Crop Protection Under Drought Stress

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Introduction

Climate change and its effect on the variability of weather patterns have a significant impact on agricultural practices, the availability of natural resources, and the nature of the environment. According to the National Climate Assessment (NCA), climate change will continue to have a significant impact on crop production and agricultural practices over the next few decades and possibly beyond. Because of these issues, climate change will significantly impact global food security and terrestrial ecosystems. The complexity of these problems is shown by the increase in the frequency and intensity of droughts in some regions around the world and the increase in the intensity of heavy precipitation events on a global scale (IPCC 2019). The Intergovernmental Panel on Climate Change (IPCC) (2019) has predicted a temperature rise of 1.5 °C between 2030 and 2052, plus a significant change in precipitation patterns, which, together with a greater frequency of extreme weather events, will significantly affect agricultural production. These findings provide strong evidence that human-driven emission of greenhouse gases is causing climate change risks, which should not be ignored. In this respect, it is important to understand that the global mean land surface air temperature is increasing faster than the global mean surface temperature (combined land surface and sea surface temperature) (Fig. 1).

Climate variables, such as temperature and precipitation, have direct impact on crop production because they contribute to crop growth, health, and yield, thus affecting cropping system efficiency over time (Ray et al. 2018; Howden et al. 2007; Kang et al. 2009; Lehmann 2013; Paudel et al. 2014; Liang et al. 2017). In the future, climate extremes are expected to increase due to the effects of climate

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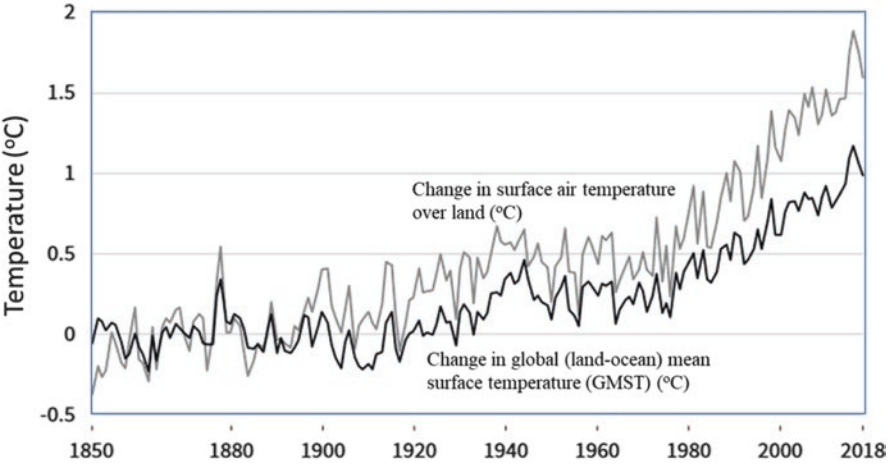

Fig. 1 Change in air and mean temperatures from 1850 to 1900. (Modified from IPCC 2019)

change, which may significantly increase the negative impacts on crop production (Troy et al. 2015). Given this scenario, it is remarkable that numerous researchers have studied the effects of climate change on agriculture. However, past studies have not focused on adaptive changes to improve cropping practices to manage the impact of drought on crop production (Troy et al. 2015).

Water stress resulting from drought is known to reduce crop production because of its negative impacts on plant growth (Karl et al. 2009). Plants, including crops, are naturally subjected to a variety of abiotic stresses such as drought, salinity, heat, and other factors in their life cycle (Manzoor et al. 2016; Hussain et al. 2018; Tandzi et al. 2019; Nabi et al. 2019) and are equipped with different resistance mechanisms for such stresses, the effectiveness of which vary from species to species and even within species (Manzoor et al. 2016; Jaleel et al. 2009). Particularly, in the context of drought, some crops have high drought tolerance capacity (e.g., pomegranate, sorghum, cassava, millet, sweet potato), while others have low tolerance capacity (e.g., sugarcane, banana, citrus, cotton, rice). Mechanism of drought tolerance in the plant is a complex phenomenon as interactions between stress factors and different molecular, biochemical, and physiological factors affect crop growth and development (Jaleel et al. 2009; Razmjoo et al. 2008). Therefore, it is important to understand the impact of water stress and drought on crop growth and its development, physiological process, morphology, and yields and available genetic and agronomic tools for crop protection from drought.

Drought stress is a critical limiting factor at the initial stage of plant's physical growth and development, determining plant height, stem size, number of and size of leaves, flower and fruit production, root size and distribution, and seed development. Moreover, drought stress causes a change in the physical environment, which subsequently affects physiological and biochemical processes in plants (Silva et al. 2009; Fathi and Tari 2016). Water stress causes negative effects on the overall growth and development of crops, resulting in a significant reduction in crop production, which will contribute to a reduction of global food supplies (Lesk et al. 2016). However, proper strategies for drought mitigation combined with the best agricultural management practices can reduce the impact of climate extremes on crop production under changing climate effects.

These "best management practices" that contribute to drought adaptation due to climate change, and which support mitigation processes, include appropriate agronomic and genetic tools for crop protection under drought. For example, during drought events, it is important to have planned strategies on how best to (i) utilize available water resources, (ii) scale back on acreage to be planted, (iii) select early maturing and drought-tolerant crop varieties, (iv) select the most effective irrigation practices, and (v) use reduced tillage practices. These strategies are suggested because it has been observed that sustainable agricultural management practices are not widely adopted due to lack of access to resources, knowledge, and practical experiences. In addition, it is necessary to continue our efforts on selecting improved varieties of all crops for better yield and higher quality and expanded cultivation environment to enhance their drought tolerance. It is possible to enhance the drought tolerance limit of a crop by introducing foreign genetic materials that confer added drought tolerance through genetic transformation. This is a recent biotechnological approach that shows much promise (Rejeb et al. 2016).

The aim of this chapter is to provide a critical and comprehensive review of recent studies related to the impact of climate extremes, such as drought, on crop physiology, crop morphology, and crop yields. It will also investigate issues of global food security and available genetic and agronomic tools in addressing drought stress and the protection of crops under drought conditions. Furthermore, this chapter is focused on adaptation strategies to mitigate the effects of drought and to augment crop management for sustainable and climate-smart agriculture. This assessment will provide a technical review of climate-smart agriculture, which may assist farmers and growers to better understand crop needs under changing climate conditions.

