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Drought risk management for increased cereal production in Asian Least Developed Countries

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ABSTRACT

Drought stress is a serious abiotic factor inhibiting nutrient acquisition by roots and limiting cereal crop production in Asian Least Developed Countries (LDCs). Many studies revealed that balanced fertilization can improve photosynthetic activity by stabilizing superoxide dismutase (SOD) activity, improve proline, abscisic acid (ABA) and make the crop drought tolerant with efficient root system and finally improve crop yield. To mitigate drought stress, along with the usage of resistant and efficient genotypes, soil and foliar applications of macro- and micro-nutrients are being used in Asia. According to drought sensitivity index, the efficient genotypes are found more drought-tolerant than the inefficient ones. Studies revealed that irrigation alone is not sufficient to obtain satisfactory grain yield without balanced fertilization. At drought stress, the efficient genotypes accumulate higher quantities of ABA and proline, and exhibit higher activities of SOD, as compared with inefficient genotypes through greater nutrient accumulation by their longer and thinner root systems with high efficiency. Under severe drought with low nutritional status, the rate of photosynthesis, particularly water-use efficiency (WUE) increases in the efficient genotypes than in the inefficient ones. Consequently, these physiological and morphological parameters result in better yield performance by efficient use of water. Under drought, soil application of NPK along with foliar application of zinc (Zn), boron (B) and manganese (Mn) increase grain yield as well as micronutrients concentration of the grain. The rate of photosynthesis, pollen viability, number of fertile spikes, number of grains per spike, and WUE are increased by late foliar application of these micronutrients. This indicates that, by increasing WUE foliar application of Zn, B and Mn at booting to anthesis can reduce the harmful effects of drought that often occur during the late stages of cereal production in Asian LDCs. Therefore, it can be concluded that soil application of Zn, B and Mn in early stage combined with foliar application in late stage, especially at the flowering stage, is a promising approach to alleviate drought stress. Another attractive environmental friendly approach is to select efficient and drought tolerant genotypes with a more efficient root system. These findings are of high relevance for farmers' practices, the extension service and fertilizer industry to mitigate the drought stress in Asian LDCs. A few recommendations are made for extension of scientific knowledge to find more scope in support of mitigating drought situation.

1. Introduction

Rice (*Oryza sativa*, L.), maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.), are three cereals that feed the world, with an estimated global production of 470,854 and 655 million tons and consumption of 469,866 and 673 million tons of rice, maize and wheat, respectively in 2012–2013 (International Grain Council, 2013). FAO's latest forecast for global cereals production in 2012 stands at below last year's level, but close to the average of the past five years (FAO, 2012). This level is considerably below expectations earlier in the year, largely reflecting the impact of severe droughts in Europe and Asia. Water and nutrition are two of the major components of environmental variations and together provide limitations to successful crop production. Mineral nutrients are essential for plant growth and development through their fundamental roles in plant metabolism, while drought is prominent among the most important ecological factors that impact crop growth and productivity (Bagci et al., 2007; Passioura, 2007). Many physiological processes in plants are impaired by drought stress, including photosynthesis, enzyme activity, membrane stability,

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pollen viability and ultimately growth (Flexas et al., 2004; Schoper et al., 1987; Valentovic et al., 2006; Westgate and Boyer, 1986) and several reports have demonstrated that proline and abscisic acid (ABA) accumulation in plants can enhance tolerance to abiotic stresses (Bray, 1997; De Ronde et al., 2004; Hmida-Sayari et al., 2005). Drought is a major cause of yield and quality loss in cereal crops throughout many of the world's cereal growing area, as well as Asian Least Developed Countries (LDCs) (Akanda, 2010; Bagci et al., 2007; Passioura, 2007; Sheng and Xiuling, 2004). Almost half (47%) of the terrestrial land surface in the world, equal to 6.45 billion hectares, is comprised of dry lands and are distributed among all the different regions of the earth (Fig. 1).

One billion hectares are hyper arid and 5.45 billion hectares are made up of arid, semi-arid and sub-humid areas. There are 70% (5.2 billion hectares) of dry lands around the world used for agriculture with a limited productivity where, crop yield depends on the mode of drought (UNEP, 1997). Despite the fact that rice, maize and wheat are grown in Asian LDCs, the occurrence of drought stress is a frequent phenomenon across the Asian LDCs rice, maize and wheat belts during growing season, particularly during the flowering to grain filling period (Akanda, 2010; Li, 1990). Drought has been found to be one of the major environmental factors which limits both quantity and quality of rice, maize and wheat production in Asian LDCs. Drought stress is often accompanied by a number of other environmental stress factors, including temperature, high solar radiation and wind. While the interactions of drought stress and these other stresses have generally received a reasonable amount of discussion in the literature, the interaction of drought stress and nutritional stress seems to have received little attention. Soils in the Asian LDCs are deficient in many macro- and micro-nutrients essential to plant growth and zinc (Zn), boron (B) and manganese (Mn) are no exception. Low Nutritional status of soils is widespread throughout Asian LDCs, and they commonly occur in areas where crop plants are also subjected to drought stress (Akanda, 2010). Zinc, B and Mn are involved in a wide range of physiological process within the plant cell, and several of these are also associated with tolerance to drought stress. These nutrients also play a key role in the maintenance of photosynthetic activity (Brown et al., 1993; Karim et al., 2012a), pollen viability (Karim et al., 2012a; Sharma et al., 1990), the preservation of membrane integrity (Bettger and O'Dell, 1981; Cakmak and Marschner 1988a; Welch et al., 1982) and the continuance of enzyme activity (Cakmak and Marschner, 1988b; Seethambaram and Das, 1985), as well as being an important factor in a plant's defense against reactive oxygen species, which proliferate under various stress conditions, including drought stress (Cakmak, 2000). This suggests that adequate nutrition may be important for maintaining high plant productivity in drought stress under arid and semiarid environment. This information concerning the relationship between nutrition and drought stress available in the literature, and interaction does not appear to have been studied before in Asian LDCs cereals to any depth. Therefore, the present study is designed to investigate the possible roles of nutrients in improving drought tolerance of cereals crops to nutrient supply and drought stress during early vegetative growth, flowering to grain filling stages, and the effects of these two stresses on grain yield and quality are also examined.

Drought and low nutritional status of soils often occur in combination throughout the world's cropping areas especially in Asian LDCs, and yet the possible interaction between these two stress factors has been largely overlooked. This review describes current knowledge of the independent effects of drought stress and NPK along with Zn, B and Mn nutrition on the growth, grain yield and grain quality of cereals crops. The physiological responses of plants to drought stress are discussed, together with genetic variation in these responses that exists between cereal genotypes. genotypes. Consideration is given to the various roles of these micro- and macro-nutrients as an essential plant nutrients, and some of the better-understood mechanisms responsible for genotypic variations in their efficiency are described. Particular attention is given to the effects of drought on grain yield. Finally, the possible role of NPK along with Zn, B and Mn in the provision of drought tolerance of plants under drought stress is discussed.

