Managing Abiotic Stresses in Wheat

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Abstract

Wheat, a major staple crop of the world as well as of India, provides food and nutritional security to millions of the global populace. While the rate of genetic gain in productivity during the recent years has not been as impressive as in the past, the cultivars under development are being tailored to meet the demand for higher production together with the challenges imposed by several abiotic stresses such as high temperature, restricted access to irrigation water, drought, salinity/alkalinity, waterlogging, mineral deficiency, crop lodging and preharvest sprouting. Since the conventional approaches being practiced for wheat improvement will not be sufficient to achieve the productivity targets, it is essential to integrate the modern approaches leveraged by advances in phenomics, molecular biology, functional genomics, etc. Furthermore, stress mitigation options particularly through agronomic interventions are also essential to stabilize the productivity in wheat. Recent efforts being attempted in this direction have been highlighted in this article.

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14.1 Introduction

Wheat (*Triticum aestivum* L.) is the second most important cereal crop after rice in providing food and nutritional security to the masses in India. Wheat production in India has progressively scaled new heights over the years with phenomenal increase in area, production and productivity. The Indian wheat programme has been very vibrant during the last four decades, but there is no scope for complacency and the programme needs to be more responsive to the new emerging challenges posed by climatic changes. Vulnerability to abiotic stresses is evident from a substantial dip in wheat production to 86.53 million tonnes, due to erratic rains, during 2014–2015 over the high production of 95.85 M tonnes obtained during the previous year 2013–2014. The country produced 93.50 M tonnes of wheat during 2015–2016 crop season.

Wheat is grown in India under six diverse agroclimatic zones, wherein the Indo-Gangetic plains (IGP) comprising the north-western plains zone (NWPZ) and the north-eastern plains zone (NEPZ) are the major wheat tract covering over 20 million hectares, followed by the central zone (CZ) and the peninsular zone (PZ). The northern hills zone (NHZ) and southern hills zone (SHZ) are the two other wheat-producing zones falling in the hills agroecosystem. This classification of zones for wheat cultivation has been based on climatic conditions, soil types and duration of the wheat crop. During the growing season, expected changes in climatic factors, viz. precipitation/winter rains, minimum and maximum temperature, wind velocity and its direction, sunshine hours, etc., need to be considered while developing strategies for enhancement of production and productivity in wheat. It is obvious that any significant change in the climate will have an impact on agriculture and food production. However, realizing the vast variation in the climatic conditions in different wheat-growing regions of India, the ongoing programmes are tuned to address even the micro-niches besides the region-specific needs.

14.2 Abiotic Stresses Affecting Wheat Production

Although more than 95% of the wheat area sown in India has access to irrigation, major parts face water deficits due to restrictions in the quantity of water availability particularly at critical plant growth stages. Wheat grown in the rest of the area is dependent on rains and hence highly vulnerable to water stress which reduces the productivity and production (Fig. 14.1).

The productivity in wheat is most affected by water deficits. The effect of drought on wheat becomes more conspicuous when the south-west monsoon fails to precipitate sufficient soil moisture essential for early establishment of the crop. Drought stress may occur throughout the growing season, early or late in the season. Crop yield is reduced mostly when water stress occurs at heading time, but its effect on yield is highest when it occurs after anthesis. It is evident from restricted irrigation experiments that the grain yield obtained in many wheat cultivars under rainfed condition can be doubled by providing a single post-sown irrigation. Therefore, improvement in drought tolerance ability of wheat genotypes is crucial in view of

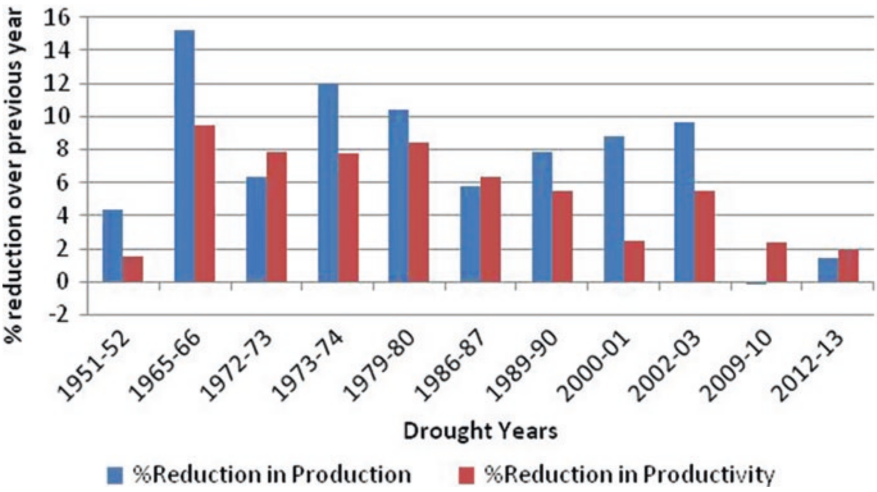

Fig. 14.1 Percent reduction in wheat yield during drought years in India (Based on DOAC data)