Effects of Drought on the Physiological Processes of Crop Plants

Plant growth, physiology, and reproduction are negatively impacted during severe droughts (Fig. 2), which causes substantial decline in crop yields (Yordanov et al. 2000, 2003; Farooq et al. 2009). As shown in Fig. 2, cell elongation in higher plants under drought stress is inhibited by reduced turgor pressure. Reduction in water uptake caused a reduction in tissue water content. Turgor is lost due to a lack of water. Similarly, drought stress also limits the photo assimilation and metabolites which are essential for cell division. Moreover, under drought stress, impaired mitosis, cell elongation, and expansion result in reduced crop growth, leave parameters such as leaf length, and leaf area index (Farooq et al. 2009).

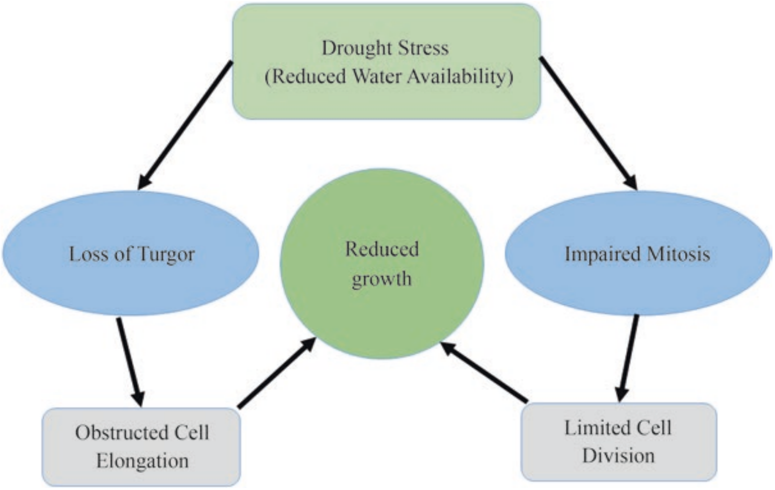

Fig. 2 Description of possible mechanisms of growth reduction under drought stress. (Modified from Farooq et al. 2009)

Harris et al. (2002), in their review, noted that the foremost effect of drought is weak growth and poor stand establishment, and other studies have also indicated that drought has a significant impact on germination as well as seedling stand (Kaya et al. 2006; Farooq et al. 2009). As shown in Fig. 2, plant growth occurs through cell enlargement and cell division, which involves genetic, ecological, physiological, and morphological processes and their complex interactions (Fahad et al. 2017). The quality and quantity of plant growth depend on these processes, and it is important to note that they are significantly affected by water deficit. Under critical water deficiency, cell elongation of higher plants can be reduced by water flow interruption from the xylem to the surrounding elongating cells (Nonami 1998). Plants need nutrients and sufficient water throughout their growth period in order to allow maximum production (Silva et al. 2013), and thus a reduction in water content in the soil intimately affects plant growth and development. As a result of reductions in soil moisture, changes in the physical environment occur, which subsequently affect physiological and biochemical processes in plants (Sarker et al. 2005; Sircelj et al. 2005; Silva et al. 2009; Fathi and Tari 2016). Water is also essential for photosynthesis, respiration, and other physiological and biochemical processes of plant growth (Farooq et al. 2009). Therefore, when there is unavailability or shortage of water, changes inevitably occur in all aspects of plant growth and development.

Physiological parameters include net CO_2 assimilation rate (Pn), transpiration rate (T), stomatal conductance (*g*s), chlorophyll content, leaf water potential (lwp), and water use efficiency (WUE). However, the process of photosynthesis includes all of the physiological parameters in the crop growth cycle, which are also termed “photosynthetic parameters.” A major effect of drought is the reduction of photosynthesis within a plant, which arises from the changes in net CO_2 assimilation rate, transpiration rate, stomatal conductance, chlorophyll content, leaf water potential, water use efficiency, and other factors (Athar and Ashraf 2005). For example, under drought stress, Pn, gs, WUE, T, adenosine triphosphate (ATP), photochemical quenching, and rubisco protein activity are decreased. Conversely, non-photochemical quenching is increased, which ultimately affects photosynthesis and plant growth. In addition, the earliest response to drought is stomatal closure, which decreases photosynthesis but protects the plant from extensive water loss, which might cause cell dehydration and death (Athar and Ashraf 2005; Farooq et al. 2009).

After the stomatal closure, CO_2 levels inside the leaf and transpiration rates start to decrease, which causes an increase in heat (Yokota et al. 2002). In the past, researchers also found that the stomatal response to drought is more closely linked to soil moisture than the leaf water (Farooq et al. 2009). In addition, the rate of stomatal closure is proportional to the rate of increase in drought stress. However, physiological parameters are not controlled by soil moisture availability alone; rather, they are also impacted by other complex interactions among intrinsic and extrinsic factors such as plant traits, phenological strategies, and hydro-climatic drivers (Vico et al. 2017; Farooq et al. 2009).

Plants can respond, adapt, and survive under drought stress by using various drought resistance mechanisms linked to biochemical, morphological, and physiological parameters. Since drought stress affects the plant's water balance and its effects at the cellular, tissue, and organ levels, proper physiological, molecular, and morphological mechanisms are important for drought mitigation. For example, plants may control/limit drought stress by reducing the growing period and maintaining high tissue water potential either by reducing water depletion from plants or improving plant water uptake (Farooq et al. 2009). Osmotic adjustment, osmoprotection, antioxidation, and a scavenging defense system are the essential bases responsible for drought resistance. According to Farooq et al. (2009), cell and tissue water conservation, an antioxidant defense system, cell membrane stability, aquaporins, and stress proteins are important mechanisms for the drought resistance. Moreover, drought stress can also be managed by the production of appropriate genotypes, seed priming, plant growth regulators, and the use of silicon, osmoprotectants, and others.