1.1. Drought stress and crop productivity

1.1.1. Frequencies and impacts of droughts in Asian LDCs

Production of agricultural crops in Asian LDCs is very much influenced by drought stress that occurs during crop growth. Drought poses the most important environmental constraint to plant survival, distribution and crop productivity, causing notable economical losses. Recent plant breeding techniques have assisted this to some extent, with the selection and development of crop cultivars well adapted to the drought that exists throughout Asian LDCs. However, drought stress continues to impose limitation on crop yield, especially in cereals crops. Areas vulnerable to drought in Bangladesh are shown in Fig. 2.

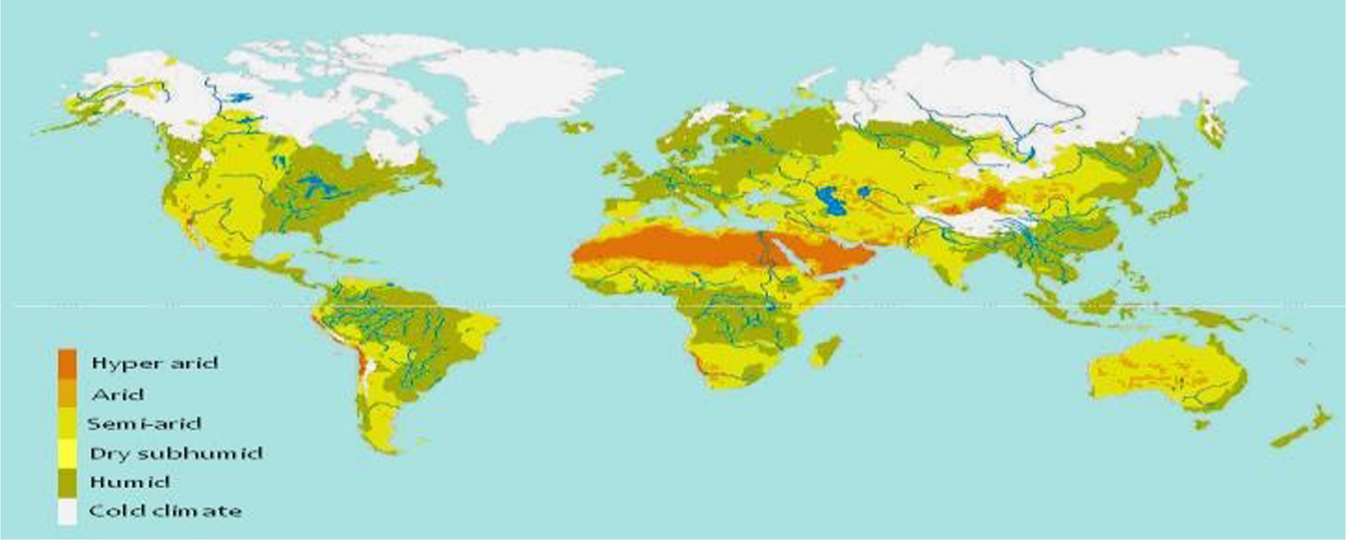


Fig. 1. Geographical distribution of drought affected areas in the world.

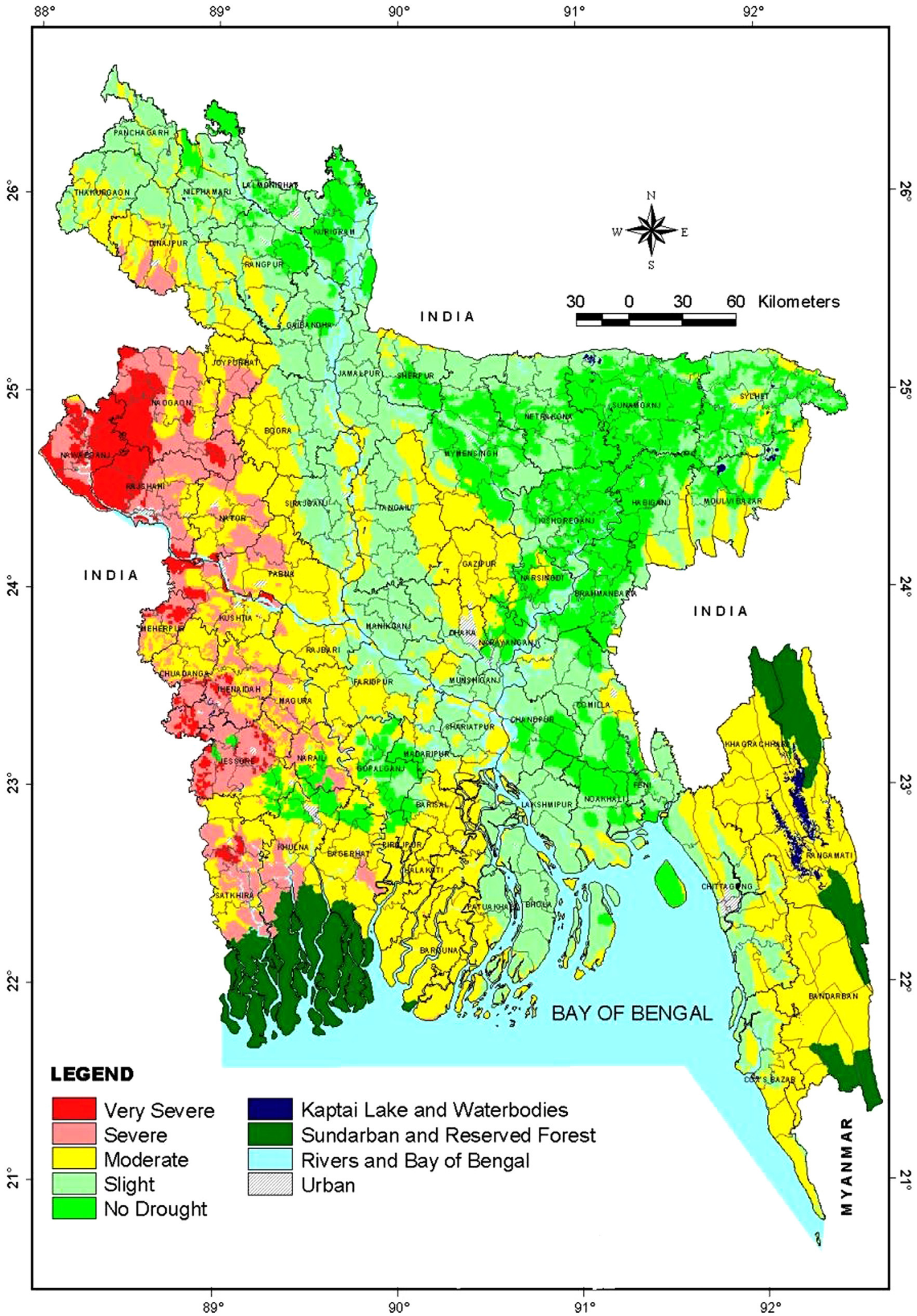


Fig. 2. Drought in Bangladesh (*Source*: (http://www.apipnm.org/swlwpnr/reports/y_sa/z_bd/bdmp265.htm).

