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Increased heat and drought stress under climate change and their impact on physiological growth and development of crops: A review

GIRJA SHANKER TIWARI[1], NAVNEET PAREEK[2] and KIRAN P RAVERKAR[3]

G B Pant University of Agricultural and Technology, Pantnagar, Uttarakhand 263 145

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ABSTRACT

Abiotic stresses are major constraints to crop production and food security worldwide, the increasing trend and projection under climate change pose further challenge and warrants close attention of researchers and policy makers. Heat and drought are judged as most common stresses having adverse impact on growth and productivity of the crops. Understanding of the physiological, biochemical, and ecological responses of these stresses is prerequisite to develop management practices. The plant responses to these stresses can be categorized into morphological, physiological, and biochemical responses quantified to assess their impact. Though plants have capability to modify their growth pattern and physiological process to cope with heat and drought stresses but it costs dearly in terms of overall performance and yield, therefore it is a must to understand plant response to various stresses in order to develop suitable adaptation strategies. This review focuses on the plant responses towards heat and drought stresses pointing on the commonalities and differences. Due to physical damages, physiological disruptions, and biochemical changes under limited water supply and elevated temperatures there is negative impact on crop growth and yields. Both conventional and modern approaches are desired to deal with heat and drought stresses. A holistic approach including short term strategy comprising management practices promoting *in-situ* moisture conservation, water harvesting, micro environment modification etc, and long term strategies including developing heat and drought tolerant varieties, developing irrigation infrastructure, permanent change in land configuration, etc are required. The recent government. initiative like PMKSY aiming irrigation to each field (*Har Khet Ko Pani*) through water harvesting, conveyance, drip irrigation in the back drop of time bound target of doubling farmers income will be a big boost to cope heat and drought stress and to induce climatic resilience.

Key words: Climate change, Crop production, Drought, Heat stress, Plant responses, Stress management

The myth of climate change deniers was shaken as 2014, 2015, and 2016 each broke the global surface temperature records. Year 2017 has been declared as second warmest year in recorded history just behind 2016. Evidence of warming is mounting and there is almost unanimous agreement among scientists that tropics will be first and most to bore brunt of climate change even though the magnitude of projected change as well as past climate trend is moderate as compared to other parts of the world (Kumar *et al.* 2017). Poor economic conditions of majority of population, higher dependence on natural resources and ecosystem service and relatively narrow base temperature ranges in the tropics as compared to other part of the world are reason for more suffering. Narrow base temperature ranges means even the small deviation is likely to have significant effect (Martin 2015). Estimated changes in terrestrial metabolic rates in the tropics are large, because of warm base line temperature (Dillon *et al.* 2010). Average global combined temperature of land and ocean surface has increased by 0.85ºC between 1880 and 2012 (IPCC 2014), whereas temperature change between 1950 to July 2017 was about 1°C (Fig 1). An average increase of at least 0.2°C per decade is projected from now onwards.

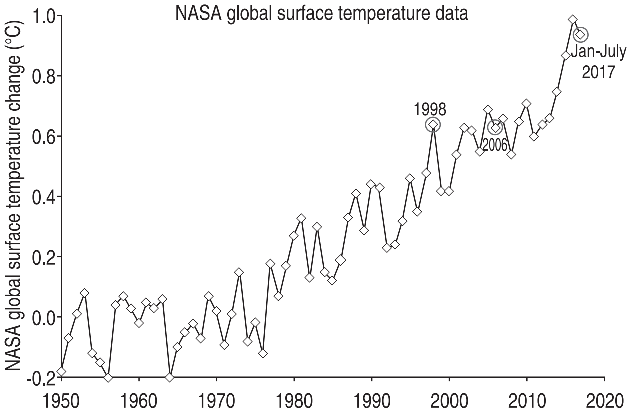

Fig 1 Global surface temperature change between 1950 to 2017.

[1]Ph D Scholar (e mail: tiwarigirjashanker103@gmail.com), [2]Professor (e mail: pareeknav@gmail.com), [3] Professor (e mail: kraverkar@gmail.com), Department of Soil Science.

Table 1 Projected temperature under climate change (IPCC, AR-5-2014)

Temp change	Mean and *likely* range	
	2046-2065	2081-2100
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP6.0	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6-4.8)

The change in terms of temperature and precipitation associated with climate change has never been smooth and likely to be expressed in terms of increased uncertainties and extremities of weather. The frequency of extreme temperature, drought and floods has increased in recent past. Number of heat waves witnessed during last 25 years (1990-2015) in tropics has exceeded the number in preceding 70 years (Kumar *et al*. 2017).

The weather extremities in terms of increased temperature, elongated dry spell and flood induced waterlogging impose stress on annual as well as perennial plants and adversely affect the growth and economic yield. Plants in nature during their life cycle are exposed to a wide variety of favourable and unfavourable abiotic factors including that of heat and drought. The plant and abiotic stress interactions ultimately determines the existence, growth and survival of a species in the ecosystem mode. To maintain its functional and structural integrity, a plant has to be resistant towards unfavourable abiotic factors. Each organism including plant has a unique range of genetically determined characters for physiological resistance, within which a factor affecting is tolerable. If a stress factor surpasses this range, the plant has to trigger additional energy and adjusts physiological–biochemical mechanisms to survive under unfavorable conditions but it costs in terms of overall growth and performance.

