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Water stress and its management strategies on rainfed maize: A review

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Abstract
Drought (water stress) is one of the most important environmental stresses and occurs for several reasons, including low rainfall, salinity, high and low temperatures, and high intensity of light, among others. Drought stress is a multidimensional stress and causes changes in the physiological, morphological, biochemical, and molecular traits in plants. Water stress is considered as one of the most devastating environmental stresses worldwide as it has rendered large area of agricultural land unproductive around the globe. It is more likely that increasing population and changing climatic conditions will increase water scarcity, which will cause a further decrease in crop productivity in the world. Alterations in rainfall pattern and rising temperature are major causes of drought and have contributed an appreciable decline in maize productivity Current trends of climatic changes will increase water scarcity and will reduce maize productivity by 15- 30%. Globally maize is the third most important crop in the world. The main maize crop is generally grown as rained. In India, approximately 2.4 mha (~ 32.4%) of total maize growing areas is prone to face water or excess moisture stress. Mechanisms involved in plant tolerance to drought follow a general plan: maintaining cell homeostasis in water-deficit situations, which is possible by increasing the water inlet to the cells. Drought avoidance is other common drought resistance mechanism in annual plants. With this mechanism, escape from stress conditions is the main strategy for plant growth under drought conditions. Different strategic characters are improved by numerous biological approaches which enable the plants to escape, avoid, and tolerate the water stress. Screening of germplasm for assessment of tolerant variants, development of tolerant genotypes through conventional breeding, mutation breeding, molecular breeding, and transgenic approaches are possible options which are working and can further be employed for further improvement.

Keywords: Water stress, maize, different strategies

Introduction
Maize is one of the three most important cereal crop species (after wheat and rice), and is grown throughout a wide range of climates. The total sowing area, production and yield in 2002 were 138,755,000 ha producing 602,589,000 at an average yield of 4.34 t ha-1 (FAO Production Yearbook 2002). A major shift in global cereal demand is underway, and by 2020, demand for maize in developing countries is expected to exceed demand for both wheat and rice (Pingali and Pandey 2001) [48]. Maize is desired for its multiple purposes as human food, animal feed, and pharmaceutical and industrial manufacturing. It is the basic food for the majority of people in Mexico and Latin American countries, and consumed in many other countries as, for example, cornflakes, corn syrup and oil. For animal feed, it is highly desirable because of its high yield and feed value of grain, leaf and stem, and is becoming increasingly important in many countries. For industrial and pharmaceutical applications, it can be used to produce starch, ethanol, plastics, and as a base for antibiotic production. Because of its importance, maize area has been either increasing or remaining stable in the majority of producing countries in recent decades, while other crop species might be reduced because of declining land availability or farming adjustment. Over the past 40 years the global total area sown to maize has increased by about 40% and production has doubled.

Water use efficiency by maize
Maize originated from Mexico, and is mainly grown in the warmer temperate regions and humid subtropics. It is a C_4 plant, which confers potentially more efficient use of CO_2, solar radiation, water and N in photosynthesis than C_3 crops. Water use efficiency (WUE) of maize is approximately double that of C_3 crops grown at the same sites. Its transpiration ratio (molecules of water lost per molecule of CO_2 fixed) is 388, corresponding to 0.0026 in WUE (Jensen 1973) [33], while that of wheat is 613, soybean 704.

Even though maize makes efficient use of water, it is considered more susceptible to water stress than other crops because of its unusual floral structure with separate male and female floral organs and the near-synchronous development of florets on a (usually) single ear borne on each stem.
Maize has different responses to water deficit according to development stages (Cakir 2004) [11]. Drought stress is particularly damaging to grain yield if it occurs early in the growing season (when plant stands are establishing), at flowering, and during mid to late grain filling (Heisey and Edmeades 1999) [28]. At the seedling stage, water stress is likely to damage secondary root development. During stem elongation (after floral initiation) leaves and stems grow rapidly, requiring adequate supplies of water to sustain rapid organ development, water stressed plants being shorter and with reduced individual and cumulative leaf area (Muchow 1989) [41]. The most critical period for water stress in maize is ten to fourteen days before and after flowering, with grain yield reduced two to three times more when water deficit coincides with flowering compared with other growing stages (Grant *et al*. 1989) [24]. During this period, ear growth is susceptible to competition from other organs that are still growing as its growth is source limited, often leading to low grain number per ear and occasionally barren ears. Grain yield of maize suffering water stress at flowering and during grain fill is highly correlated with kernel number per plant (Bolanos and Edmeades 1996) [8] indicating the importance of adequate water supplies during flowering.