In some LDCs like Nepal, Laos and Cambodia, the income from tourist industry also suffers seriously. Prolonged droughts cause starvation, famine, epidemics and death of lives and force mass migration of human and animals. Other impacts are water crisis due to drying up of perennial streams of the hilly regions of Nepal, Bhutan, Afghanistan, Bangladesh, Myanmar, Laos and Cambodia. Ground water-table declines and high humid flora and fauna are affected and thus inducing desertification. Recent drought in the

Mekong Basin has affected the livelihoods. This severe drought is having an impact on agriculture and food security which in turn affected the economic development.

1.1.2. Physiological effects of drought stress

Many important physiological and biochemical processes in plants are impaired by drought stress, resulting in a decrease in growth, yield and grain quality of crops (Fig. 3). Drought stress induces changes in a number of physiological processes in plant, including photosynthesis, membrane integrity, enzyme stability, proline and ABA (Flexas et al., 2004; Schoper et al., 1987; Valentovic et al., 2006; Westgate and Boyer, 1986).

1.1.3. Growth responses to drought stress in cereals

1.1.3.1. Pre- and post-anthesis growth. Depending on the cereal species and on the geographical location of plant cultivation, drought may occur during the phase of vegetative/generative transition in the shoot apical meristem. The appropriate matching of the pattern of inflorescence development and the time of flowering to the temporal variation in water availability is recognized as one of the most important traits conferring adaptation to drought (Bidinger et al., 1987; Passioura, 1996). Although grain crops show sensitivity to drought during floral initiation and the pre-meiotic differentiation of floral parts (Barlow, et al., 1977; Winkel et al., 1997), the effects of drought on floral meristem are among the least understood aspects of crop reproductive development under water-limited conditions (Saini and Aspinall, 1981). In cereals, apical morphogenesis is sensitive to water deficit. Drought stress during flower induction and inflorescence development leads to a delay in flowering (anthesis), or even to complete inhibition (Mahalakshmi and Bidinger 1985; Winkel et al., 1997; Wopereis et al., 1996).

1.1.3.2. Root growth. A well-developed root system as a constitutive trait is favorable in many environments. It enables the plant to make better use of water and minerals and it is an important component of drought tolerance at different growth stages (Blum, 1996; Weerathaworn et al., 1992). The potential quantity of accumulated water depends on the extent of root proliferation in the soil volume. Patterns of resource allocation change when water is limited: root tissues tend to grow more than the leaf tissues. When drought stress occurs during early growth stages considerable changes occurs in the root/shoot ratio (Nielsen and Hinkle, 1996). A longer phase of growth of late genotypes is associated with greater biomass, both above and below ground; this leads to higher root length density in the soil and, consequently, a greater potential productivity (Blum, 1996). It was assumed that vigorous root growth occurs at the expense of grain production, despite the advantage of improved water acquisition in dry soils (Bruce et al., 2002). Increases in grain yield under drought, resulting from selection for drought tolerance, are associated with a smaller root biomass in the upper 50 cm of the root profile in a tropical maize population (Bolanos et al., 1993). Recent research at the International Maize and Wheat Improvement Center (CIMMYT) has investigated the possibility of measuring the root capacity to assess the absorptive area of the roots and to use this as a selection parameter for enhanced drought tolerance. Special emphasis has been placed on determining whether a greater number of brace roots and the extensive development of fine roots (both indicated by a large capacity) favor the formation of above-ground biomass (Edmeades et al., 2000).

1.1.4. Nutrient concentration

Nutrient deficiencies in soils are a critical problem for cereal production causing severe reduction in yield and nutritional

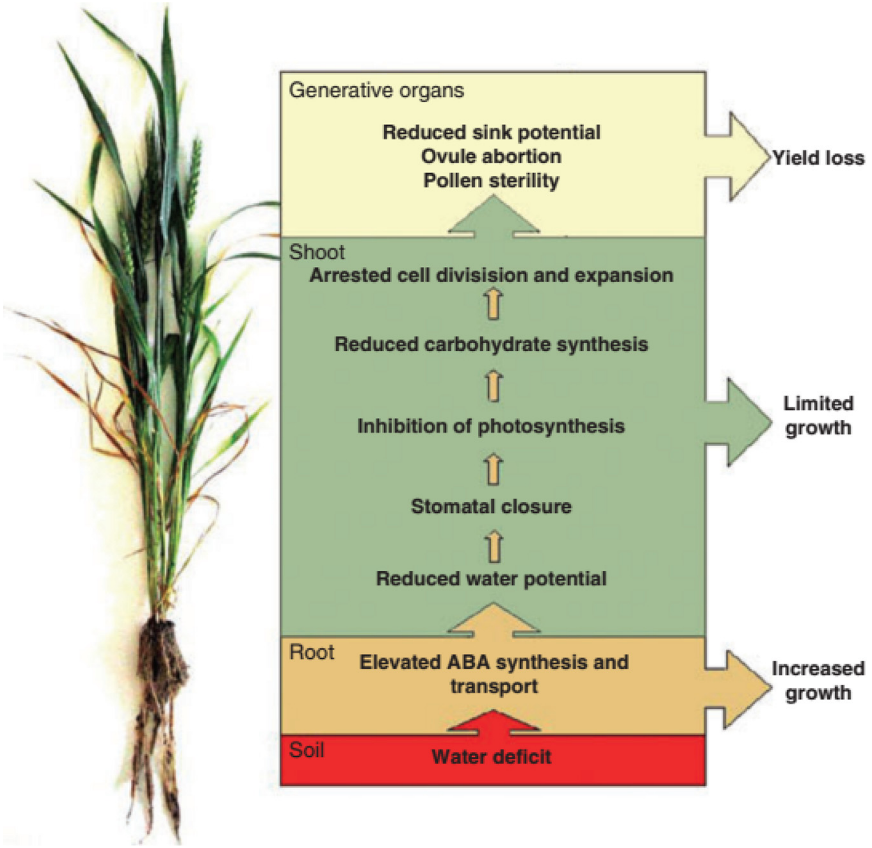


Fig. 3. Drought-induced abscisic acid (ABA)-dependent plant responses (Barnabás et al., 2008).

quality of the grains. These nutrient deficiencies in soils are common problem under arid and semi-arid conditions, like in different parts of Afghanistan, Nepal, Bhutan, Myanmar, Laos Cambodia, India, Pakistan, China, Philippine and also in Bangladesh resulting in severe decreases in grain yield (Alloway, 2008; Karim et al., 2006; Misra et al., 1992;). Increasing evidence is available showing that nutrient deficiency stresses in plants becomes more pronounced under water limited conditions (Bagci et al., 2007; Ekiz et al., 1998; Graham et al., 1992; Karim et al., 2012a). Therefore, development of genotypes with high tolerance to both drought and nutrient deficiency stresses is a high priority research area, and combination of these traits with high grain micro- and macro-nutrient concentrations would be a most desirable breeding goal especially for the arid and semi-arid regions.