No matter, being taken as our food or treated with great commercial significance, plants mean a lot to us therefore it is must to protect, make use of, and most important of all, get on well with plants in the site of their existence as it is unable to escape from the surrounding circumstances. Thus, when they are exposed to extreme stress, their only choice is to try their best to tolerate them.

Environmental stress: Environmental stresses represent the factors which limit agricultural productivity worldwide. These stresses not only have an impact on current crop species, but they are also significant barriers to the introduction of crop plants into areas that are not presently being used for their cultivation. Stresses associated with temperature, salinity and drought, single or in combination are likely to enhance the severity of problems to which plants will be exposed in the coming decades. The stress may be defined according to physiological and ecological requirements of an organism throughout its life-cycle (Chapin 1991) and it is understood as the response of a biological system to extreme environmental factors that, depending on their intensity and duration, may cause significant changes in the system (Godbold 1998).

Stress in relation to plants may be biotic or abiotic. Biotic stress occurs as a result of damage done to plants by living organisms, such as bacteria, viruses, fungi, parasites, beneficial and harmful insects, weeds, and cultivated or native plants. Abiotic stress includes all the non-living environmental factors that can negatively or even harmfully affect the growth and productivity of plants. Some of the common abiotic stresses affecting agricultural productivity are drought, flooding or submergence, salinity, extreme temperatures, wind, light etc. Heat and drought are most common stress and may be considered as typical features of tropical climate. Native vegetation is somewhat attuned to abiotic stress through frequent exposure under natural conditions. However for optimum growth and expected performance plants need special management to help cope with stresses. There are reports suggesting that changed rainfall patterns are responsible for the frequent onset of droughts around the globe (Lobel *et al*. 2011). Severe droughts pose negative impacts on plant growth, physiology, and reproduction which results in substantial decline in crop yields (Yordanov *et al*. 2000, Barnabas *et al*. 2008). Human induced activities are the important factors attributed to climate change

Chemical residues generated from agricultural practices to improve yield also generate stress, which may induce changes in the atmosphere and thereby contribute towards the damaging effect.

Physical attributes of the environment can affect physiological patterns in a positive or a negative manner. For example, a rise in temperature increases enzyme function within a certain range, above which strong inhibition results. The rise in green house gas concentration is a concern as it may keep fuelling global warming much beyond the adaptation limit. Some likely positive effects of increase in CO_2 concentration is projected to be offset by the adverse effect of warming and associated weather extremities and uncertainties. A rise of 30% and 150% in the concentration of the CO_2 and methane has been observed over the past 250 years (Lal 2004, Friedlingstein *et al*. 2010). This review aims at understanding plant responses to heat and drought stress in the backdrop of climate change in order to develop suitable adaptation strategies. Though heat and drought stress rarely operates separately in the field condition, attempt has been made to discuss in separate section for academic understanding.

Heat stress: Globally, wheat production was simulated to decline by 6% for *each degree Celsius* rise in temperature (Asseng *et al.* 2015). This situation is more alarming in non-traditional wheat area like Madhya Pradesh, Gujarat, Rajasthan, and Maharashtra where wheat crop is already underperforming due to heat and moisture stress, as the yield of rainfed wheat is projected to reduce by about 2 q per *degree centigrade* rise in temperature (Kumar *et al.* 2010). However, elevated temperatures are beneficial for crop production in some cooler regions of the world, but overall impact on global food security is still negative (Challinor *et al*. 2014).

A series of morphological, biochemical and physiological changes occur due to high temperature stress which affects growth and development of the plants (Wahid *et al.* 2007). Due to the rising atmospheric temperatures, heat shocks are becoming one of the major detrimental factors to crop productivity around the globe. The growing periods and the distribution of the agricultural crops are greatly affected by the elevating temperature (Porter 2005). Proteins are severely damaged by high temperature stress as temperature increment beyond a limit disturb their synthesis, inactivate major enzymes and damage membranes. Cell division is also affected by heat stress (Smertenko *et al.* 1997). Combining all these damages the growth of the plant is severely affected. Heat stress during the seed filling stage can result in accelerated but shortened filling which finally result in poor quality of grains and reduced yield. Some of the basic responses of crop plants to drought and heat stress along with the management options which can be adopted to minimize the harmful effects of these abiotic stresses are discussed in the following sections.