Improvement of water use efficiency in maize

WUE of maize is a function of multiple factors, including physiological characteristics of maize, Genotype, soil characteristics such as soil water holding capacity, meteorological conditions and Agronomic practices. To improve WUE, integrative measures should aim to optimise cultivar selection and agronomic practices.

Genotype improvement through plant breeding

The use of drought-adaptive secondary traits in breeding Drought tolerance of plants is determined by a large number of physiological and morphological traits. Secondary traits that indicate drought tolerance in plants have been reviewed extensively (Blum 1988, Boyer 1996) [7, 9]. Drought resistance consists of three main strategies: drought escape, dehydration avoidance and dehydration tolerance. The relevant morphological and physiological attributes include resistance to wilting, rapid maturity, short anthesis-silking (in maize) interval, deep root systems, waxy cuticle, heavy glaucousness or dense pubescence, leaf-water retention, stay-green characteristics, osmotic adjustment, cellular membrane stability and high harvest index. Stomatal behavior of plants in drying soil can be regulated by long distance signals provided by plant hormones such as abscisic acid, xylem sap pH, and inorganic ions that provide the shoot with some measure of water availability (Davies *et al*. 2002) [14]. These traits can be modified through breeding, such as pedigree breeding, backcross breeding, bulk-population breeding, recurrent selection, and gene transference using biotechnology (Xiao *et al*. 2004) [61].

Drought-adaptive improvement through conventional breeding

Selection for drought resistance can be conducted in the field or greenhouse. Provided reasonable control is achievable, the field environment is highly desirable for selection work (Blum 1988) [7]. However, the natural, semiarid environment toward which breeding work is often directed is often difficult for plant selection because rainfall is often characterized by very high intra and inter seasonal variations in timing and amount of rainfall received. Field selection can be undertaken in very low rainfall environments (for example, <100 mm), where water-stress conditions can be more readily controlled by the use of supplementary irrigation. Selection under managed levels of drought stress at one location together with multilocation testing may be desirable in breeding maize for drought-prone areas (Byrne *et al*. 1995) [10]. There has been some success using conventional breeding for improved drought resistance by selection for one or more secondary traits conferring drought tolerance (Chapman and Edmeades 1999, Zaidi *et al*. 2004) [12, 17, 62]. However, no selection index for drought resistance can be used singly for achieving progress in selection (Sammons *et al*. 1980) [56], rather success will depend on integration of several criteria into one index. In choosing which traits to use to improve selection efficiency, those which contribute to productivity will generally be more useful than those which contribute to survival. The key to improved rate of progress in breeding and selection has been the use of managed field-based stress around the flowering period, when maize is relatively susceptible to water stress (Otegui and Slafer 2000) [46].

Drought-adaptive improvement through modern biotechnology

Substantial progress in understanding of processes and genes implicated in plant response to drought has been made since about 1990 (Kumar 2001, Chaves *et al*. 2003) [38, 13], a period during which use of biotechnology has become important to crop improvement. Techniques that have been found useful include molecular biology, gene isolation and gene transfer (Betran *et al*. 2003) [4]. High–resolution genetic linkage maps and molecular markers (MMs) are also now available for maize (http:// www.agron.missouri.edu/). They can be used to facilitate a priori selection of parents for source populations, estimating genetic distance between lines, assigning lines to breeding patterns, and to assist in identifying hybrid combinations that are most likely to be successful (Lee 1995) [39]. Further, they have been used to detect and locate quantitative trait loci (QTLs) for drought resistance (Ribaut *et al*. 1997) [52], anthesis-silking interval and yield components in maize (Xiao *et al*. 2004) [61]. Introducing foreign DNA to maize potentially increases genetic variation within the species as well as increasing the speed and precision with which genes for specific traits can be introduced. Transformation methods are becoming more routine and genes coding for osmoprotectants, such as glycine, betaine, proline, and mannitol have been identified and engineered into several crop species, including rice (Nguyen *et al.* 1997) [42]. Recombinant DNA can be used to investigate and understand the role of genes. This approach could be used to attempt to directly manipulate one or more genes to improve crops WUE and resistance to water deficit. Molecular mechanisms by which plant cells withstand dehydration have been investigated using a number of ‘models’. Molecular tools such as markers and transgenes promise to improve the rate of accumulation of desirable drought-adaptive alleles without adversely affecting the specific and general combining abilities in drought susceptible genotypes that have other desirable characteristics species (Bohnert and Cushman 2000, Bartels and Salamini 2001) [7, 3]. Nevertheless, despite the promise of biotechnology, successful breeding programs for improved drought tolerance frequently combines two or more of the strategies, and this reliance is expected to continue. For example, the development of enhanced stress tolerance in CIMMYT's lowland tropical germplasm combined selection under managed stress and selection for secondary traits (Heisey and Edmeades 1999) [28]. Products of biotechnology will still need to be assessed using these approaches – an important benefit of biotechnology being the rate of progress possible and thus reduction in time to achieve success in selecting for drought tolerance.