1.1.5. *Genetic variation in tolerance to drought stress*

Drought is one of the variables that cannot be easily manipulated in the field, and thereby crops are often selected on the basis of their responses to drought in a particular region. Some degree of drought tolerance may therefore already exist in rice, maize and wheat since selection for performance under drought stress conditions will have screened out any genotypes susceptible to drought stress. It was demonstrated that some of the genetic variation in drought tolerance exists among rice, maize and wheat genotypes in studies of several genotypes sown under drought stress conditions (Bagci et al., 2007; Fukai et al., 1999; Kamara et al., 2003). A reduction in several yield components was observed in some genotypes, including biomass, yield contributing characteristics and grain per yield plant. However no such responses were observed in other, more drought tolerance genotypes.

Drought can strike at any time, but plants are most prone to damage due to limited water during the flowering stage. There are many traits that can lead to a more robust plant under moisture limited conditions, but synchrony between male and female flowering time is particularly important. In maize, the synchrony is called the Anthesis Silking Interval (ASI). Male and female flowers are physically separated, and silks are particularly prone to desiccation. Plants may delay silk production after pollen is shed, but the longer the delay, the fewer grains develop. In addition to ASI, the regulation of carbohydrates is of interest to researchers working on drought tolerance, because the diminished supply of carbohydrates to the developing floral and seed organs that occurs under drought reduces seed set. Again, stress at early kernel development has a much greater negative effect on final yield than stress at a later stage (kernel filling). Abundant evidence shows that ABA is involved in turning on many stress-responsive genes, and that it plays a key role in cell growth regulation, especially during flowering. Therefore, genes involved in ASI, genes in the carbohydrate production pathway, and genes in the ABA production pathway or genes affected by ABA itself, can be very important for the development of drought resistant maize plants (http://www.maizegenetics.net/drought-tolerance). CIMMYT assumes that 50% of yield losses worldwide are due to drought stress before flowering. Stress during flowering is considered to be more important for two reasons: firstly, maize is particularly susceptible to drought at this stage. The grain yield can be reduced to nearly zero by severe stress during a relatively short period at flowering (Edmeades and Deutsch, 1994; Kiniry et al., 1989). According to Bolanos and Edmeades (1996), the ability to produce an ear under stress is the most important characteristic associated with drought tolerance. Secondly, at the flowering stage, the season is too far advanced to consider replanting or adjustment of cropping patterns. It was distinguished between constitutively expressed genes and stress-adaptive genes (Blum, 1997). If stress-adaptive genes of beneficial traits exist in the breeding material, then they are expressed only when the stress is sufficiently severe (Boyer, 1996).

1.2. *Plant nutrition and drought tolerance*

Studies of genotypic variation in drought tolerance have revealed several criteria associated with drought tolerance, including the maintenance of photosynthesis activity under drought stress, improved membrane stability and maintenance of enzyme activity. Coincidentally or otherwise, Zn, B and Mn are also involved in maintaining photosynthetic activity (including maintaining the activity of drought sensitive enzymes), and preserving membrane integrity. These independent effects of Zn, B and Mn nutrition may have a role in alleviating the detrimental effects of drought on crop plants.

Zinc, B, and Mn applications raise the resistance of plants to drought stress (Azza et al., 2006; Khan et al., 2004; Movahhedy-Dehnavy et al., 2009; Wei et al., 2005). The strong interrelationship between micronutrient supply to plants and soil moisture is well established. The transport of micronutrients to plant roots predominantly occurs via diffusion (Marschner, 1995; Römheld and Neumann, 2006), so that soil moisture plays a major role in providing micronutrients to plant roots in soils with low levels of plant-available micronutrients. Micronutrient nutrition of plants growing under drought condition is generally under high risk as reported (Ekiz et al., 1998; Karim et al., 2012a; Pant et al., 1998). The effects of water stress depend on the timing, duration, and magnitude of the deficits (Pandey et al., 2001). The cultivation of wheat in arid and semiarid environments requires the efficient use of available water, and previous studies have shown that the sensitivity of wheat to water stress depends on the growth stage. In Asia, winter wheat was particularly sensitive to water stress between stem elongation and milking stage (Li, 1990). Winter wheat in the US Great Plains was most affected by drought stress from booting to the soft-dough stage (Hanks and Rasmussen, 1982). It is of importance to recognize that during these growth stages plants have a particular high transient demand for micronutrients (Agarwala et al., 1981; Sharma et al., 1990, 1991).

It was recognized that Zn, B and Mn have a vital role in alleviating drought stress (Bagci et al., 2007; Karim et al., 2012a; Peleg et al., 2008). These researchers showed that Zn, B and Mn application could obtain better growth and significantly improved drought tolerance in wheat genotypes. As discussed above, Zn, B and Mn are involved in both detoxification of Reactive Oxygen Species (ROS) and inhibition of ROS production, and are thus important factors in an organism's defense against these destructive species. Superoxide dismutase, in particular is known to play a critical role in the oxidative defense system of all biological tissue (Bowler et al., 1992; Scandalios, 1993), and it follows therefore that plants with reduced SOD activity under Zn deficiency should be more sensitive to oxidative stress factors, including drought stress (Cakmak, 2000). Involvement of the Zn status in plants may therefore be of great importance for their survival under oxidative stress. It was demonstrated that Cu/Zn-SOD activity increased in maize during drought stress (Wang and Jin, 2007), while field studies have shown that drought stress in wheat became more pronounced in plants suffering from Zn deficiency (Ekiz et al., 1998). It had been suggested that these results are due to the reduced activity of enzymes scavenging O_2^- and H_2O_2 in Zn deficient tissues (Cakmak, 2000). Field observation of barley has indicated that adequate Zn nutrition can increase drought tolerance (King, 1994), while decrease in grain yield due to drought stress in wheat was shown to be more marked when plants were Zn deficient (Bagci et al., 2007; Ekiz et al., 1998).