the restricted access to irrigation water due to the diversion of more water to nonagricultural uses. Early drought in wheat at seedling establishment stage reduces the number of plants per unit area and tillers per plant; mid-season drought at CRI to ear emergence stage reduces the total biomass, number of productive tillers and grain number per spike; and terminal drought at ear emergence to physiological maturity reduces the current photosynthesis, spike fertility and grain weight. The losses in the present varieties of wheat due to moisture stress in central India can range from 11.6 to 43.6% if no irrigation is provided to the crop (Tiwari et al. 2015).

While the most optimum temperature for growth and development of the wheat plant is considered to be around 21° to 24 °C, the optimal temperature range may vary depending on the prevailing agroclimatic situation at the place where the crop is grown. The whole wheat-cropped area in India experiences heat. While the central and peninsular parts experience heat stress all through the crop season, significant parts of north-western and north-eastern plains experience terminal heat. The trend by farmers in north-western and central India towards early sowing of wheat to take advantage of residual moisture is demanding development of wheat genotypes for both early and terminal heat tolerance (Misra and Varghese 2012).

The temperature often rises above 30 °C during the subsequent stages of its growth, thereby severely affecting the formation and filling of grains (Al-Khatib and Paulsen 1984; Randall and Moss 1990; Stone et al. 1995; Wardlaw and Moncur 1995; Rane et al. 2007). High temperature imposed before anthesis can also decrease yield (Wardlaw et al. 1989; Hunt et al. 1991). Under controlled experiments, grain yield of wheat per spike was reduced by 3–4% per 1 °C increase in temperature above 15 °C. (Wardlaw et al. 1989). The effect of short periods of exposure to high temperatures (>30 °C) is thought to be equivalent to 2–3 °C warming in the seasonal mean temperature (Wheeler et al. 1996). Also yield reduction (up to 23%) has been reported from as little as 4 days of exposure to very high temperatures (Randall and

Moss 1990; Stone and Nicolas 1994). The effect of high temperature is likely to assume much larger proportion considering the current trends and future predictions about global warming continue. According to the fifth assessment report of the Inter-Governmental Panel on Climate Change (2014), the globally averaged combined land and ocean surface temperature data show a warming of 0.85 °C (0.65–1.06) over the period 1880 to 2012, and temperature is projected to rise over the twenty-first century. Besides high temperature, wheat plants also suffer damage due to cold or frost injury when there is a sudden dip in the temperature in northern India and mountainous and sub-mountainous regions of the northern hills zone. However, the loss due to cold or frost injury in these areas is not that severe as high heat conditions.

About 6.73 million ha land in India is salt affected, out of which 3.77 and 2.96 million ha are covered by sodic and saline soils, respectively. The Indo-Gangetic plains include 2.5 million hectares of sodic soils and 2.2 million hectares affected by seepage water from irrigation canals (CSSRI 1997). Salinity- and alkalinity-affected soils lead to reduction in crop yield. The soil where water stands on the surface for a prolonged period of time or the available water fraction in the soil surface layer is at least 20% higher than the field water capacity falls in the category of waterlogged soil. Waterlogging adversely affects production in about 4.5 million hectares in irrigated soils of the Indo-Gangetic plains of northern India (CSSRI 1997). The combined effect of salt and waterlogging stresses significantly reduces wheat yield by causing reduction in grain weight, length of spike and spikelet number and also shows more adverse effect than salt stress alone in the case of compacted soils. Due to the increased frequency of extreme climate events like heavy rains and storms, particularly where water table is high and soils are sodic, waterlogging has become an important constraint to crop production globally.