Modification of agronomy

Drought resistance for a crop can be affected by many agronomic measures. Some measures are Critical for improving WUE, and can be achieved with relatively simple changes to production practices.

Planting date

Short crop duration contributes an important attribute of drought escape (Debaeke 2004) [15], so earlier maturing genotypes are better adapted to environments where the period of favourable water supply is short and the risk of water stress is relatively high. Planting date coupled with selection of appropriate genotypes facilitates drought escape by matching the crop growth cycle to rainfall and temperature patterns to mimimise the chance of exposure to water deficit at drought susceptible stages. Of course, selection of planting date and cultivar must ensure that the thermal environment is favourable to crop establishment and completion of its life cycle. Where the length of the growing season is limited by the duration of rainy season, the earliest possible planting of suitable cultivars reduces the probability of drought during the late grain-filling stage (Heisey and Edmeades 1999) [28]. A modeling approach to selection of planting date– ultivar combinations is included in Birch *et al*. (2006) [6, 29].

Planting geometry

Planting geometries or planting patterns can influence WUE, there being many planting patterns for maize according to the environment and cultural conditions. The most common is equal row spacing pattern, of about 70-90 cm row spacing and different intra row plant spacing producing different plant population densities. Intercropping may be used with maize and has the benefit to use water from different soil layers by the companion crops and enhances overall WUE where water supply is adequate (Adiku *et al*. 1998) [1]. Skip row sowing (with 1 row not planted between every 2 or 3 rows of sowing) has been proposed as a means of improving crop reliability by restricting water use early in the season and maintaining a reserve of water in the soil in the wide row space produced by the omitted row. However, though significant yield benefits have been shown for grain sorghum, research by Robertson *et al*. (2003) [6] and Madhiyazhagan (2005) [40] in Australia failed to show similar benefits for maize, both finding maize does not exploit the water remaining in the wide row space. However, in South Africa, relatively late maturing maize grown under an annual rainfall of 500-600 mm is often sown at densities as low as 10,000 plants per hectare in row up to 2 m apart (Heisey and Edmeades 1999) [28]. There may be specific circumstances where wide rows may be beneficial, but Australian research to date is unsupportive of the practice.

Tillage

Based on the level or organic residues left on the soil surface, two broad classifications of tillage are used: conventional tillage and conservation tillage. Result of various investigations from almost all world climatic zones suggest that ploughing causes common soil-related problems of compaction, soil erosion, reduced water percolation and thus increased runoff and high energy and time requirements (Titi 2003) [59]. While conservation tillage, including no-tillage, ridge tillage, mulch tillage, and any systems with at least 30% residue cover remaining after planting (Derpsch 2001) [16], is generally designed to reduce soil erosion (Reinbott *et al*. 2004) [51], it also improves water infiltration (Guzha 2004) [25], water storage and thus yield potential and improved WUE (Hartkamp *et al*. 2004) [27].