The productivity of crops growing in arid and semiarid environments not only depends on the amount of water available for growth and used by the crop, but also on the water-use efficiency (WUE) of crop. Micronutrients may influence a crop's response to periods of soil water deficit (Ekiz et al., 1998; Karim et al., 2012a). For example, the reductions in yield under rainfed conditions were greater than that in Zn-deficient plants. Micronutrient nutrition may influence plant growth and WUE under rainfed conditions in a number of ways: (i) affecting the plant's ability to access soil moisture reserves, (ii) mediating water loss through the stomata and by influencing plant water status, and (iii) affecting the plant's sensitivity to plant water deficits (King, 1994). Micronutrients have a protective role against photo-oxidative stress (Cakmak, 2000), and therefore micronutrient deficient plants may be more sensitive to drought induced oxidative stress. The relative importance of the different effects of Zn, B and Mn nutrition on water use, growth and yield is likely to be related to the severity of nutrient deficiency and water deficit. Consequently, the effects of Zn, B and Mn deficiency may be manifested in a number of ways: as changes in water use, in WUE and greater sensitivity to drought stress compared to plants supplied with adequate levels of Zn, B and Mn. Zinc, B and Mn fertilization resulted in an increase in WUE (Ahmed et al., 2009; Karim et al., 2012a; Khan et al., 2003, 2004; Wang and Jin, 2005). These findings verify that addition of Zn, B and Mn in deficient soils of the arid environment may prove very beneficial by improving WUE. The factor that will determine the effect of improved micronutrient nutrition on WUE is the harvest index (HI) of the genotype and its ability to respond to the higher levels of nutrition. The HI of inefficient genotypes fell following the addition of micronutrients and this was reflected in reduced WUE, whereas the HI of efficient and drought-tolerance genotypes is maintained and the WUE increased. An efficient genotype tended to be less adversely affected by a period of drought than an inefficient genotype, suggesting that nutrient efficiency may be associated with greater tolerance to drought (Khan et al., 2003). Therefore, the combination of high productivity with high minerals under water limited conditions may be a feasible breeding objective.

1.3. *Plant nutrients and crop productivity*

1.3.1. *Relative sensitivity of crops to nutrient deficiency*

Although nutrient deficiency is known to affect a wide range of crops in many parts of the world, genotypic differences between species render some crops more susceptible to deficiency than others. Apart from inter-specific differences, there are also important intra-specific differences which can in some cases be greater than differences between species. In the case of wheat, durum wheat (*Triticum durum*) is more susceptible to Zn deficiency than bread wheat (*Triticum aestivum*). However, there are considerable varietal differences in both types of wheat. The varieties (or cultivars) of crops, such as wheat, which is recognized as being more tolerant have a relatively low sensitivity to deficiency compared with crops such as maize. If maize or beans were grown on the same soils as wheat, they would probably be even more severely affected. Therefore, although the ranking of crops is useful for comparing sensitivity to deficiency and response to Zn fertilizers, it does not indicate the extent to which these crops are affected by Zn deficiency in various parts of the world (ILZRO, 1975; Martens and Westermann, 1991). It can be seen that crops such as maize, rice and beans are highly sensitive to Zn deficiency and that wheat has only a low sensitivity. However, wheat crops in many parts of the world are still badly affected by Zn deficiency even though wheat has a relatively low sensitivity to deficiency compared with crops such as maize (ILZRO, 1975; Wang and Jin, 2005). Wheat would probably be more severely affected by B deficiency than Zn deficiency in many part of Asian LDCs such as Bangladesh, Nepal (Bodruzzaman et al., 2003; Jahiruddin et al., 1992; Misra et al., 1992).

1.3.2. *Physiological effects of nutrients deficiency*

Zinc, B and Mn play the most important role in plant metabolism. They act as a functional, structural or regulatory cofactor of a large number of enzymes. Many of the physiological effects resulting from Zn, B and Mn deficiency are associated with the disruption of normal enzyme activity in certain tissues. Reduced enzyme activity as a result of Zn, B and Mn deficiency can lead to impaired carbohydrate metabolism (a reduction in photosynthesis), decreased chlorophyll content and the abnormal structure of chloroplasts, induced impairments in cellular function and integrity, and a depression of male fertility (Agarwala et al., 1981; Brown et al., 1993; Cakmak et al., 1995; Cakmak and Römheld, 1997; Cakmak, 2000; Ducic and Polle, 2005; Karim et al., 2012a; Kastori et al., 1995; Khan et al., 2004; Marschner, 1995; Sharma et al., 1990, 1991; Wei et al., 2005).

1.3.3. *Genotypic variation in tolerance to nutrients deficiency*

Plants vary in their ability to grow in nutrient deficient soils. This variation occurs not only between species but also within species. Tolerance to deficient soils is usually termed “cultivar efficiency” which is defined as the ability of cultivar to grow and yield well in soils too deficient in nutrients for a standard cultivar (Graham, 1984). Genotypic variation in nutrients deficiency has been recognized and reported for a number of crops, including rice (Graham et al., 1992), maize (Clark, 1978; Furlani et al., 2005), and wheat (Schulin et al., 2009). Several physiological mechanisms have been proposed to explain nutrient efficiency in crop plants including: (i) a greater proportion of longer, fine roots(≤ 0.2 mm in diameter), (ii) differential changes in rhizosphere chemistry and biology, (iii) the greater release of phytosiderophores, (iv) an increased uptake rate resulting in a net increase in nutrient accumulation, (v) more efficient utilization and compartmentalization of nutrients within cells, tissues and organs, (vi) a greater activity of carbonic anhydrase, and antioxidative enzymes, and (vii) maintaining sulphydryl groups in the root-cell plasma membranes in a reduced state and a differential pattern of biosynthesis (Rengel, 1999). However, these mechanisms of differential nutrient efficiency among cultivars are still unclear, and it may be that more than one mechanism is responsible for the level of nutrient efficiency in particular cultivars (Graham and Rengel, 1993).

1.4. *Interaction of water and nutrients in WUE*

According research results, nutrients that are found to be most limiting in the loess hilly region of Asia are N, P, K, Zn and B (Ahmed and Hossain, 1997; Alloway, 2008; Deng et al., 2003; Jahiruddin and Islam, 1999; Shan and Chen, 1993). The deficiency is really a problem of high pH and runoff (Wei et al., 2000). The increased yield and WUE from added N, P, K, Zn and B was observed in several dry land areas where crops were grown on the same land for several years (Brown et al., 1993; Jahiruddin and Islam, 1999). Liu et al. (1998) indicated that the maximum yield and highest WUE were achieved under the optimum fertilizer input under the semiarid field conditions of loess hilly area. Increased fertilizer application was positively correlated with grain yield and WUE of wheat (Karim et al., 2012a; Shan and Chen, 1993). Increasing the level of fertilizer significantly increased the number of fertile spikelets, kernels/spike and kernel weight. The number of fertile spikelets was particularly sensitive to fertilization, whereas kernel number and weight were more affected by plant density. Fertilizer applied in spring wheat improved the development of the root system and especially enhanced root growth in the cultivated 0–20 cm soil layer. The increased root system in the fertilized plants was able to improve crop water use and nutrient absorption and hence crop yield and WUE were increased.