Effect of heat stress on growth

Excessive radiations and elevated temperatures under the tropical climates are another major limiting factor to plant growth and development. High temperature causes scorching of the leaves and twigs and show symptoms of sunburn, leaves senescence, growth inhibition and discoloration of fruits and leaves (Ismail and Hall 1999, Vollenweider and Gunthardt-Goerg 2005). Increased temperature reduces the germination potential of the seeds and, thus, results in poor germination, seedling growth and stand establishment. Deleterious effects of high temperature on cereal crops vary with the timing, duration, and severity of the heat stress (Fahad *et al.* 2016b). High temperature stress leads to reduced number of spikes and number of florets/plant in rice and negative effect of seed-set in sorghum (Prasad *et al.* 2006, Fahad *et al.* 2016b). Inside the flower, anthers, and pollens are more vulnerable to high temperature than ovules. Under high temperature (>30°C), floret sterility has been correlated with reduced anthesis, poor shedding of pollens, poor germination of pollen grains on the stigma, decreased pollen tubes elongation and reduced the pollen germination (Fahad *et al.* 2016b). Significant reduction in the growth and net assimilation rate (NAR) has been observed in maize and sugarcane (*Saccharum officinarum* L.) under heat stress (Ashraf and Hafeez 2004, Wahid and Close 2007). Under heat stress, Ebrahim *et al.* (1998) noticed a significant reduction in the internodal length and biomass accumulation along with early leaf senescence in sugarcane.

Heat stress and yield

High temperature exposure during the reproductive period can cause substantial reduction in the yield of major cereals. The quality of the final produce in cereals and oilseed crops are also negatively affected by heat stress as it reduces the oil, starch, and protein contents substantially (Wilhelm *et al*. 1999, Maestri *et al.* 2002). Significant reduction in grain weight and total number of grains in wheat due to increased temperatures has been observed by Ferris *et al.* (1998). Fahad *et al.* (2016a) found tillering very sensitive to elevated night temperature in rice, affecting the yield. In the stress free environment, grain weights for a rice cultivar are nearly stable (Mohammed and Tarpley 2010), however, under high night temperature, a decline in individual grain weight resulted in significant reduction in rice grain production per unit area (Fahad *et al.* 2016a). Heat stress also caused substantial yield reductions in common beans (*Phaseolus vulgaris* L.) and peanut (*Arachis hypogaea* L.) (Vara Parasad *et al.* 1999, Rainey and Griffiths 2005). Drought and heat stress causes significant reductions in growth and yield of several important crops; however, the extent of damage depends upon growth stage of the crop and severity of the stress. In general, it was recognized that the reproductive phase is more critical to the stresses causing a considerable reduction in the yield.

Heat stress—water and nutrient relations

When ample quantity of moisture is available, plants try to stabilize their tissue water content irrespective of temperature changes; however, the elevated temperature proves fatal under limited supply of water (Machado and Paulsen 2001). Unfortunately, in tropical and sub-tropical environments, heat stress commonly coincides with water scarcity (Simoes- Araujo *et al.* 2003). At high temperature, rapid reduction in leaf tissue water contents occurred in sugarcane despite of ample quantity of water available in the soil (Wahid and Close 2007). This suggests that heat stress could have a negative impact on the root conductance. Generally, heat stress leads to more water loss during day time mainly due to increased rate of transpiration. Heat stress also affects the number, mass and growth of the roots which ultimately limits the supply of water and nutrients to the above ground parts of the plant (Huang *et al.* 2012).

Direct impact of heat stress on the nutrient relations of crops is less known (Basirirad 2000, Rennenberg *et al.* 2006). The activity of nitrate reductase, an enzyme involved in the nutrient metabolism, is significantly reduced under high temperature stress (Klimenko *et al.* 2006). The reduced nutrient uptake under heat stress might be due to various factors such as reduced root mass and nutrient uptake per unit root area (Basirirad 2000). In a nutshell, drought and heat stresses affect nutrient cycling, uptake and availability to plants by hampering different physiological functions of plants.

Drought stress: Increased transpiration and deficit supply of water to the roots are the conditions favouring drought (Anjum *et al*. 2011). The severity of the damage caused is generally unpredictable as it is caused by various factors including, the rainfall patterns, water holding capacity of the soil, and water losses through evapotranspiration. Drought hampers the growth, nutrient and water relation, photosynthesis, assimilates partitioning and ultimately leads in significant yield loss (Farooq *et al*. 2009, Praba *et al*. 2009). Plant's response to drought stress generally varies from species to species depending on plant growth stage and other environmental factors (Demirevska *et al*. 2009). Major yield reducing factors under limited supply of soil moisture include reduced absorption of photosynthetically active radiations, impaired radiation use efficiency and decreased harvest index (Earl and Davis 2003). Plants modify their growth patterns and physiological processes to cope with the drastic effects of drought stress (Duan *et al*. 2007).

