al., 2007). This mini-core collection is based on morphological and agronomic traits (Upadhyaya and Ortiz 2001) and not a systematic screening for diversity of molecular markers. More recently, a reference collection of chickpea has been assembled using marker data from 50 SSR markers screened in over 3,000 genotypes (Upadhyaya et al., 2006). Although the reference collection includes all the germplasm in the mini-core collection, 89 additional entries of cultivated chickpea with additional molecular variability have been identified (Upadhyaya et al. 2008).

Groundnut

Groundnut is a very important oilseed crop globally and particularly in many developing countries of the SAT where salinity is an ever-increasing crop production constraint. It is not only the grain yield is important but also the protein-rich crop residues as dry fodder. In spite of the importance of the constraint as well as the crop very little has been published with groundnut being affected by soil salinity. In a salinity tolerance screening saturating soil once with with 80 mM NaCl solution and testing 288 groundnut genotypes/ germplasm accessions it has been found that the shoot biomass productivity was the least affected (0-30%) while the pod yield was affected by 50 to 100%. However there were genotypes that could produce pod yields >half of the control but these were very few (Srivastava 2006).

Pigeonpea

Pigeonpea is one of the major legume crops grown in the semi arid tropics, particularly in India. Its high sensitivity to salinity coupled with the dry growing environment pose a major constraint to crop production in certain areas. Salinity affects plant growth, development and yield of pigeonpea. However the quantum of work that had been carried out with pigeonpea under salinity is scarce. A study involving a tolerant (ICPL227) and a sensitive (HY3C) cultivated pigeon pea genotypes and some tolerant (*Atylosia albicans*, *A. platycarpa* and *A. sericea*) and sensitive (*Rynchosia albiflora, Dunbaria ferruginea, A. goensis* and *A. acutifolia*) wild relatives tested over a range of salinity levels (0, 4, 6, 8 and 10 dS/m) have shown that transpiration rate decreased with increasing salinity in tolerant and sensitive pigeon pea genotypes alike, while key difference was the greater salinity tolerance of *A. albicans, A. platycarpa* and *A. sericea* was associated with efficient sodium and chloride regulation in the plant system (Subbarao et al. 1990).

Shoot sodium concentrations of the tolerant wild species were found to be 5 to 10 times less than those of the sensitive species, while root sodium concentrations in the tolerant species were 2 to 3 times higher than in the sensitive species. Thus the efficiency of regulation of ion transport to shoots seemed to explain the differences in salinity response among pigeon pea genotypes and related wild species. Srivastava et al. (2007) assessed the morphological and physiological variation in pigeonpea for salinity tolerance in 300 genotypes, including the mini core collection of ICRISAT, wild accession and landraces from putatively salinity-prone areas worldwide. A large range of variation in salinity susceptibility index and the percent relative reduction (RR %) in both cultivated and wild accessions were shown to exist. Also less Na+ accumulation in shoot was indicative tolerance and this relationship was limited to the cultivated material. Some of the wild species reported tolerant are *C. platycarpus*, *C. scarabaeoides* and *C. sericea* whereas *C. acutifolius, C. cajanifolius* and *C. lineata* were more sensitive. In another study, six pigeonpea genotypes were tested under five different NaCl concentrations (0, 50, 100, 125, 150 mM) under controlled conditions. Salt concentration of 75 mM was identified to be the critical one as it reduced the biomass production by an average 50%. For pigeonpea, as SCMR was positively associated with higher biomass under salinity, SCMR was suggested to be an early indicator for salinity tolerance. The Na+ accumulation did not help to be of any indication of tolerance in pigeonpea.

3. Technology that can assist in estimating crop growth and productivity under abiotic stresses

Plant biomass is an important factor in the study of functional plant biology and growth analysis, and it is the basis for the calculation of net primary production and growth rate. The conventional means of determining shoot dry weight (SDW) is the measurement of oven-dried samples. In this method, tissue is harvested and dried, and then shoot dry weight is measured at the end of the experiment. For the measurement of biomass of a large number of plants, this method is time consuming and labor intensive. Also, since this method is destructive, it is impossible to take several measurements on the same plant at different time points. With the establishment of advanced technology facilities for high throughput plant phenotyping, the problem of estimating plant biomass of individual plants is becoming increasingly important. There are several technologies that can help to assess the effect of abiotic stresses like drought and soil salinity on plant growth while assisting in predicting crop yield under various environmental conditions.

3.1 Near-infrared spectroscopy on agricultural harvesters and spectral reflectance of plant canopy

The use of near-infrared spectroscopy on agricultural harvesters has the advantage of not being time and resources consuming. In contrast to conventional sample-based methods, near-infrared spectroscopy on agricultural harvesters secures a good distribution of measurements within plots and covers substantially larger amounts of plot material (Welle et al., 2003). Thus, this method reduces the sampling error and therefore, provides more representative measurements of the plot material.