Effects of Drought on Morphology of Crop Plants

Drought, among other environmental factors, is an important environmental stress that weakens plant growth and development (Shao et al. 2008; Tátrai et al. 2016). Drought stress occurs in plants either when the water supply to roots becomes limited or when evapotranspiration of water from plants becomes very high (Anjum et al. 2017). Plant growth and developmental processes affected by drought include alterations in germination, plant height, stem size, number of leaves and their sizes, flower and fruit productions, root size and distribution, seed development, yield, and quality (Anjum et al. 2017; Jaleel et al. 2007).

The effect of drought on the morphology of plants includes a decrease in stem length, stem diameter, volume of leaves, leaf size, and leaf area and a reduction in plant height (Riaz et al. 2013). For example, Specht et al. (2001) found a reduction in stem diameter of soybean plants, Wu et al. (2008) found a reduction in the height of citrus seedlings under water deficit conditions, and Tangu (2014) found a significant reduction in volume of leaves, leaf size, and leaf area of olive plants under drought stress. Moisture stress induces plant structural changes, which are all critical in responding to drought stress, and it has been commented that a deep rooting system is a "drought avoidance strategy" (Hund et al. 2009). Effective plant drought tolerance includes changes at the tissue and molecular levels and the exposure of the plant to a single occurrence or combination of these basic changes, which determines the ability of the plant to sustain itself under low water content.

While plant growth is supported by mitosis, cell elongation, and differentiation, drought stress can impair mitosis and cell elongation, resulting in poor growth because water is a major component of plant cells and facilitates germination and growth processes. Also, plant growth includes an increase in volume, size, or weight and enhances the process of seed germination, which requires healthy soil, adequate sunlight, and sufficient water. In addition, favorable climatic and hydrologic parameters (e.g., temperatures and soil moisture) also play a significant role in enhancing the process of plant growth (Farooq et al. 2009). Several studies have shown how the negative impacts of drought and heat stress substantially affect seed yields by reducing seed size and number (Fahad et al. 2017; Kaya et al. 2006; Farooq et al. 2009). The quality and quantity of any plant growth depend on the aforementioned events, which can be severely affected by water deficit (Tardieu et al. 2018). A short-term water deficit affects the expansion rate, and this usually happens when crops are irrigated during the dry season (Heuer and Nadler 1995).

Water stress greatly restrains cell expansion and cell growth under low turgor pressure, which also affects the expansion of leaves. Water stress, which shrinks cells, causes a reduction in plant height (Jaleel et al. 2009). Moreover, water-limiting conditions result in impaired cell elongation, mainly because of the poor water flow from the xylem to the nearby cells (Nonami 1998). Reduced turgor pressure and the slow rate of photosynthesis under drought stress greatly limit leaf expansion (Rucker et al. 1995). The volume of leaves for any plant is influenced by water stress, and diminishing longevity and reduction of individual leaf size are affected by the reduction in soil water potential (Anjum et al. 2011). Moreover, water deficit has an adverse effect on crop production and plant growth which is caused by a reduction in fresh and dry biomass production (Zhao et al. 2006). Reduced leaf size is well correlated with drought stress, and indeed many xerophytes have developed small leaves during their adaptation to survive in severe environmental conditions. A small leaf area is advantageous to limit water use in plants and can be responsible for the low productivity of crops (Sinclair and Muchow 2001). They noted that different crops or genotypes behave differently.

Overall, all plants exposed to drought and suffering critical water deficit have significant morphological changes. For example, according to Mangena (2018), water deficit had a significant negative impact on the shoot and root morphology of soybean, including a reduction in the (i) number of new branches, (ii) initiation of leaves and expansion of the lamina, and (iii) number of trifoliate leaves. The reduction in shoot growth and root development caused a reduction in overall crop development and crop yield. Therefore, it is important to have robust agricultural management practices and drought mitigation strategies to minimize the impact of drought on crop morphology.

Effects of Drought on Crop Yields and Global Food Security

Challenges in ending hunger and food insecurity still exist, though extensive discussions have been ongoing to address the major causes of poverty and long-term hunger to reduce human anguish (Tanumihardjo et al. 2007; Haile 2005). The problem of drought onset has continued to receive close attention, given that it represents a key type of extreme climate event (Dai 2011), which causes loss of food production and, consequently, spikes in food prices (Lobell et al. 2011). The threats to global food security caused by climate change are one of the most critical challenges of the twenty-first century. While there is a need to supply adequate food for a growing global population, at the same time, there is also a need to sustain the already stressed environment. Availability of nutritious and quality food is an essential requirement for all humans, and agricultural sustainability is needed to ensure that the food demands of people are met (Brown and Funk 2008).

Although water stress may cause negative effects on overall growth and development of crops, the most significant impact of drought and water stress is a reduction of crop production, which contributes to the diminution of global food supplies (Lesk et al. 2016). Worldwide demand for food is anticipated to double by 2050 because of population growth, dietary change, and bioenergy use (Tilman et al. 2011), and an expected annual rate of yield increase of 2.4% will be necessary to meet this demand with existing farmlands (Fig. 3) (Ray et al. 2013). Meeting the growing need for food demand in the context of global warming requires better understandings of climate change and climatic factors, which influence crop production, and what is most important is to examine how crop yields respond to various climates and extremes. Adequately informed farmers are capable of adapting to the gradual changes in mean climate conditions, but for extreme events, there is a need for a better understanding of the impacts of climate extremes on crop production (Zampieri et al. 2017; Lesk et al. 2016). Drought, like an extreme weather event, will further harm crops and reduce yield (Lesk et al. 2016). Climate change has already caused critical effects on water resources such as irrigation and hydropower production (Beck and Bernauer 2011), food security, and human well-being. This is particularly noted in African countries but is currently beginning to involve the entire world (Magadza 2000).