Effect of drought on growth

The initial effects of drought on the plants are poor germination and impaired seedling establishment (Kaya *et al.* 2006, Farooq *et al.* 2009). Reduced germination potential, early seedling growth, root and shoot dry weight, hypocotyl length, and vegetative growth have been observed in different field crops including pea (*Pisum sativum* L.), alfalfa (*Medicago sativa* L.), and rice (*Oryza sativa* L.) under drought stress (Okcu *et al.* 2005, Manikavelu *et al.* 2006, Zeid and Shedeed 2006). Cell division, enlargement, and differentiation are major growth processes in plants. Drought debilitates mitosis and cell elongation which results in poor growth (Hussain *et al.* 2008). Drought leads to loss of turgor which limits the process of cell growth (Taiz and Zeiger 2006). Low supply of water from xylem to the nearby cells results in impaired cell elongation (Nonami 1998). Number and size of leaves are also less under drought conditions. As leaf expansion normally depends upon the turgor pressure and the supply of assimilates, therefore, reduced turgor pressure and slow photosynthesis rate mainly limit the leaf expansion under drought conditions (Rucker *et al*. 1995). Plant fresh and dry matter is also severely reduced under reduced water supply (Zhao *et al*. 2006). Reduced plant height, leaf size, and the stem girth were observed under water stress conditions in maize (Khan *et al*. 2015). Kamara *et al*. (2003) reported reduced biomass accumulation in maize under drought conditions.

Effect of drought on yield

Yield is basically the result of complex association of different physiological processes. Mostly, these physiological processes are negatively affected under drought stress. The negative impacts of drought on yield mainly depend on severity of the stress and the stage of plant growth. Drought imposed at the pre-anthesis stage shortened the time to anthesis while post anthesis drought reduced the period of grain filling in cereals (Estrada-Campuzano *et al.* 2008). Four major enzymes, i.e. sucrose synthase, starch synthase, starch branching enzyme, and adenosine diphosphate glucose pyrophosphorylase control the process of grain filling in cereals (Taiz and Zeiger 2006). Under drought, a decreased activity of these enzymes has been observed which ultimately pose a negative impact on the yield of major cereal (Ahmadi and Baker 2001). Complete sterility of the flowers has been found in pearl millet (*Pennisetum glaucum* L.) due to prolonged exposure to drought during flowering. This may be due to the disturbed assimilate movement to the developing ear (Yadav *et al.* 2004).

Drought induced reduction in yield may also be due to reduced rate of photosynthesis (Flexas *et al.* 2004), disturbed assimilate partitioning (Farooq *et al.* 2009), or poor flag leaf development (Rucker *et al.* 1995). Drought conditions at the tasseling stage resulted in a significant yield loss in maize (Anjum *et al.* 2011). Similarly, a reduced rate in the boll production and abortion of the produced bolls was observed in cotton under drought conditions which ultimately affected the lint yield (Pettigrew 2004). Drought conditions in barley (*Hordeum vulgare* L.) resulted to less number of fertile tillers and grains along with less 1000 grain weight (Samarah 2005). The exposure of pigeon pea (*Cajanus cajan* L.) to drought stress at the flowering stage resulted in over 50% reduction in the seed yield (Nam *et al.* 2001).

Physiological responses—Drought-water and nutrient relations

Leaf water potential, leaf and canopy temperature, transpiration rate, and stomatal conductance are some of the factors which influence water relations. Drought stress disturbs all these factors in plants however, stomatal conductance is affected the most (Farooq *et al.* 2009). Drought conditions lead to reduced leaf water potential and transpiration rate which ultimately increased the leaf and canopy temperature (Turner *et al.* 2001). Water use efficiency, an important feature for plant physiological regulation, is increased under drought stress (Abbate *et al.* 2004). The improved water use efficiency is mainly due to the accumulation of the dry matter by consuming less amount of water due to the closing of stomata and less rate of transpiration. Costa *et al.* (1997) observed reduced water use efficiency in potato (*Solanum tuberosum* L.) when exposed to an early season water shortage which ultimately resulted in poor biomass accumulation and yield.

Nutrient relations of the plants are also influenced by drought stress. Several important nutrients including, nitrogen, silicon, magnesium, and calcium are taken by roots along with water, but drought conditions limit the movement of these nutrients and leads to retarded plant growth (Barber 1995). Less moisture in the soil restricts the growth of the roots and, hence, reduces the uptake of the less mobile nutrients such as phosphorus (Garg 2003). Root–microbe interactions are also disturbed due to drought. The disturbed carbon and oxygen flux to the nodules along with N accumulation under drought stress inhibited N fixing ability of certain legumes (Ladrera *et al.* 2007). Mineral uptake under moisture stress is also influenced and varies among the species. Generally, N uptake is increased and P uptake is declined while potassium remains unaffected under drought conditions.

Heat and drought stress—Photosynthesis

Photosynthesis is very much affected by heat and drought stress (Farooq *et al.* 2009). There is reduced leaf expansion, improper functioning of the photosynthetic machinery and leaf senescence (Wahid *et al.* 2007). Stomata are closed under drought which reduces the CO_2 availability and makes plant more susceptible to photo damage (Lawlor and Cornic 2002). Moisture deficiency induces negative changes in photosynthetic pigments, damages the photosynthetic machinery (Fu and Huang 2001) and disturbs the performance of important enzymes (Monakhova and Chernyadev 2002) which causes considerable damage to plant growth and hampers yield. Heat stress reduces the activity of photosystem II (Camejo *et al.* 2005) and impairs the regeneration capacity of RuBP (Wise *et al*. 2004).