Residue retention and plastic mulch

In semiarid areas, as much as 50% of total evapotranspiration from a crop can be lost through evaporation from the soil surface (Unger and Stewart 1983) [60]. Mulching with crop residues is an obvious way to reduce evaporation and it may have other desirable effects such as reducing run off, increasing infiltration, and decreasing surface temperature, contributing the improve WUE (Hartkamp *et al*. 2004) [27]. Usually, surface mulching reduces evaporation by protecting the moist layer of air close to the surface from wind and moderates soil temperature. Maximum soil temperature is often reduced because mulching materials generally reflect more solar radiation and have lower thermal conductivity than soil (Jalota and Prihar 1998) [32]. Retention of crop residue and minimum tillage improves several measures of soil quality, sustains or improve crop production, and increases WUE of maize in semi-arid subtropical areas (Gicheru *et al*. 2004, Rahman *et al*. 2005) [22, 50] and humid tropical areas (Pramanik 1999) [49]. Plastic mulching has become a well established technique for increasing the profitability of many horticultural crops, and is now being considered more widely for field crops. Large yield increases have been achieved by using plastic mulching on rainfed maize, more than doubling yields (Fisher 1995) [20]. In cool climates that are marginal for crop establishment, plastic mulch may increase temperature, while protecting water from evaporation. For cotton, adopting an integration of micro-topography and plastic mulch has increased WUE from 0.49 to 0.76-0.86 kg/m3 (Jin *et al*. 1999) [34], but adoption of this technology is dependent on cost effectiveness and overcoming concerns with in field degradation or removal and disposal of used plastic film.

Weed control and fertilizer use

Weeds compete with agricultural crops for light, nutrients and water (Norsworthy and Frederick 2005) [44], as both exploit limited resources at a site. The impact of weeds depends on the type and intensity of interference with crop plants, and in maize, like other crops, effective control of weeds leads to more efficient use of water (Peterson and Westfall 2004) [47]. The most important management interaction in many drought-stressed maize environments is between soil fertility management and water supply. In areas subject to drought stress, many farmers are reluctant to risk economic loss by applying fertilizer, strengthening the link between drought and low soil fertility. While not exploring the underlying physiology or the impact on individual nutrients on crop yield and thus WUE in this paper – there are a multitude of review papers on these topics – reduced plant growth rate in nutrient-deficient plants is generally associated with reduced WUE (Bacon 2004) [2]. Therefore, management of nutrient supply is a strategy to improve WUE. For example Ogola *et al*. (2002) [45] reported that the WUE of maize was increased by application of nitrogen and Gao *et al*. (2004) [21] found that silicon, though not widely considered a plant nutrient, improves WUE in maize plants under water stress by reducing leaf transpiration and water flow rate in xylem vessels.

Irrigation management

Although only about 18% of cropland is irrigated, it accounts for about 40% percent of world crop production (Gleick 2000) [23] and two-thirds of the total of rice and wheat production (Rosengrant 2000) [55]. WUE can be improved with better systems for water conveyance, allocation and distribution (Hamdy *et al*. 2003) [26] and water loses can be drastically reduced by using advanced irrigation methods including drip irrigation systems that allow water to be delivered precisely when and where it is needed. Average application efficiencies of different systems are surface (flood) irrigation, 60 to 90%; sprinkler irrigation, 65 to 90%; drip irrigation, 75 to 90% (Fairweather *et al*. 2003) [19]. Distribution uniformity in the field is also very important for enhancing WUE and is favoured by precise delivery systems. Managing maize irrigation at the field scale can be improved by quantifying the water balance and using advanced techniques for irrigation scheduling for more effective and economic use of limited water supplies. The irrigation scheduling is not necessarily based on full crop water requirement, but designed to ensure the optimal use of allocated water. Deficit (or regulated deficit) irrigation is one strategy for maximizing WUE for higher yields per unit of irrigation water applied. The crop, for example, maize crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season, without significant reduction in yields (Sepaskhah and Ghahraman 2004) [57]. Success with deficit irrigation is more probable in finely textured soils such as vertisols of the northern grain belt of Australia, by making water available at critical stages of maize development. Kang *et al*. (2000a) [35] reported that soil drying at the seedling stage plus further mild soil drying at the stem-elongation stage is an optimum irrigation method for maize production in a semi-arid area. Alternate furrow irrigation (one of the two neighboring furrows is alternately irrigated during consecutive watering) and controlled alternate partial root-zone irrigation (part of the root system being exposed to drying soil while the remaining part being irrigated normally) are also ways to increase WUE of maize (Kang *et al*. 2000b, Kang and Zhang 2004) [36, 61].

Conclusion

Numerous strategies are available for improvement of WUE in maize. These include plant improvement strategies, using conventional methodologies and biotechnology, and a range of agronomic practices. Of necessity, a combination of both will be needed to optimize maize production as water supplies become more limiting, with careful attention being given to the combination of practices that optimize WUE and crop reliability.

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