Drought has aggravated the problem of food production because it is a global climatic threat that simultaneously influences food security (Haile 2005). Evaluating the impact of drought on crop production is difficult because drought itself is driven

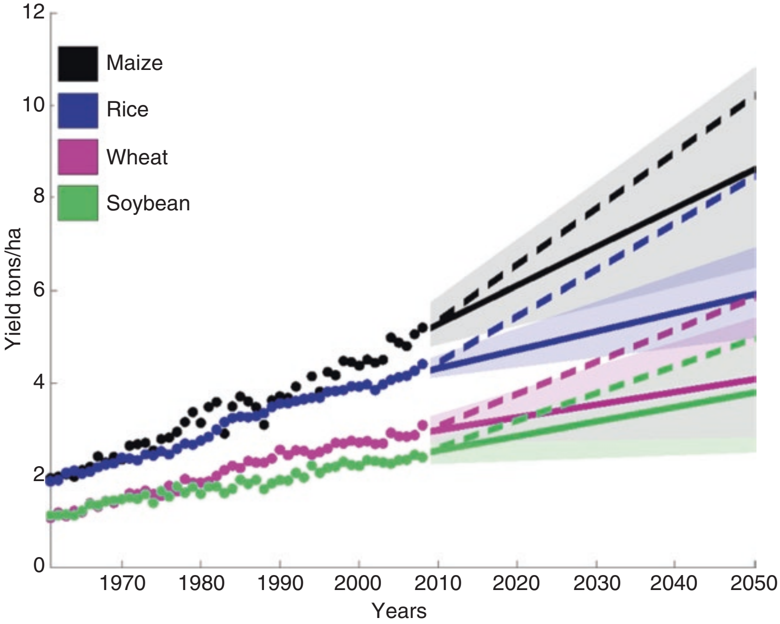

Fig. 3 Global projections: observed area-weighted global yield (1961–2008) shown using closed circles and projections to 2050 using solid lines for four crops (maize, rice, wheat, and soybean). Gray shading shows the 90% confidence region derived from 99 bootstrapped samples. The dashed line shows the trend of the ~2.4% yield improvement required each year to double production in these crops by 2050 without bringing additional land under cultivation starting in the base year of 2008. (Adapted from Ray et al. (2013)

by complex climatic conditions (Leng and Hall 2019). A crop failure during the rainy season is almost a complete agricultural failure, which reduces food availability at the household level as well as limits rural employment opportunities. If climate change acts to reduce crop production and, at the same time, populations increase, there is likely to be increasing hunger.

Agronomic Tools to Protect Crops from Drought

Agronomic tools used to mitigate the effects of drought on crops range from variety selection and the timing of seeding to cultural practices. Cultural practices include tillage and cultivation, crop production systems, mulching, fallowing, nutrient and irrigation management, and use of soil inoculants such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) (Bodner et al. 2015; Creswell and Martin 1998; Parry et al. 2005). In addition, the exogenous application of protectants like glycine betaine and plant growth regulators has been useful for protecting crop plants under drought conditions (Farooq et al. 2009;

Lamaoui et al. 2018; Porcel et al. 2003; Porcel and Ruiz-Lozano 2004; Habibzadeh 2015).

Crop and Variety Selection Crop and variety selections most suited to the planting area are probably the most fundamental decisions to be made for crop production under drought conditions (Ferrante and Mariani 2018). Disregarding its importance has led to several crop failures in the past (Creswell and Martin 1998). Crop and variety selection for drought stress tolerance should be based on the tolerance level of the crop or variety, the time that the crop or variety takes to mature, and the characteristics which favor survival under drought conditions (Creswell and Martin 1998; Idowu et al. 2012). Early maturing crop varieties typically grow and mature before a drought reaches its peak during the growing season, while varieties with short stems with small leaf surface area can reduce transpiration. Similarly, varieties with deep and extensive root systems improve the capture and use of available soil moisture (Creswell and Martin 1998).

Time of Planting It is critical to choose the best time for seeding when cropping under dry conditions, because it helps match water availability to crop demand and optimizes crop establishment and early plant vigor (Bodner et al. 2015). Early sowing is encouraged in dry environments because it can improve the water use efficiency of crops (Brown et al. 1989; Eastham et al. 1999) and can ensure flowering and grain filling (both critical growth stages of crops) which occur during periods of better soil water availability (Herero and Johnson 1981). Early sowing also helps crops to develop deeper roots and avoid early droughts (Barraclough and Leigh 1984; Brown et al. 1989; Incerti and O'Leary 1990). Higher crop yields of wheat, barley, and rapeseed have also been attributed to early sowing in dry climates (Ehlers and Goss 2003; Kirkland and Johnson 2000; Latiri et al. 2010). On the other hand, late sowing could lead to reduced crop yield (Mahdi et al. 1998).

Stand Density Reducing stand density is another agronomic tool often explored for water saving in cropping systems situated in moisture-deficient environments (Bodner et al. 2015). Though this practice tends to (i) lower crop interception of solar radiation, (ii) increase evaporation losses of water and runoff, and (iii) increase weed competition, especially for crops with wide rows, it appears to be very effective at water savings and hence yield optimization under intermittent terminal stress levels (Bodner et al. 2015).

Tillage Practices Tillage practices impact on soil hydraulic properties, including soil hydraulic conductivity, implying that these practices can affect moisture storage in the soil. A review of literature on the influence of tillage on soil hydraulic properties (Bodner et al. 2015) revealed that reduced tillage tends to increase water storage in the soil through higher storage in fine pores in spite of reduced total porosity and macropore volume. They found that this trend applied to similar hydrological regimes and different soil textures. Bodner et al. (2015) reported that saturated hydraulic conductivity (for those which are macropore dependent) showed no unique trend in tillage experiments because the effects of tillage on soil macropores change over time. This suggests that knowledge of temporal variability is necessary for a full understanding of the effects of different tillage practices on soil moisture storage.

Crop Production Systems Polyculture or multiple crop production systems that control erosion, increase water and nutrient retention, and also have a potential to increase yield, should be employed for crop production under dry environments. Examples of these systems include crop rotation and strip cropping. Though crop rotation is typically more commonly practiced in humid regions, it can be useful in dry regions if crop rotations are planned around crop moisture requirements. In the Sahel regions of West Africa and dry regions of India, the inclusion of mulched fallows in crop rotations has significantly helped crop survival and hence healthy stand establishment (Creswell and Martin 1998). Crop rotations in these environments should also focus on selecting crops that help improve soil structure and the addition of organic matter to the soil to minimize soil erosion. These are typical in dry cropping environments (Bodner et al. 2015; Creswell and Martin 1998). Such planning can also maintain and/or improve the nutrient levels of soils in these environments. Strip cropping essentially involves planting crops in alternate strips which are usually planted perpendicular to slopes or the direction of prevailing winds to control erosion problems. Strip cropping also incorporates elements of crop rotation, contour cultivation, and stubble mulching, which are all good farming practices (Creswell and Martin 1998). Hence, the soil water storage potential of this approach is attributable to the combined benefits of all of these advantageous practices.