Oxidative damage: a common response to drought and heat stress

Plants exposed to drought stress initially causes oxidative damage by the formation of reactive oxygen species (ROS). These ROS damages lipids and proteins and affects cell functioning. In pea, as observed by Moran *et al*. (1994) the lipid and protein peroxidation was increased by four times under drought stress as compared with normal conditions. These ROS are mainly produced in the chloroplast (Reddy *et al.* 2004) but, reaction of oxygen with the components of electron transport chain in mitochondria also results in the generation of ROS (Moller 2001). Under high temperature stress, production of the ROS has also been reported (Liu and Huang 2000, Wahid *et al.* 2007). Plants usually rely on the antioxidant defence to cope with the oxidative stress. These defence mechanisms may be either enzymatic or non-enzymatic. Enzymatic defence is usually considered as the most effective (Farooq *et al.* 2008). Major enzymes involved in this system are SOD, GR, POD, and CAT (Farooq *et al.* 2009). Carotenoids and glutathione, non-enzymatic components, also play part in the antioxidant system. Under drought induced oxidative damage, an increased content of malondialdehyde has been reported (Moller *et al.* 2007). Therefore, maintenance of the higher levels of the anti-oxidants can be a good strategy by the plants to counter the negative effects of ROS (Sharma and Dubey 2005). Phytohormones are also natural defence molecules in plants which maintain higher levels of the anti-oxidants under stress condition. They help plants to acclimatize to varying environments by mediating growth, development, source/sink transitions, and nutrient allocation (Fahad *et al.* 2015).

Management options

Management strategies developed may be short term and long term. Short term adaptations mainly include the methods which are applied instantly at or before the onset of stress. These include mulching, covering of the canopy area, micro site modification through use of water, management practices including water conservation, harvesting through temporary land configuration. Long term adaptations mainly include the permanent management practices like development of stress tolerant/resistant varieties, development of permanent irrigation infrastructure, induced climate favorable change in land use, change in land configuration for moisture conservation etc. Several cultural practices have been long practised to cope with abiotic stresses; however, the use of the genetic tools for this purpose is relatively recent inclusion. As the climate change induced projected heat and drought stress is persistent in nature, a good amalgamation of long terms and short term management strategy is required. So far main focus of researchers was on the development of high yielding varieties. However, changed climate condition and projection are alarming and compelling reason to develop long term adaptation strategy including development of stress tolerant varieties. Conventional as well as molecular breeding approaches need to be fully explored (Farooq *et al.* 2009). Search for wild relatives and stress tolerant parent lines at the place of origin are one of the alternatives. Overcoming abiotic stresses in crops through crop breeding has proven to be an effective means of increasing food production (Evenson and Gollin 2003). A wider genetic diversity is fundamental for the development of new varieties with good quality and higher yields (Holden and Williams 1984). A quick development of package of practices for the newly developed varieties may be helpful is realizing the actual benefit.

Conclusion and future prospects

Abiotic stresses are major constraints limiting the crop productivity worldwide. These stresses are likely to increase under projected climate change and it is being evidenced by as increase in number of extreme events. Drought and heat are most common stresses associated with climate change and, both often encountered simultaneously and often one is manifestation of other. Plants show a wide range of responses to drought and heat stresses which are mostly depicted by a variety of alterations in the growth and morphology of plants. Although drought and heat stress may cause negative effects on overall growth and development of the plants, reproductive phase is most susceptible as even a mild stress at anthesis or grain filling phase can substantially reduce the crop yield. Other noticeable effects of these stresses are damaged photosynthetic machinery, oxidative damage, and membrane instability. Plants ability to withstand these stresses greatly varies from species to species. Though major achievements have been made in minimizing the negative effects of these abiotic stresses either by adopting the genetic approaches to induce the stress resistance in plant or by suitable adaptation strategies comprising management practices.

Despite of the major advances in the genetic approaches such as QTL mapping and transgenic approaches, there is still a big room for improvement. Adaptation to increasing heat and drought stress warrants holistic approach including improving resistance variety, developing climate favorable management practices and infrastructure. The recent initiative in form of *Prime Minister Krishi Sichai Yojana* (PMKSY) aiming '*Har Khet Ko Pani* through various component including, water harvesting, developing irrigation infrastructure, conveyance, drip irrigation etc will be a big boost in helping crop plants coping with drought and heat stress, thus inducing climate resilience to the production system.

REFERENCES

Abbate P E, Dardanellib J L, Cantareroc M G, Maturanoc M, Melchiorid R J M and Sueroa E E. 2004.Climatic and water availability effects on water-use efficiency in wheat. *Crop Sci* **44:** 474–83.

Ahmadi A and Baker D A. 2001.The effect of water stress on the activities of key regulatory enzymes of the sucrose to starch pathway in wheat. *Plant Growth Regul* **35:** 81–91.

Anjum S A, Wang L C, Farooq M, Hussain M, Xue L L and Zou C M. 2011. Brassinolide application improves the drought tolerance in maize through modulation of enzymatic antioxidants and leaf gas exchange. *J. Agron. Crop Sci* **197:** 177–85.

Ashraf M and Hafeez M. 2004. Thermo tolerance of pearl millet and maize at early growth stages: growth and nutrient relations. *Biol. Plant* **48:** 81–96.