2. Strategy to alleviate drought stress in cereal production

Episodes of drought stress during the growing season are a common phenomenon throughout many of the world's cereal cropping areas and Asian LDCs are no exception, and often these regions also have soils that are low in plant available Zn, B and Mn. However, certain aspects of root morphology and plant physiology are most affected when these stresses occur individually or simultaneously. Individually both stresses are known to be responsible for limiting grain yield in cereals (Boyer and Westgate, 2004; Potarzycki and Grzebisz, 2009), but the interaction of these two stresses was largely overlooked in Asian LDCs crop production. A number of deleterious changes in plants are caused by drought stress, including denaturation of enzyme activity (Wang and Jin, 2007), reduced photosynthesis (Wang et al., 2009) and retarded development of anther and pollen grains and induced losses of pollen viability (Karim et al., 2012a). Coincidently micronutrient deficiency affects similar process in plants, resulting leaky membranes, reduction in photosynthesis activity (Ashraf and Bashir, 2003) and pollen viability (Sharma et al., 1990). Sufficient soil moisture contributes greatly to micronutrient nutrition of plants and thus minimizes the negative effects of low micronutrient nutritional status on plant yield. Although their effects changed from genotype to genotype, both irrigation and micronutrient application resulted in significant yield increases (Bagci et al., 2007). The study presented in this review is explained to investigate the possible role of micronutrients in the provision of drought tolerance of cereals. A number of researchers have examined the involvement of micronutrients in plant stress tolerance, particularly with respect to oxidative defense system (Cakmak, 2000; Karim et al., 2012a); however the unique nature of this study is to consider the overall plant responses to micronutrient supply of grain yield and its associated traits of aboveground shoots and root system, particularly under drought stress and low micronutrient nutritional conditions, and also to confirm that the foliar application of Zn, B, and Mn alone can alleviate drought stress of cereal at a late growth stage. Investigations of photosynthetic and SOD activity, pollen viability, accumulation of proline and ABA were also undertaken to further elucidate the physiological mechanisms by which Zn, B, and Mn may provide a plant with tolerance to drought stress.

Drought can decrease both grain yield and quality of cereals (Bagci et al., 2007; Kamara et al., 2003). Hence any drought tolerant mechanism would be welcomed in the ongoing efforts to meet the challenge of global water deficits in crop production. The present review examines the responses of grain yield and yield's related morphological and physiological parameters such as vegetative growth, water-use efficiency (WUE), fine roots (≤ 0.2 mm), photosynthesis, enzyme activity, pollen viability and also proline and ABA to drought stress when micronutrients are supplied with and without micronutrient application. The role of micronutrients in involving each of these processes with drought tolerance is discussed below.

Stability of photosynthesis is essential for plant productivity during vegetative growth (Ashraf and Bashir, 2003). It appears that adequate Zn, B and Mn fertilization on deficient soils at least, may have a potential stability effect on photosynthesis activity under drought stress conditions (Wang et al., 2009). In general there were significant effects of drought stress found on shoot dry matter production. Therefore, it can be argued that the drought stress causes substantial reduction in growth. It has been demonstrated that micronutrients could prevent the suppression of leaf elongation under drought and finally the shoot dry matter production (Fukai et al., 1999; Pant et al., 1998; Peleg et al., 2008). It was shown that certain cereal genotypes, particularly drought sensitive ones will be more vulnerable to environmental stresses of low yielding sites (such as drought stress) when also grown under conditions of low nutrient availability. The Zn and B application will increase yield stability of these genotypes, thus supporting the hypothesis that Zn and B have the ability to provide cereal plants with some tolerance to drought stress. However, Zn and B application did not prevent the decline in grain yield of the Zn/B-inefficient and drought sensitive genotypes under drought stress. Nevertheless, the results suggest that the detrimental effects of low available Zn/B and drought stress, particularly on Zn/B-inefficient genotypes, will be mostly magnified when these stresses occur in combination. However, certain genotypes have shown the highest Zn/B efficiency value and grain yield under drought stress conditions with or without Zn/B supply and these genotypes also exhibited very high drought tolerance (Bagci et al., 2007; Karim et al., 2012b; Pant et al., 1998). These results indicate that certain genotypes represent a very promising opportunity for the breeding programs aimed at the development of genotypes with high tolerance to both low micronutrient nutritional status and drought stress. However, it was demonstrated that foliar application of Zn, B and Mn can increase grain yield of winter wheat under drought stress, where this micronutrient is not growth-limiting at an adequate water supply (Karim et al., 2012b). Similar findings have been reported for sunflower (*Carthamustinctorius* L.) (Movahhedy-Dehnavy et al., 2009). Therefore, it can be stated that Zn, B and Mn are essential micronutrients to alleviate drought stress and raise grain yield in cereal production systems especially in the arid and semiarid regions.

The loss in yields under drought stress compared with adequate irrigation was reduced in efficient genotypes due to the high efficiency observed in the previous study, which reflects different aspects of the interaction between Zn/B nutrition and drought stress. The supply of Zn and B increased growth and water-use considerably. However, compared with the inefficient genotypes, the efficient genotype did not increase growth and water-use to the same extent as adding Zn/B. The higher Zn/B uptake may help Zn/B-efficient genotype to maintain the physiological activity of the plant without increasing water-use substantially. The fact that irrigation increased yields more than Zn and B application also indicated that WUE of plants was decreased under low Zn/B nutritional status (Bagci et al., 2007; Khan et al., 2003; Pant et al., 1998). However, several studies showed that Zn, B and Mn sprays increased WUE in cereals under drought (Karim et al., 2012a; Khan et al., 2004; Nuttall et al., 2001; Wei et al., 2005). In the current study, the more efficient use of water with foliar Zn, B and Mn application under drought stress was associated with increased yield because of the production of larger number of fertile spikes per plant and the larger number of grains per spike (Karim et al., 2012a). Therefore, adequate water and available Zn, B and Mn are very important for cereal production system in arid or semi-arid environments.

Zn-efficiency generally involves root morphology, mobilization of Zn by root secretions, root Zn uptake, Zn translocation from roots to shoots, Zn utilization use-efficiency on the cellular level, or Zn reutilization (Nuttall et al., 2001). The acquisition of nutrients by the roots plays the most important role in nutrient efficiency (Gutschick, 1993) which largely depends on root size and morphology (Dong, et al., 1995). In this study, low Zn nutritional status significantly increased the total fine root length and root surface in Zn-efficient genotypes, but decreasing trend of these root parameters was observed in Zn-inefficient genotypes under all water regimes (Karim et al., 2012b). The Zn efficiency is closely associated with a longer fine root and larger root surface area in maize (Karim et al., 2012b) and wheat (Dong, et al., 1995). In fact, root surface area is particularly important in Zn uptake because Zn ions are transported towards roots by diffusion (Römheld and Neumann, 2006). Therefore, longer and thinner roots may be one of the contributing characters associated with the Zn-efficient drought tolerant genotypes.

The WUE of crops in Asian LDCs is surprisingly low (Deng et al., 2006). Therefore, the main purpose of our study is to increase the WUE. Biological water-saving aims to increase crop WUE and drought tolerance by genetic improvement and physiological regulation. Zinc, B and Mn fertilizer application significantly increased number of fertile spikes per plant and the number of grains per spike in wheat plant. The number of fertile spikelets was particularly sensitive to Zn B and Mn fertilization. Zinc fertilization and Zn-efficiency also improved development of the fine root (≤ 0.2 mm) system and especially enhanced the root length and surface area of cereal. The increased root system in the fertilized and Zn/B-efficient cereal plants was able to improve crop water use and nutrient absorption and hence crop yield and WUE were increased. Improving agricultural WUE continues to be a topic of concern because drought is an important factor limiting grain production worldwide. Greater yield per unit of water is one of the most important challenges in water-limited agriculture.