Preharvest sprouting (PHS) is also of major concern for wheat cultivation in eastern and far- eastern parts of India due to early cessation of rains around maturity time during the month of March. The PHS in wheat is characterized by premature germination of kernels in a mature spike prior to harvest due to early breakage of seed dormancy under moist weather conditions that persist after physiological maturity. PHS causes loss in yield due to decrease in thousand grain weight and also ultimately affects the end product quality. Bread baked from sprouted wheat grain express smaller volume and a compact interior. This decrease in the quality is mainly due to early α-amylase activity which can be characterized by Hagberg falling number. The erratic rainfall patterns in such areas, where temperature and moisture during grain development adversely affect the expression of dormancy, lead to an increase in problems like PHS and call for the development of wheat genotypes with a balanced degree of seed dormancy.

Crop lodging caused by storms and hail is another important factor which severely affects the wheat production. The development of genotypes with good stem structural strength for lodging tolerance is now gaining more attention. As productivity enhancement is targeted in high-fertility environments, genotypes with strong stem strength are needed to sustain under lodging situations. In addition, mineral deficiency is also likely to emerge as a major abiotic constraint in zones under intensive cultivation (Arvind et al. 2015).

14.3 Adaptive Traits Imparting Tolerance

Under natural condition, the plants adapt to abiotic stress condition mainly by three important mechanisms, viz. stress avoidance, stress escape and stress tolerance. These mechanisms are in turn governed by many associated traits. In avoidance mechanism, the plant avoids the stress through such traits like reduction in leaf area, increased pubescence, leaf rolling and leaf reflectance with epicuticular wax accumulation. In escape mechanism, plants sense the future occurrence of stress and adjust the phenology to complete their life cycle early so that the effect of stress is not evident in the genotypes. While, in tolerance mechanism, the plant experiences stress but is able to withstand the stress condition through a number of adaptive features like deep root system, accumulating osmolytes, maintaining membrane integrity and relative water content, etc.

To improve grain yield under stressed environment, it is essential to improve the adaptation to abiotic stresses. Hence, traits contributing to such adaptation are crucial. Observing the plant morphological and anatomical traits such as coleoptile length, leaf phyllotaxy, orientation and angle, pubescence, wax, stem length, peduncle length and root traits vis-à-vis the abiotic stresses helps in underlining the stress tolerance adaptations. The past arguments that empirical selection for grain yield can indirectly place selection pressure for adaptive traits are getting diluted as is evident from recent slowdown in genetic gain in the yield potential of wheat. This necessitates trait based selection for improvement in adaptation to abiotic stresses. It is known that every genotype has different adaptive mechanisms with different associated traits. This can be achieved with the knowledge gained about adaptive traits, feasibility of using them as traits for selection and their inheritance pattern. In spite of new developments in phenotyping techniques, still it is not always true that a single trait will account for all the variations present in the population for tolerance to abiotic stress. Hence, there is a need to develop a protocol which is able to capture numerous traits associated with abiotic stresses.

Water stress mostly leads to stunted plant growth, and leaf wilting is the first visible sign to observe stressed plants. Drought stress reduces the number of days to heading, peduncle length and plant fresh and dry biomass production. The stomatal closure under drought condition to prevent transpirational water loss also limits photosynthesis through limiting CO_2 uptake by leaves (Cornic 2000). Water stress also causes reduction in the relative water content. Although a number of morphological traits and physiological parameters have been put forward for identifying drought-tolerant genotypes of wheat, none of these parameters could become practically feasible for selecting individual plants from the breeding generations. Hence, selection of individual segregants is based on survival under natural drought conditions which in effect may or may not result in improvement in grain yield. Nevertheless, on limited scale, the segregating material can be exposed to artificial moisture stress under controlled conditions to select drought-tolerant and susceptible plants based on seedling survival. Recently, the carbon isotope discrimination (CID) technique has been successfully utilized in identification of drought-tolerant genotypes (Rebetzke et al. 2002).

The magnitude of damage in wheat due to high temperature depends on the background ambient temperature, stage of plant development and the genotype. Extremes of temperature prevailing at sensitive developmental stages are especially detrimental. Temperature above 30 °C around anthesis time can affect pollen formation and reduce yield. For wheat, there are two critical stages that are sensitive to temperature during reproductive growth, viz. the first at micro- or mega-sporogenesis (approximately 12 to 3 days prior to anthesis), leading to loss of fertility, and the second at pollination/fertilization stage leading to decreased levels of pollen shed, pollen reception on stigma, pollen tube growth and fertilization as well as early abortion. It is established that many physiological traits/parameters, viz. grain-filling duration (GFD) and canopy temperature (CT), have a strong correlation with terminal heat tolerance (THT). It is assumed that reduced GFD will avoid the damage due to terminal heat stress, while a low CT will help the plant to withstand terminal heat stress (Sharma et al. 2015). In view of this, both GFD and CT have been used while selecting for higher yield under high temperature at the time of maturity and thus can be effectively utilized for QTL analysis as parameters for terminal heat tolerance.