Fallowing Fallowing involves keeping the land free of vegetation for at least one growing season, with the intention of storing moisture gained from rainfall in the soil for use by a subsequent crop. In the US High Plains, alternating winter wheat with fallows has more than doubled wheat yields (Waldren 2003). Similarly, it is reported that maintaining about 2–2.4 ha of land each year, in summer fallows in India, has helped farmers to almost completely reduce drought-induced famine (Creswell and Martin 1998). It is noteworthy that for a fallow system to be successful, it must maintain high infiltration rates, protect the soil from erosion, and control weeds using good tillage practices that maintain sufficient residue on the soil surface (Waldren 2003; Creswell and Martin 1998). In this regard, the use of less stirring tillage practices, such as tine cultivation, the timing of tillage operations, and proper management of soil surface residues, are paramount.

Mulching and Stubble Tillage This technique involves covering up the soil surface with a protective layer, which may be organic or inorganic. Mulching helps hold moisture in the soil by reducing evaporation and runoff, which protects the soil and enhances its condition for supporting crop growth (Jabran 2019). High amounts of mulch (>50% of total straw produced by a crop field) are required for covering the soil surface, which is one of the demerits of mulches (Bodner et al. 2015; Kálmar et al. 2013). The extent to which mulching reduces evaporation is reported to range up to 28% (Zaongo et al. 1997; Eberbach et al. 2011), while moisture storage by mulched soils is documented to range between 8 and 22% (Kálmar et al. 2013; Jabran et al. 2015; Ramakrishna et al. 2006). Stubble tillage is also aimed at improving soil moisture storage and soil protection. However, it is more of a postharvest measure used during fallow periods between successive crops (Bodner et al. 2015). According to Creswell and Martin (1998), at least one ton of residue cover per hectare is required for stubble tillage to be effective. While they contend that this practice is beneficial with respect to water retention in the soil, other researchers (Kálmar et al. 2013; Unger et al. 1991) have reservations on its effectiveness as a water conserving management practice in semiarid areas.

Nutrient Management Studies have shown that proper nutrient management (at both macro and micro levels) can improve water use efficiency and promote crop yield (Farooq et al. 2017). Notable macronutrients include phosphorus and potassium, while important micronutrients include selenium, silicon, zinc, iron, and boron. Studies have shown that beans and sorghum grown during drought showed increased root growth, stomatal conductance, photosynthesis, membrane stability, and leaf water potential as a result of phosphorus nutrition (Alkaraki et al. 1996). Similarly, an adequate supply of potassium for grain legumes during drought conditions improved their tissue water potential and maintained photosynthesis at expected levels (Sangakkara et al. 2000). While selenium is reported to increase the ability of roots to uptake water under drought conditions (Farooq et al. 2014), silicon addition to drought-stressed plants increased their relative water content through increases in proline and glycine betaine (Hattori et al. 2005). Kurdali et al. (2013) have reported that the application of silicon alone or in combination with potassium to drought-stressed chickpea plants resulted in dry matter yield increases. The exogenous application of silicon has been reported to reduce the effects of drought in wheat and rice (Gong et al. 2005; Gautam et al. 2016). Besides increasing the relative water content of drought-stressed grains, applying zinc and iron can also positively affect their protein and micronutrient contents (Yadavi et al. 2014). Boron, on the other hand, is noted to improve the number and mass of nodules in soybeans grown under drought conditions when supplied through foliar application (Yamagishi and Yamamoto 1994).

Irrigation Since irrigation in cropping systems is not efficient and water wasted in the process is estimated to be over 50% of the amounts applied in some regions of the world (Parry et al. 2005), it is imperative that water use in crop production systems in dry environments is optimized. Water waste typically stems from technical issues associated with the distribution and inadequate maintenance of irrigation systems. This is often compounded by the high evapotranspiration and usually infertile fragile soils in dry environments that are prone to degradation and salinization (Parry et al. 2005; Ramoliya et al. 2004). Efficiency strategies include scheduling irrigation at night to reduce evapotranspiration, limiting overdependence on aquifers, and upgrading traditional irrigation systems to precision types coupled with precision agriculture (Parry et al. 2005). Other options include the use of recycled drainage water and gray water and irrigating crops during only critical growth stages as determined by crop requirements (Abu-Zeid and Hamdy 2002; Oweis et al. 1998; Araus et al. 2002; Parry et al. 2005). Another technique that has some documented success is partial root-zone irrigation or drying in which case irrigation is applied alternately to different sides of the root zone (Santos et al. 2003; de Souza et al. 2003; Loveys and Davies 2004).

Inoculating Soil with Arbuscular Mycorrhizal Fungi (AMF) and Plant Growth-Promoting Rhizobacteria (PGPR) Arbuscular mycorrhizal fungi (AMF) help plants resist drought through many mechanisms. First, they enhance water uptake from the soil through their extensive extra-radical mycelia (Porcel and Ruiz-Lozano 2004; Habibzadeh 2015). Second, AMF increases the antioxidant potential of plants under drought reducing lipid peroxidation in addition to producing more osmoprotectants (Porcel et al. 2003; Porcel and Ruiz-Lozano 2004; Habibzadeh 2015). The mechanisms by which plant growth-promoting rhizobacteria assist with plant drought stress resistance include solubilization of phosphorus, siderophore production, nitrogen fixation, and production of organic acids and plant growth enhancing substance and enzymes such as ACC deaminase, chitinase, and glucanase (Glick et al. 2007; Hayat et al. 2010). A listing of AMF and PGPRs that impact drought resistance in grain legumes is provided by Farooq et al. (2017).