Zinc, B and Mn supply can improve the photosynthetic activity of cereals under drought stress (Karim et al., 2012a). Photosynthetic activity was lowest when plants are subjected to both drought stress and low Zn, B and Mn availability concurrently. The results also showed that low Zn/B-tolerant cereal genotypes had a higher photosynthesis activity than that of sensitive genotypes under drought stress and low Zn/B status due to its higher efficiency. However, drought depressed the growth of wheat plants by decreasing the photosynthesis rate and photosynthesis-related parameters possibly by an imbalance of nutrition. In this study, the consequences of these effects were reflected in a depression of dry matter accumulation and grain yield of cereal which could be alleviated by foliar application of Zn, B and Mn. The influence of Zn, B and Mn was associated with an increase in photosynthesis rate and other yield related parameters. It seems that adequate Zn, B and Mn has the ability to maintain photosynthetic activity, possibly grain yield and grain quality under drought stress. The results of the study suggest that drought stress and Zn, B and Mn deficiency act independently on photosynthesis activity and grain yield. Further work is necessary to determine the mechanism(s) by which elevated Zn, B and Mn nutrition can provide the photosynthetic apparatus with tolerance to drought stress.

Drought stress may represent an oxidative stress and may affect plants by inducing production of ROS, especially during photosynthesis (Sairam and Saxena, 2000; Selote et al., 2004). It is, therefore, likely that drought stress-related production of ROS and sensitivity of plants to photoxidative damage in chloroplasts are additionally accentuated when plants simultaneously suffer from Zn deficiency stress. The Zn nutritional status may affect drought sensitivity of plants in different ways. Firstly, Zn is involved in detoxification of ROS and in this respect may play a protective role in preventing photoxidative damage catalyzed by ROS in chloroplasts (Cakmak, 2000). Secondly, Zn might greatly contribute to drought stress tolerance by protection against oxidative damage of membranes (Cakmak, 2000). It has been suggested that Zn supply may reduce a plant's sensitivity to drought stress by increasing the activity of the ROS-scavenging enzymes and SOD (Cakmak, 2000). Zn supply did improve SOD activity of maize seedlings relative to those which had not received Zn following drought stress (Karim et al., 2012b). However, under drought stress, a higher SOD activity was shown in high Zn-efficient maize genotypes. This suggests that Zn nutrition may be of some importance in the recovery of cells following drought stress through the maintenance of SOD activity (Cakmak, 2000). Tolerance to drought stress in plants has been associated with an increase in antioxidant enzyme and it resulted in very little loss in photosynthetic capacity. Furthermore, maize genotypes with higher level of SOD activity were also found to have a greater tolerance to drought stress than those genotypes with a lower level of antioxidant activity (Karim et al., 2012b).

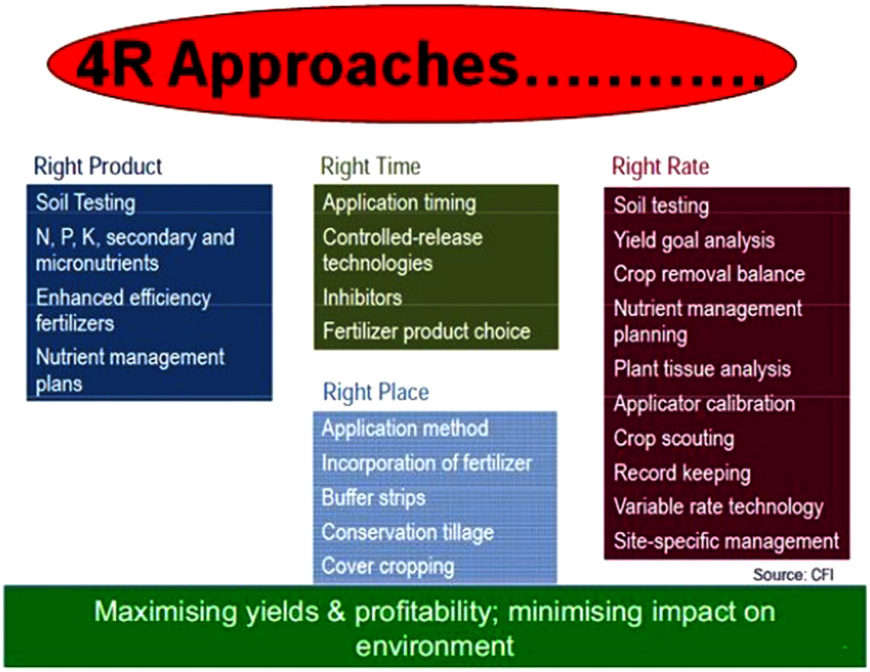
Previous reports indicated that a limitation of Zn (Sharma et al., 1990), B (Agarwala et al., 1981), and Mn (Sharma et al., 1991) negatively affected the development and functioning of the male reproductive organs of cereals. Drought during flowering depresses the needed adequate acquisition of Zn, B and Mn. By reducing the translocation of assimilates from shoots to spikes and by reducing pollen viability, drought may reduce the number of fertile spikelets per spike. In our current study, drought retarded the development of anthers and pollen grains and induced loss of pollen viability in winter wheat. These effects were overcome by a raised Zn, B and Mn status of the plants (Karim et al., 2012a).

Accumulation of free proline and ABA is a common response in plants exposed to drought stress. It could function as hydroxyl radical scavenger to protect against membrane damage and protein denaturation (Bray, 1997; De Ronde et al., 2004). Several reports have demonstrated that proline and ABA accumulation in plants can enhance tolerance to abiotic stresses (Bray, 1997; De Ronde et al., 2004; Hmida-Sayari et al., 2005). The proline content in shoots increases progressively with an increase in the length of time of exposure to Zn (Bassi and Sharma, 1993) and Zn also induced ABA content of leaves (Rauser and Dumbroff, 1981). It is demonstrated that high Zn-efficient genotype accumulated relatively higher levels of free proline and ABA than other genotypes under drought without Zn application. Consequently, that free proline and ABA also contributes to the better protection against reduced oxidative damage in drought tolerant maize genotype (Karim et al., 2012b).

3. Approaches to alleviate drought and low nutritional problem

Previous investigations have demonstrated that rice, maize and wheat are sensitive to water deficit stress and low micronutrient nutritional status of soil (Karim et al., 2012b; Liu, 1996; Pant et al., 1998; Sajedi et al., 2010). The key question is, how do we sustain food production? 4R is the right approach: right product, right time, right rate and right place (Fig. 4) – this can maximize yields and profitability, as well as minimize the impact on the unfavorable environment.