Asseng S, Ewert F, Martre P, Rotter R P, Lobell D B and Cammarano D. 2015. Rising temperatures reduce global wheat production. *Nat. Clim. Chang* **5:** 143–7.

Barber S A. 1995. *Soil Nutrient Bioavailability: A Mechanistic Approach,* 2nd Edn. Wiley, New York.

Barnabas B, Jager, K and Feher A. 2008.The effect of drought and heat stress on reproductive processes in cereals. *Plant Cell Environ* **31:** 11–38.

Basirirad H. 2000. Kinetics of nutrient uptake by roots: responses to global change. *New Phytol* **147:** 155–69.

Camejo D, Rodriguez P, Morales M A, Dellamico J M, Torrecillas A and Alarcon J J. 2005. High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. *J. Plant Physiol* **162:** 281–9.

Challinor A J, Watson J, Lobell D B, Howden S M, Smith D R and Chhetri N. 2014. A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Change* **4:** 287–91.

Chapin F S. III 1991. Effects of multiple stresses on nutrient availability and use. (*In) Response of Plants to Multiple Stresses*, pp 67-880. Mooney H A, Winner W E, and Pell E J). (Eds) Academic Press, San Diego.

Costa L D, Vedove G D, Gianquinto G, Giovanardi R and Peressotti A. 1997. Yield, water use efficiency and nitrogen uptake in potato: influence of drought stress. *Potato Res* **40:** 19–34.

Demirevska K, Zasheva D, Dimitrov R, Simova-Stoilova L, Stamenova M and Feller U. 2009. Drought stress effects on Rubisco in wheat: changes in the Rubisco large subunit. *Acta Physiol Plant* **31:** 1129–38.

Dillon M E, Wang G and Huey R B. 2010 Global metabolic impacts of recent climate warming**.** *Nature* **467**: 704–6.

Duan B, Yang Y, Lu Y, Korpelainen H, Berninger F, Li C. *et al.* 2007. Interactions between drought stress, ABA and genotypes in Piceaasperata. *J Exp Bot* **58:** 3025–36.

Earl H and Davis R F. 2003.Effect of drought stress on leaf and whole canopy radiation use efficiency and yield of maize. *Agron J.* **95:** 688–96.

Ebrahim M K, Zingsheim O, El-Shourbagy M N, Moore P H and Komor E. 1998. Growth and sugar storage in sugarcane grown at temperature below and above optimum. *J Plant Physiol* **153:** 593–602.

Estrada-Campuzano G, Miralles D J and Slafer G A. 2008. Genotypic variability and response to water stress of pre- and post-anthesis phases in triticale. *Eur J Agron* **28:** 171–7.

Evenson R E and Gollin D. 2003 Assessing the Impact of the Green Revolution, 1960 to 2000. *Science* **300:** 758–62.

Fahad S, Bajwa A A, Nazir U, Anjum S A, Farooq A, Zohaib A, Sadia S, Nasim W, Adkins S, Saud S, Ihsan M Z, Alharby H, Wu C, Wang D and Huang J. 2017. Crop production under drought and heat stress: Plant responses and management options. *Front Plant Sci* **8:** 1147.

Fahad S, Hussain S, Matloob A, Khan F A, Khaliq A, Saud S. *et al.* 2015. Phytohormones and plant responses to salinity stress: a review. *Plant Growth Regul* **75:** 391–404.

Fahad S, Hussain S, Saud S, Hassan S, Tanveer M, Ihsan M Z *et al.* 2016a. A combined application of biochar and phosphorus alleviates heat-induced adversities on physiological, agronomical and quality attributes of rice. *Plant Physiol Biochem* **103**: 191–8.

Fahad S, Hussain S, Saud S, Khan F, Hassan S, Amanullah *et al.* 2016b. Exogenously applied plant growth regulators affect heat-stressed rice pollens. *J Agron Crop Sci* **202**: 139–50.

Farooq M, Aziz T, Basra S M A, Cheema M A and Rehman H. 2008. Chilling tolerance in hybrid maize induced by seed priming with salicylic acid. *J Agron Crop Sci* **194**: 161–8.

Farooq M, Wahid A, Kobayashi N, Fujita D and Basra S M A. 2009. Plant drought stress: effects, mechanisms and management. *Agron Sustain Dev* **29**: 185–12.

Ferris R, Ellis R H, Wheeler T R and Hadley P. 1998. Effect of high temperature stress at anthesis on grain yield and biomass of field grown crops of wheat. *Ann Bot* **82**: 631–9.

Flexas J, Bota J, Loreto F, Cornic G and Sharkey T D. 2004. Diffusive and metabolic limitations to photosynthesis under drought and salinity in C3 plants. *Plant Biol* **6**: 269–79.

Friedlingstein P, Houghton R A, Marland G, Hackler J, Boden T A, Conway T J *et al.* 2010. Update on CO_2 emissions. *Nat Geosci* **3**: 811–2.