Spectral reflectance of plant canopy is a non-invasive phenotyping technique that enables the monitoring with high temporal resolution of several dynamic complex traits, such as biomass accumulation (Montes et al., 2007). Investigations at the individual plant level under well controlled environmental conditions showed that spectral reflectance could be used to monitor plant photosynthetic pigment composition, assess the water status and detect abiotic or biotic plant stresses (Penuelas, and Filella, 1998; Chaerle, and Van Der Straeten, 2000).

Current methods for measuring biomass production in cereal plots involves destructive sampling which is not suitable for routine use by plant breeders where large numbers of samples are to be screened. The measurement of spectral reflectance using ground-based remote sensing techniques has the potential to provide a nondestructive estimate of plant biomass production. Quick assessment of genetic variations for biomass production may become a useful tool for breeders. The potential of using canopy spectral reflectance indices (SRI) to assess genetic variation for biomass production is of tremendous importance. The potential of using water-based SRI as a breeding tool to estimate genetic variability and identify genotypes with higher biomass production would be helpful to achieve higher grain yield in crops.

3.2 Infrared thermography

The integrator of drought is the plant water status (Jones, 2007), as determined by plant water content or water potential. A direct measurement of these variables is difficult and currently not possible in a high-throughput phenotyping approach. Probably the most commonly used technique in this context is thermal infrared imaging, or infrared thermography (IRT) to measure the leaf or canopy temperature.

Plant canopy temperature is a widely measured variable because it provides insight into plant water status. Although thermal imaging does not directly measure stomatal conductance, in any given environment stomatal variation is the dominant cause of changes in canopy temperature (Jones and Mann 2004).

Thermal imaging is becoming a high-throughput tool for screening plants for differences in stomatal conductance (Merlot et al. 2002). Thermal infrared imaging for estimating conductance has potential value as it can be used at the whole plant or canopy level over time. Leaf temperature has been shown to vary when plants are subjected to water stress conditions. Recent advances in infrared thermography have increased the probability of recording drought tolerant responses more accurately.

3.3 Magnetic resonance imaging (MRI) and positron emission tomography (PET)

These two methods are being used at Julich Plant Phenotyping Centre (Germany) to investigate root/shoot systems growing in sand or soil, with respect to their structures, transport routes and the translocation dynamics of recently fixed photoassimilates labelled with the short lived radioactive carbon isotope 11C. Quantitative MRI and PET data will help not only to study the differences between species, but also in phenotyping of cultivars or plant lines in which growth pattern, water relations or translocation properties are important traits with respect to plant performance (Jahnke et al. 2009). Therefore, MRI–PET combination can provide new insights into structure–function relationships of intact plants. It also allows monitoring of dynamic changes in plant properties, which has not been possible to assess systematically until now to understand plant performance such as resource use efficiency or biomass production.

3.4 RGB imaging

Digital image analysis has been an important tool in biological research and also has been applied to satellite images, aerial photographs as well as macroscopic images (Nilsson, 1995). The imaging method has been proposed to infer plant biomass accurately as a non-destructive and fast alternative to the conventional means of determining shoot dry weight. The approach predominantly cited in literature is the estimation of plant biomass as a linear function of the projected shoot area of plants using RGB images.

A relevant application of image analysis which has been used for decades is in the area of remote sensing forestry and precision agriculture in which the area of plant species cover and the biomass of the above-ground canopy are estimated from satellite and airborne images (Montès et al, 2000; Lamb and Brown, 2001).

These techniques have found a recent application in estimating the biomass of individual plants in a controlled environment and also in the field. There have been only a few reports on the application of image analysis techniques to estimate above-ground biomass of an individual plant. In these reports, the projected shoot area of the plants captured on two dimensional images was used as a parameter to predict the plant biomass (Tackenberg, 2007; Sher-Kaul et al, 1995; Paruelo et al, 2000).

3.5 Crop models and geographic information systems (GIS)

Numerous dynamic crop models have been developed for simulating crop growth in function of environmental factors (soil characteristics, climate) and of agricultural practices. Some of these models can be used for predicting crop biomass and yields and crop quality before harvest. For example the Geographic Information System (GIS) was successfully used to predict water-limited biomass production potential of various agro climatic zones of the world (Fig 3). It is very clear that the biomass producing potential of

SAT is between 300 to 600 g dry matter M^{-2} Y^{-1} that corresponds well with the observed annual productivities.