Alleviation of this problem in the field may be achieved in several ways: by proper management of inputs using modern technology, particularly irrigation water management and nutrient application (Panda et al., 2004); by application of micronutrient (for example Zn, B and Mn) fertilizer to the soil (Alloway, 2004; Pant et al., 1998); and by lowering rhizosphere soil pH to increase micronutrient availability e.g. by application of elemental sulfur or ammonium sulfate (Alloway, 2004) or by foliar spraying of Zn, B and Mn containing fertilizers (Karim et al., 2012a; Wang et al., 2009). Another attractive approach, which probably in the long run, may be less financially demanding and more appropriate for smallholder farmers in Asian LDCs, is the use of nutrient efficient drought tolerance genotypes (Bagci et al., 2007; Fukai et al., 1999; Pant et al., 1998). To achieve this three main approaches can now be exploited (Cattivelli et al., 2008): (i) plant physiology provided



Source: CFI

Fig. 4. 4R approaches to maximize yields and profitability, as well as minimize the impact on the environment.

new tools to understand the complex network of drought-related traits and several drought-related traits useful to improve selection efficiency have been proposed (e.g. stomatal resistance, photosynthesis capacity, timing of phenological capacity, anthesis silking interval (ASI), partitioning and stem reserve utilization, delay senescence, plant leaf area, rooting depth, WUE, osmotic adjustment, membrane stability, antioxidant defense, and accumulation of stress-related proteins); (ii) molecular genetics has led to the discovery of a large number of loci affecting yield under drought or the expression of drought tolerance-related traits; and (iii) molecular biology has provided genes that are either useful as candidate sequences to dissect QTLs or for transgenic approaches.

4. Provable policy for drought risk management for increasing cereal production in Asian LDCs

We focused on drought risk management for increasing cereal production in Asian LDCs and our ultimate goal is to reduce hunger and poverty for millions of poor. We should find out the best way to do this is by helping the farmers to grow and sell more foods, so they can improve their nutrition, become self-sufficient, and have better lives under this unfavorable climatic condition such as drought. To succeed over the long term, following key policies are recommended for drought risk management to increase cereal production in Asian LDCs.

4.1. *Research and development*

- Asian LDCs have neither the financial resources nor the technical capacities to meet their adaptation needs. The international community needs to provide stronger financial and technical support to the Asian LDCs both through the special funds such as the LDC Fund and other international frameworks, including the Brussels Programme of Action for the LDCs.
- Need projects that link training and support to national breeding programs that use conventional breeding with investment in private sector seed production and distribution to provide access to seeds of new crop varieties to small holder farmers in Asian LDCs
- To support development and delivery of bio-fortified staple crops, including rice, wheat, maize and millets in order to reduce micronutrient deficiencies in developing countries. This phase of work focuses on the high needs for collaborating with institutions for crop improvement, nutrition retention and efficacy studies.
- Seeks to develop drought-tolerant cereal genotypes to benefit smallholder Asian LDCs farmers in different countries.

4.2. *Agricultural policies*

- To create a global trust fund that supports efforts to improve agricultural productivity and food security in the developing Asia especially in Asian LDCs countries.
- Conduct high-quality, nationally representative, multitopic household panel surveys in Asian LDCs countries. The surveys are implemented by Asian statistics offices and include information on agricultural production and household welfare.
- Identify key policy constraints, devise solutions to policy bottlenecks, and mobilize support for regulatory and legislative reform in Asian LDCs countries.
- Establish a professional development program that strengthens the research and leadership skills of Asian LDCs women in agricultural science, empowering them to contribute more effectively to poverty alleviation and food security in Asian LDCs countries.
- Develop a specialized geographic information system (GIS) to characterize the impact of specific investments in agricultural development. The goal is to support data-driven decision making and investments to support agricultural productivity improvements and poverty reduction under unfavorable climatic condition i.e. drought.

4.3. *Access and market system*

- Help build a sustainable foundation for the agricultural sector growth by restoring Asian LDCs soil fertility through the use of improved soil fertility management practices and fertilizers that stably increase crop productivity.

- Seek to increase smallholder farmers' incomes by launching a program that connects farmers to World Food Program purchasing.
- Work to develop Asian LDCs comparative advantage in speciality cereals through interventions designed to improve quality, increase production, and link smallholders to speciality cereals buyers.
- Invest in the Market Access Program to increase the income of smallholder farmers marketing staple food crops.

4.4. *Integration of science, policy makers and stakeholders*

- To formulate policies for the Asian LDCs, integration of knowledge of the stakeholders, traditional knowledge, findings of the researchers, and policymakers of every agro climatic zone is most essential and this should be done through workshops, seminars and conferences.
- In-depth research on locally available genotypes their behavior and interaction with climatic conditions should be encouraged and supported further through science and policymakers' dialogs.

5. Conclusions

The purpose of this paper is to present a review of drought risk management for increased cereal production in the Asian LDCs and to interpret in the context of the cropping environment of Asian LDCs. This study has also identified a number of gaps in our knowledge on plant nutrition and drought tolerance, and these will be addressed through future research.

Drought stress and micronutrient deficiency are serious abiotic stress factors inhibiting micronutrient absorption by roots and limiting crop production in the Asian LDCs, particularly on calcareous soils of the arid and semi-arid regions. We reviewed several experiments to investigate the possible roles of Zn, B and Mn in improving drought tolerance of cereals to Zn, B and Mn supply and drought stress during early vegetative growth, flowering to grain filling stages, and the effects of these two stresses on grain yield. A secondary aim of the review was to investigate some of the genotype by environment interaction responses of cereals to Zn and B supply. Finally a preliminary analysis of the mechanisms by which Zn and B may provide cereal seedlings with tolerance to drought stress was presented which can be used for further studies for improving drought tolerance in cereals of Asian LDCs. The review presented here has shown that Zn and B nutrition can provide cereal plants with a level of tolerance of drought and it's relation with their efficiency. In addition, foliar application of Zn, B, and Mn can alleviate drought stress of cereals at a late growth stage, when drought commonly occurs in farmer fields. We found that soil application of micronutrient (Zn and B) could partially alleviate drought stress especially in inefficient genotypes but interestingly efficient genotypes could alleviate this stress efficiently with or without Zn/B supply because of their better physiological activity and root morphological traits. However, under drought stress, Zn, B and Mn alleviated yield losses in cereal through late foliar fertilization during booting to grain filling stage. It was shown that the timing of foliar Zn, B and Mn application is a critical issue in maximizing grain yield under drought stress (Cakmak et al., 2010). Foliar spray of Zn, B and Mn during early booting to anthesis is the best time to increase grain yield under drought stress. Therefore, it can be concluded that soil application in early stage combined with foliar application in late stage (especially flowering) is a promising approach to alleviate drought stress. Another attractive environmental friendly approach is to select efficient and drought tolerant genotypes with a more efficient root system.

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