Fu J and Huang B. 2001.Involvement of antioxidants and lipid peroxidation in the adaptation of two cool-season grasses to localized drought stress. *Environ Exp Bot* **45**: 105–14.

Garg B K. 2003. Nutrient uptake and management under drought: nutrient moisture interaction. *Curr Agric* **27**: 1–8.

Godbold D L. 1998. Stress concepts and forest trees. *Chemosphere* **36**: 859–64.

Holden J H W and Williams J T (Eds). 1984. *Crop Genetic Resources: Conservation and Evaluation.* George Alien and Unwin, London.

Huang B, Rachmilevitch S and Xu J. 2012. Root carbon and protein metabolism associated with heat tolerance. *J Exp Bot* **63**: 3455–65.

Hussain M, Malik M A, Farooq M, Ashraf M Y and Cheema M A. 2008.Improving Drought tolerance by exogenous application of glycinebetaine and salicylic acid in sunflower. *J Agron Crop Sci* **194**: 193–9.

Ismail A M and Hall A E. 1999. Reproductive-stage heat tolerance, leaf membrane thermostability and plant morphology in cowpea. *Crop Sci* **39**: 1762–8.

Kamara A Y, Menkir A, Badu-Apraku B and Ibikunle O. 2003. The influence of drought stress on growth, yield and yield components of selected maize genotypes. *J Agric Sci* **141**: 43–50.

Kaya M D, Okcub G, Ataka M, Cikilic Y and Kolsaricia O. 2006. Seed treatments to overcome salt and drought stress during germination in sunflower (*Helianthus annuus* L.). *Eur J Agron* **24**: 291–5.

Khan M B, Hussain M, Raza A, Farooq S and Jabran K. 2015. Seed priming with $CaCl_2$ and ridge planting for improved drought resistance in maize. *Turk J Agric For* **39**: 193–203.

Klimenko S, Peshkova A and Dorofeev N. 2006. Nitrate reductase activity during heat shock in winter wheat. *J Stress Physiol Biochem* **2**: 50–5.

Kumar G, Kumar A, Nath V, Pandey S D, Kumar V, Purbey S K and Kumar P. 2017. Impact of climate change on litchi systems and its adaptation strategies. *Gyanmanthan, Challenges and options in Litchi Production and Utilization.* **6**: 78–86.

Kumar G, Kurothe R S, Sena D R, Vishwakarma A K, Madhu M, Rao B K, Tripathi K P and Anuranjan. 2010. Sensitivity of wheat crop to the projected climate change in non-traditional areas. *Journal of Agrometeorology* **12**(2): 161–7.

Ladrera R, Marino D, Larrainzar E, Gonzalez E M and Arrese-Igor C. 2007. Reduced carbon availability to bacteroids and elevated ureides in nodules, but not in shoots, are involved in the nitrogen fixation response to early drought in soybean. *Plant Physiol* **145**: 539–46.

Lal R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* **123**: 1–22.

Lawlor D W and Cornic G. 2002. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. *Plant Cell Environ* **25**: 275–94.

Liu X and Huang B. 2000. Heat stress injury in relation to membrane lipid peroxidation in creeping bent grass. *Crop Sci* **40**: 503–10.

Lobell D B, Schlenker W and Costa-Roberts J. 2011. Climate trends and global crop production since 1980. *Science* **333**: 616–20.

Machado S and Paulsen G M. 2001.Combined effects of drought and high temperature on water relations of wheat and sorghum. *Plant Soil* **233**: 179–87.

Maestri E, Klueva N, Perrotta C, Gulli M, Nguyen H T and Marmiroli N. 2002. Molecular genetics of heat tolerance and heat shock proteins in cereals. *Plant Mol Biol* **48**: 667–81.

Manikavelu A, Nadarajan N, Ganesh S K, Gnanamalar R P and Babu R C. 2006. Drought tolerance in rice: morphological and molecular genetic consideration. *Plant Growth Regul* **50**: 121–38.

Martin R. 2015. Climate Change: Why the Tropical Poor Will Suffer Most *https://www.technologyreview.com/s/538586/climate-change-why-the-tropical-poor-will-suffer-most/*

Mohammed A R and Tarpley L. 2010. Effects of high night temperature and spikelet position on yield-related parameters of rice (*Oryza sativa* L.) plants. *Eur J Agron* **33**: 117–23.

Moller I M. 2001. Plant mitochondria and oxidative stress: electron transport, NADPH turnover, and metabolism of reactive oxygen species. *Ann Rev Plant Physiol* **52**: 561–91.

Moller I M, Jensen P E and Hansson A. 2007. Oxidative modifications to cellular components in plants. *Ann Rev Plant Biol* **58**: 459–81.

Monakhova O F and Chernyadev I I. 2002. Protective role of kartolin-4 in wheat plants exposed to soil drought. *App Biochem Microbiol* **38**: 373–80.

Moran J F, Becana M, Iturbe-Ormaetxe I, Frechilla S, Klucas R V and Aparicio-Trejo P. 1994. Drought induces oxidative stress in pea plants. *Planta* **194**: 346–52.