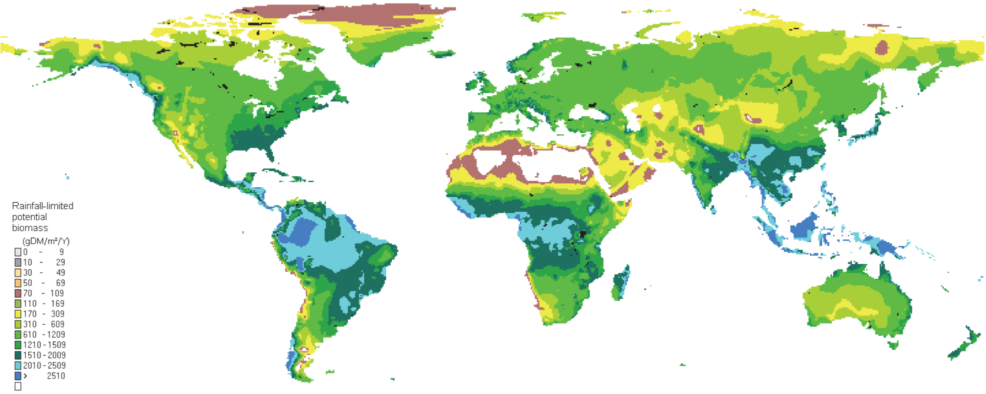

Fig. 3. Distribution of predicted rain-fall limited potential biomass production (Source: FAO-SDRN-Agrometeorology Group 1997.
http://www.fao.org/sd/EIdirect/climate/EIsp0061.htm)

The advent of remote sensing technology supported by Geographic Information System (GIS) has opened new vistas of improving agricultural statistics systems all over the world. The applications of Remote Sensing (RS) in the field of agriculture are wide and varied, ranging from crop discrimination, inventory, assessment and parameter retrieval, on one hand, to assessing long term changes and short-term characterization of the crop environment. The use of remote sensing for crop acreage and yield estimation has been well demonstrated through various studies all over the world, and has gained importance in recent years as a means of achieving these estimates possibly in a faster mode and at a cheaper cost (Murthy et al., 1996). An integrated methodology for providing area and yield estimation and yield forecasting models with small area estimates at the block level using satellite data has been developed (Singh and Goyal, 2000; Singh et al. 2002).

The remote sensing use for drought prediction can benefit from climate variability predictions. Recent research on crop-water relations has increasingly been directed towards the application of locally acquired knowledge to answering the questions raised on larger scales. However, the application of the local results to larger scales is often questionable. Crop simulation models, when run with input data from a specific field/ site, produce a point output. The scope of applicability of these simulation models can be extended to a broader scale by providing spatially varying inputs (soil, weather, crop management) and combining their capabilities with a Geographic Information System (GIS). The main purpose of interfacing models and GIS is to carry out spatial and temporal analysis simultaneously as region-scale crop behavior has a spatial dimension and simulation models produce a temporal output. The GIS can help in spatially visualizing the results as well as their interpretation by spatial analysis of model results.

4. Concluding remarks

4.1 Differential response of cereals and legumes to drought and salinity stress

Abiotic stresses (mainly drought and high soil salinity) are the major cause for the reduction in crop biomass and yield worldwide, especially in the SAT. Generally, Cereals are relatively better equipped to tolerate those stresses than the legumes, partly due to the carbon pathway differences between these two crop groups. Data collected using destructive measurements showed that under terminal drought the reduction of shoot biomass production in legumes can reach 50% especially in groundnut. In cereals, shoot biomass reduction is hardly above 40%.

Depending on the level of stress, both legumes and cereals may suffer from yield losses to a larger extent than shoot biomass reduction, however, in some cases, a better partitioning can help in a better yield. For example, reduction of chickpea seed yield due to terminal drought was recorded to be 26 to 61 % and the shoot biomass at maturity to be 31 to 63 % during three years of study using a large number of germplasm accessions. Whereas, the haulm yield of groundnut was reduced to 24 and 23% while the pod yield by 47 and 37% in the two years of field experimentation.

At a salinity level where the legumes would be completely dead, cereals like pearl millet and sorghum can thrive and be productive. However under salinity the larger adverse effect is on the reproductive growth than on the vegetative growth. Salinity affects plant growth and also equally the partitioning leading to a greater loss in seed yield. Reproductive biology is known to be more affected leading to greater yield damage. The partitioning to the root system plays a key role in tolerance to both drought and salinity.

4.2 Monitoring crop growth and productivity using remote sensing and GIS is key

The traditional approach of estimating the effect of a given abiotic stress on crop growth and productivity is becoming obsolete because of various reasons related to precision and up-scaling. Remote sensing data provide a complete and spatially dense observation of crop growth. This complements the information on daily weather parameters that influence crop growth. RS-crop simulation model linkage is a convenient vehicle to capture our understanding of crop management and weather with GIS providing a framework to process the diverse geographically linked data. Currently RS data can regularly provide information on regional crop distribution, crop phenology and leaf area index. This can be coupled to crop simulation models in a number of ways. CSM-RS linkage has a number of applications in regional crop forecasting, agro-ecological zonation, crop suitability and yield gap analysis and in precision agriculture.

In future the RS-CSM linkage will be broadened due to improvements in sensor capabilities (spatial resolution, hyper-spectral data) as well as retrieval of additional crop parameters like chlorophyll, leaf N and canopy water status. Thermal remote sensing can provide canopy temperatures and microwave data, the soil moisture. The improved characterization of crop and its growing environment would provide additional ways to modulate crop simulation towards capturing the spatial and temporal dimensions of crop growth variability.

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