Plant Growth Regulators (PGR) Plant growth regulators such as salicylic acid, cytokinins, and ABA are all reported to be involved in plant drought tolerance (Lamaoui et al. 2018). They help increase water potential and chlorophyll contents of plants under drought stress, which can all lead to crop yield increases (Zhang et al. 2004). In this regard, soybean yield increased when treated exogenously with ABA under drought conditions (Zhang et al. 2004). Transpiration is reported to have been reduced in potted miniature rose (*Rosa hybrida* L.) when applied with ABA in the spring or summer, and this was in addition to extended flower longevity (Monteiro et al. 2001). Foliar application of glycine betaine and salicylic on sunflowers improved their tolerance to drought. However, glycine betaine application was more effective s at the flowering stage (Hussain et al. 2008), suggesting a potential to increase sunflower yield under dry growing conditions.

Genetic Tools to Protect Crops from Drought

Drought is one of the most critical threats to crop production and agriculture in general. Under natural selection, various crop species have evolved to adapt to growth habitats of varying degrees of drought stress and are thus of different drought tolerance or water requirement. Information on general environmental requirements, including water requirements, and specific growth habit of a given crop can be easily obtained from the Ecocrop database,[1] which was established by the Food and Agriculture Organization (FAO) of the United Nations. Ever-continuing efforts on the breeding selection of improved varieties of all crop species for better yield, higher quality, and expanded cultivation environment since their domestication have overall been genetically enhancing their drought tolerance.

Drought tolerance is a complex multigene trait, and its genetic control and physiological mechanisms are yet to be fully understood. However, breeding for improvement of major crops, including wheat, maize, rice, and barley during the last century, has revealed many important characteristics of drought tolerance of these cereal crops responding to various selection practices. These lessons could serve as general guidance for future breeding efforts toward improvement of crop drought tolerance.

Some of these characteristics were illustrated in the generalized yield-versus-drought stress curves in Fig. 4. Of particular importance were the following observations:

1. Selections for yield increase under zero or moderate drought stress have also been successful in improvement of drought tolerance in new genotypes of higher yields (Araus et al. 2002; Slafer et al. 2005; Tambussi et al. 2005). This has been witnessed in rice and wheat (Serraj et al. 2011; Trethowan et al. 2002).
2. The selected higher-yield breed usually has an equal percentage improvement of drought tolerance under varying degrees of stress (Araus et al. 2002), exhibiting a larger yield increase in the absolute term under low drought stress conditions (Slafer et al. 1994).
3. For most crops, the selected higher-yield breed exhibited continued linear year-by-year genetic improvement of yield along with drought tolerance during a post-release multi-year cultivation period, as revealed by studies of grain yield increases in some barley and wheat genotypes commonly grown in the last century (Cattivelli et al. 2008; Slafer et al. 1994).
4. Direct selection for drought tolerance under moderate to severe drought stress has not been as successful in most crops due to polygenic control of the complex trait, epistasis, significant interactions between genotype and environment (G × E), and low heritability of selected traits (Piepho 2000). Therefore, drought tolerance of a crop may not be genetically enhanced without affecting the yield of reproductive organ of the crop. In other words, selection for genetic gains of yield in a crop without drought stress may be far better an approach for improvement of drought tolerance than those under drought stress. In addition, despite many emerging novel genetic and genomics approaches, the traditional breeding selection remains as a major genetic tool for new breeds with improved drought tolerance (Reviewed in Ashraf 2010).

Over the past half-century, research and crop improvement efforts in the area of drought tolerance have greatly furthered our understanding of physiological mecha-

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[1] http://ecocrop.fao.org/ecocrop/srv/en/home

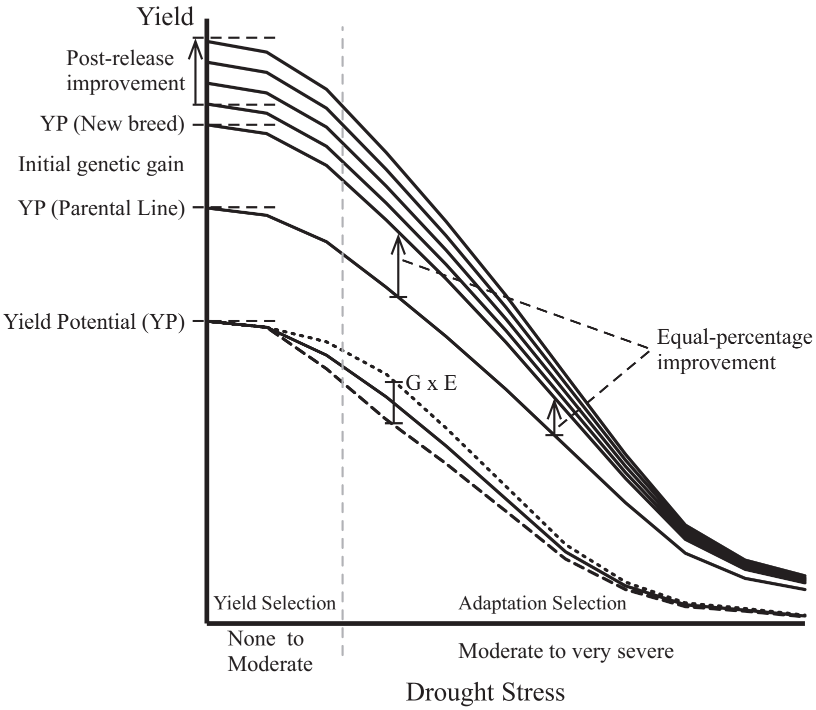

Fig. 4 Graphic illustration of the improvement of crop drought tolerance through breeding. The generalized bottom curves illustrate yield variations of a crop responding to the interaction of genotypes and environment (G × E) under varying degrees of drought stress. The top generalized curves illustrate yield improvement of a new breed grown in the initial release and post-release multiple years, as compared to that of a parental line, under varying degrees of drought stress. (Summarized from Reviews by Golldack et al. 2011; Xoconostle-Cazares et al. 2010; Chaves et al. 2003; Shinozaki and Yamaguchi-Shinozaki 2007)

nisms (Farooq et al. 2009; Golldack et al. 2011; Xoconostle-Cazares et al. 2010) and genetic control (Chaves et al. 2003; Shinozaki and Yamaguchi-Shinozaki 2007) of drought tolerance in various crops. These efforts have also led to the identification of lists of drought-responding physiological traits and tolerance-modulating genes in various crops (Cattivelli et al. 2008), and generated repertories of genetic resources, including genetic maps and transcriptome or genome sequences. Along with this advancement, two new approaches for crop improvement, (i) marker-assisted selection or breeding (MAS or MAB) and (ii) biotechnology involving direct genetic modification of target traits by transformation, have been developed and have been put to use. These two new approaches plus traditional breeding are currently the troika of genetic tools for drought tolerance improvement in all major crops and have generated long lists of new breeds of improved drought tolerance in various crops (Ashraf 2010).