Nam N H, Chauhan Y S and Johansen C. 2001.Effect of timing of drought stress on growth and grain yield of extra-short-duration pigeonpea lines. *J Agric Sci* **136**: 179–89.

Nilsen E T and Orcutt D M.1996. *The Physiology of Plants under Stress*: *Abiotic Factors*. John Wiley & Sons, New York, USA.689 p.

Nonami H. 1998. Plant water relations and control of cell elongation at low water potentials. *J Plant Res* **111**: 373–82.

Okcu G, Kaya M D and Atak M. 2005. Effects of salt and drought stresses on germination and seedling growth of pea (*Pisum sativum* L.). *Turk J Agric For* **29**: 237–42.

Pettigrew W T. 2004. Physiological consequences of moisture deficit stress in cotton. *Crop Sci* **44**: 1265–72.

Porter J R. 2005. Rising temperatures are likely to reduce crop yields. *Nature* **436**: 174.

Praba M L, Cairns J E, Babu R C and Lafitte H R. 2009. Identification of physiological traits underlying cultivar differences in drought tolerance in rice and wheat. *J Agron Crop Sci* **195**: 30–46.

Prasad P V V, Boote K J and Allen L H. 2006. Adverse high temperature on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperature. *Agric For Meteorol* **139**: 237–51.

Rainey K and Griffiths P. 2005. Evaluation of *Phaseolus acutifolius* A. Gray plant introductions under high temperatures in a controlled environment.*Genet Resour Crop Evol* **52**: 117–20.

Reddy A R, Chaitanya K V and Vivekanandan M. 2004. Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. *J Plant Physiol* **161**: 1189–02.

Rennenberg H, Loreto F, Polle A, Brilli F, Fares S, Beniwal R. *et al.* 2006. Physiological responses of forest trees to heat and drought. *Plant Biol* **8**: 556–71.

Rucker K. S, Kvien C K, Holbrook C C and Hook J E. 1995. Identification of peanut genotypes with improved drought avoidance traits. *Peanut Sci* **24**: 14–8.

Samarah N H. 2005. Effects of drought stress on growth and yield of barley. *Agron Sustain Dev* **25**: 145–9.

Sharma P and Dubey R S. 2005. Drought induces oxidative stress and enhances the activities of antioxidant enzyme in growing rice seedling. *Plant Growth Regul* **46**: 209–21.

Simoes-Araujo J L, Rumjanek N G and Margis-Pinheiro M. 2003. Small heat shock proteins genes are differentially expressed in distinct varieties of common bean. *Braz J Plant Physiol* **15**: 33–41.

Smertenko A, Draber P, Viklicky V and Opatrny Z. 1997. Heat stress affects the organization of microtubules and cell division in *Nicotiana tabacum* cells. *Plant Cell Environ* **20**: 1534–42.

Taiz L and Zeiger E. 2006. *Plant Physiology*, 4th Edn. Sinauer Associates Inc Publishers, Sunderland, MA,

Turner N C, Wright G C and Siddique K H M. 2001. Adaptation of grain legumes (pulses) to water-limited environments. *Adv Agron* **71**: 193–31.

Vara Parasad P V, Craufurd P Q and Summerfield R J. 1999. Fruit number in relation to pollen production and viability in groundnut exposed to short episodes of heat stress. *Ann Bot* **84**: 381–6.

Vollenweider P and Gunthardt-Goerg M S. 2005. Diagnosis of abiotic and biotic stress factors using the visible symptoms in foliage. *Environ Pollut* **137**: 455–65.

Wahid A and Close T J. 2007. Expression of dehydrins under heat stress and their relationship with water relations of sugarcane leaves. *Biol Plant* **51**: 104–9.

Wahid A, Gelani S, Ashraf M and Foolad M R. 2007. Heat tolerance in plants: an overview. *Environ Exp Bot* **61**: 199–23.

Wilhelm E P, Mullen R E, Keeling P L and Singletary G W. 1999. Heat stress during grain filling in maize: effects of kernel growth and metabolism. *Crop Sci* **39**: 1733–41.

Wise R R, Olson A J, Schrader S M and Sharkey T D. 2004. Electron transport is the functional limitation of photosynthesis in field-grown Pima cotton plants at high temperature. *Plant Cell Environ* **27**: 717–24.

Yadav R S, Hash C T, Bidinger F R, Devos, K M and Howarth C J. 2004. Genomic regions associated with grain yield and aspects of post flowering drought tolerance in pearl millet across environments and tester background. *Euphytica* **136**: 265–77.

Yordanov I, Velikova V and Tsonev T. 2000. Plant responses to drought, acclimation, and stress tolerance. *Photosynthetica* **38**: 171–86.

Zeid I M and Shedeed Z A. 2006. Response of alfalfa to putrescine treatment under drought stress. *Biol Plant* **50**: 635–40.

Zhao T J, Sun S, Liu Y, Liu J M, Liu Q, Yan Y B. *et al.* 2006. Regulating the drought-responsive element (DRE)-mediated signaling pathway by synergic functions of trans-active and transinactiveDRE binding factors in *Brassica napus*. *J Biol Chem* **281**: 10752–9.