Advancement of crop genomics over the recent decades has provided some new tools, especially molecular markers and genetic mapping methods for crop improvement. These genomics tools have facilitated a more efficient identification of desirable intraspecific genetic variations, including those at drought-stress-responding quantitative loci (QTLs) for drought tolerance. More effective transfers of these variations to generate new breeds of improved drought tolerance with the assistance of their associated molecular markers (i.e., MAB) have been also achieved in many crop species. A list of successful new breeds of improved drought tolerance in several crops was summarized by Ashraf (2010). All these new breeds exhibited increased yields, although the QTLs selected were mostly associated with drought tolerance improvement, mirroring the results from the breeding selection of yield improvement, as summarized in Fig. 4. However, this approach faces a major hurdle, which is the genetic constraint in a crop. Multivariate selections of multiple desirable QTLs in a new breed may not yield desired expression levels for all these quantitative traits, nor have the desired additive effect from the combination of these QTLs, due to the genetic constraint in the crop (Juenger 2013). A crop species that has evolved to adapt to an environment of a certain water availability range may thus be genetically constrained to a drought tolerance limit.

Theoretically, it is possible to enhance the drought tolerance limit of a crop by introducing foreign genetic materials by conferring added drought tolerance through genetic transformation, which is a biotechnological approach. There have been many genetically engineered crop lines with improved drought tolerance conferred by foreign genes expressing organic osmolytes, transcription factors, late embryogenesis proteins, and hormones (Juenger 2013). Nevertheless, it is unclear if the drought tolerance limit of these crops was actually enhanced, or if the improved drought tolerance was simply achieved by a new combination of intraspecific genetic variations through traditional breeding or MAB. Although the biotechnology approach for enhancing crop drought tolerance is a promising new technology (Deikman et al. 2012), it is currently not a cost-effective, nor publicly favorable, approach due to lengthy and costly research and development requirements, strict regulations, and unfavorable customer acceptance to genetically modified organisms.

It is worth mentioning that grafting, which is strictly a nongenetic tool, may be far more cost-effective and is thus still prevalent in the agricultural production of some vegetable and fruit crops. Grafting seedlings of vegetable crops such as some cucurbit species (cucumber, melon, and watermelon) and solanaceous crops (eggplant, pepper, and tomato) to rootstocks (e.g., special breeds of pumpkins), which have a stronger water-uptake capability, can (i) improve the drought tolerance of these crops, (ii) expand their cultivation to otherwise non-cultivable land, and (iii) enhance their tolerance to other abiotic stresses such as low temperature and resistance against some soil diseases such as root rot (Schwarz et al. 2010). The grafting approaches in these crops are not only cost-effective when compared to breeding and biotechnology approaches but are also currently irreplaceable in some crops for combatting certain root diseases, as no natural genetic variations conferring resistance against these diseases have been identified in these crop species (King et al. 2008).

Strategies for Drought Mitigation and Crop Management Under Changing Climate Conditions

Agricultural drought generally results from the deficiency of precipitation over an extended period of time that exacerbates dry conditions and leads to water stress, which causes a reduction in crop growth and development (Solh and van Ginkel 2014). Generally, drought is the result of a combination of below-average precipitation and above-average temperatures, which can be for a short duration (such as 1 week) or can persist across multiple years (McFadden et al. 2019). The potential effects of climate change on crop yield are on the increase, and it is necessary to make farming more resilient to climate extremes like drought. The impact of drought can be reduced through appropriate strategies (drought preparedness and mitigation strategies) and adapting the best agricultural management practices (crop rotation, growing drought-tolerant crops) under the changing climate scenario. Most farmers believe climate change is occurring, and they need to act on it because adaptation strategies at the farm level can contribute to counteracting these adverse climatic effects (Brumbelow and Georgakakos 2001). Building drought resilience to manage the impacts of climate change on human activities is the main responsibility of water managers, either in planning for weather extremities or optimizing long-term resource utilization (Muller 2007).

Drought Mitigation, Preparedness, and Adaptation

A drought mitigation plan is designed to reduce the impacts of drought by identifying the principal activities, groups, or regions most at risk (Wilhite et al. 2000). It is expected that climate change might increase or alter the intensity and frequency of droughts throughout the world in the future (Logar and van den Bergh 2013); thus, in the face of increasing uncertainties on the location, frequency, intensity, and duration of future drought, it is important to have a suite of better preparedness planning schemes, mitigation actions, and response strategies (Cai et al. 2015; Strzepek et al. 2010). It is widely accepted that drought impact can be minimized through preparedness and mitigation approaches. A better drought prediction system could help to mitigate the effects of drought, but although model performance has continued to improve, the general circulation models (GCM) used to predict climate change and associated drought parameters are mixed in their predictions for precipitation and temperature, which affect drought preparedness and mitigation (Cai et al. 2009).

According to Solh and van Ginkel (2014), drought cannot be prevented, but through better preparedness and mitigation actions, it is possible to minimize the impact of drought on crop production, develop more resilient ecosystems, and improve resilient systems to recover from the drought. Preparedness strategies are employed including geographical shift of agricultural systems (e.g., if a certain zone has high aridity, an appropriate cropping system can be adapted), climate-proofed rainfed cropping systems (growing drought-tolerant crops and their varieties), implementing high efficient irrigation system (improving efficiency of irrigation systems), and adapting combined rainfed and irrigated systems (Solh and van Ginkel 2014).

In addition, integrated approaches and strategies for better preparedness, mitigation, and adaptation are necessary to cope with future drought (Fig. 5). Moreover, drought policy should emphasize risk management through the implementation of best preparedness, mitigation, and adaptation (Wilhite 2002). Also, robust and effective monitoring systems, best management practices, and prediction and warning systems further help to reduce the impact of drought on crop production and development. In addition, efficient risk and impact assessment, response, and recovery systems will enhance the approaches to drought mitigation, preparedness, and adaptation strategies, not only during the drought period but also in acting to cope with future drought.

Drought-Resilient Agriculture

Although it is well recognized that drought is one of the major causes of crop yield reductions, limited options are available for farmers to minimize the damaging effects of drought (McFadden et al. 2019). Any mitigation actions that reduce drought risk and vulnerability will definitely increase resilience. For example, dur-

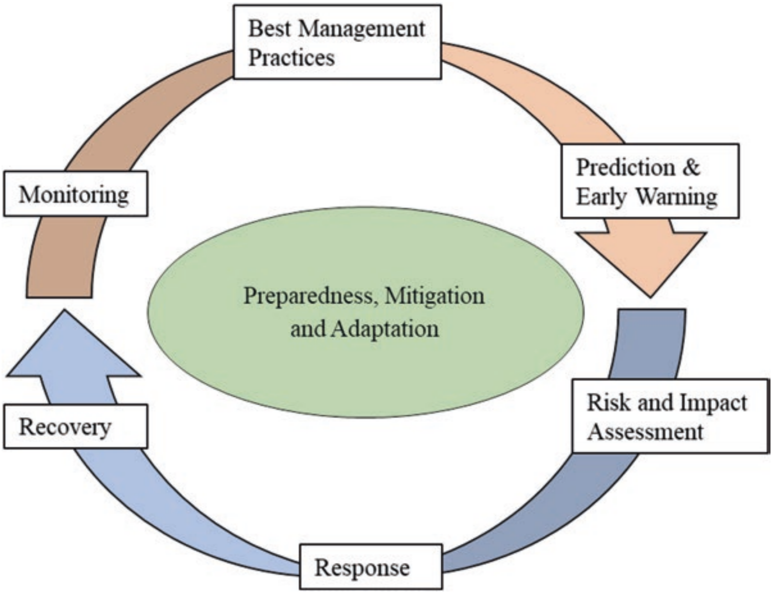

Fig. 5 Cycle of drought preparedness, mitigation, and adaptation

ing drought, it is essential at least to adapt to the best water conservation and crop management practices. For water conservation, farmers and growers have to use an efficient irrigation system, reduce water losses, and use nonconventional water resources for irrigation and plant crops with low water requirements. Similarly, for best crop management, farmers, growers, researchers, and governmental and non-governmental agencies need to work together to develop drought-tolerant crops and their varieties. They also need to reduce tillage and introduce crop rotation, mixed cropping, and cover cropping systems. These measures will lead to the better management of available soil moisture and water resources and reduce the impact of drought/water stress on crop production and development. For example, where residue cover or cover crops are present even under low rainfall conditions, more soil moisture will be available to the crop compared with a bare soil situation. On the other hand, traditional farming accelerates soil moisture loss through reduced ability of the plowed soil to capture, drain, and store rainwater. However, alternatively, using crop residues as covering mulch or mixing mulch into the soil will help to increase soil moisture storage and decrease evaporation from the soil surfaces. In addition, cover crops protect the ground against water loss and improve infiltration and limit water evaporation (Waskiewicz et al. 2016).

Since resilience is the capacity to deal with potential change and recover after the event, it is beneficial for farmers and growers to practice leaving fields fallow for resting and accumulating moisture, which can provide more stability and yield in the long run. In addition, farming practices that make the soil richer in organic matter help to improve the moisture storage capacity of the soil, which ultimately increases biodiversity, making crop production more stable and drought resilient (Tirado and Cotter 2010). Protected cultivation, which includes the use of greenhouses, is an agro-technology, which is becoming highly popular among farmers and growers. It is noted that protected cultivation is a highly efficient way to adapt to drought conditions (Gruda et al. 2019).

Overall, crop rotations, reduced tillage, cover cropping, mulching, adding manure and compost, leaving fallows, and protected cultivation are all proven and available farming practices which not only increase stability and resilience to droughts but also help to climate change mitigation in the long run (Gruda et al. 2019; Tirado and Cotter 2010).

Hence, farmers and growers, along with the governmental and nongovernmental agencies, must employ a variety of drought mitigation and preparedness strategies to enhance drought resilience and reduce the impact of drought on crop production.

Conclusions

This chapter has reviewed the effects of drought on the physiological process of crop plants and has investigated issues of crop morphology, crop yield, and food security, available genetic and agronomic tools, and the best strategies for drought preparedness, mitigation, and adaptation. This comprehensive review has discussed some of the critical issues that need to be addressed to protect crops under drought stress. This chapter implies that to reduce the impact of drought stress on crop development and production, best crop management practices, monitoring mechanisms, drought prediction and early warning systems, effective and timely risk and impact assessment, effective response, and recovery strategies, and appropriate genetic and agronomic tools, may need to be undertaken. In addition, knowledge of the relationship between climate change-induced agricultural drought and crop production will be critical for many decision-makers including farmers, growers, and governmental and nongovernmental agencies; therefore, it would be of utmost importance to implement educational and awareness programs for drought preparedness, mitigation, and adaptation strategies from a local to a global scale.

Climate change predictions suggest that there will be increased frequency and severity of such droughts, which gives an even greater sense of urgency to identify crops that are resilient and can produce under such adverse conditions (Motsa et al. 2015; Modi and Mabhaudhi 2013). It is also recommended to develop a plant hardiness zone map in each region, which helps to understand and select potential crops in a particular location for better management practice under changing climate. For example, information on intra-seasonal variability might be useful to adjust the crop planting season (Cai et al. 2009). To strengthen drought preparedness, mitigation, and adaptation strategies, governments and policymakers should increase their efforts to enhance research works to minimize the impact of climate extremes such as drought on agriculture. An integrated approach to the effects of drought on crop production, crop responses to drought, and potential strategies for drought preparedness, mitigation, and adaptation is necessary to help us better understand crop and drought management under drought stress.

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