The abiotic stresses like heat, drought and salt concentration can be quantified by recording some physiological, biochemical and developmental traits in wheat plants as given below.

Early Vigour A greater biomass/plant canopy during early growth stages provides more efficient water utilization by shading the soil and thereby minimizes evapotranspiration from the soil. Thus, retained residual moisture will be utilized by the plants under severe stress condition to survive. Indirectly, early vigour is attributed to a deeper root system. Under abiotic stress condition, early vigour and delayed leaf senescence showed positive correlation with grain yield. Genetic variability exists for early vigour in wheat (Rane et al. 2002), and this trait may be used as a suitable selection criterion under a range of moisture conditions. It can be measured quickly and easily through visual score or using NDVI and can also be used for quick evaluation of large populations.

Osmotic Adjustment (OA) Osmotic adjustment maintains cell water contents by increasing the osmotic force that can be exerted by cells on their surroundings and thus increasing water uptake. OA involves the net accumulation of organic or inorganic solutes/osmolytes, total soluble sugars, total free amino acids, proline, glycinebetaine, sodium, chloride and potassium in cells in response to a fall in the water potential. As a consequence of this net accumulation, the cell osmotic potential is lowered, and turgor pressure tends to be maintained along with more water in leaf cells with greater OA resulting in higher turgor as compared with leaves having less OA. Osmoregulation and turgor maintenance allow continuous growth of roots and uptake of moisture from the soil (Sharp and Davies 1979). Free amino acids and proline accumulation contributed significantly for osmotic adjustment in wheat flag leaves under salinity stress contributing to higher grain yield (Bandeh-hagh et al. 2008).

Relative Water Content (RWC) Assessment of water loss from excised leaves has been indicated as a good criterion for characterizing drought resistance. RWC is related with grain yield under irrigation and dryland conditions. Drought-tolerant genotypes have higher RWC, and this trait can be used for screening and identification of genotypes (Sonia et al. 2015).

Membrane Leakage A major impact of plant environmental stress is cellular membrane modification which results in its abnormal function or total dysfunction. The exact structural and functional modification caused by stress is not fully resolved. However, the cellular membrane dysfunction due to stress is well expressed through increased permeability and leakage of ions, which can be readily measured by the efflux of electrolytes. Hence, the estimation of membrane dysfunction under stress by measuring cellular electrolyte leakage from affected leaf tissue into an aqueous medium is finding growing use as a measure of cell membrane stability (CMS) and as a screen for stress resistance. The CMS is positively associated and explains above 70% of drought tolerance as compared to other physiological traits. The membrane leakage showed negative relation with heat tolerance for 2 consecutive years in a set of spring wheat genotypes under late sown condition (Sharma et al. 2015).

Chlorophyll Content Index Chlorophyll loss is associated with environmental stress, and the variation in total chlorophyll/carotenoids ratio may be a good indicator of stress in plants. High chlorophyll content is a desirable characteristic as it indicates a low degree of photoinhibition of the photosynthetic apparatus. Water stress condition causes reduction in chlorophyll content up to 20%. Hence, the flag leaf chlorophyll content and its stability over time can indicate resilience of the photosynthetic activity.

Canopy Temperature The canopy temperature reflects transpirational cooling efficiency of the plants. The relationship between canopy temperature, air temperature and transpiration is complex, and it involves atmospheric conditions (vapour pressure deficit, air temperature and wind velocity), soil (mainly available soil moisture) and plants (canopy size, canopy architecture and leaf adjustments to water deficit). These variables are considered when canopy temperature is used to develop the crop water stress index (CWSI) which is used for scheduling irrigation in crops (Lopes and Reynolds 2010). It has been shown that bread wheat genotypes with cool canopy temperatures under drought and heat stress have been associated with increased plant access to water as a result of deeper roots.

Chlorophyll Fluorescence The Fv/Fm measurements during drought stress reveal the effects of co-occurring stresses (heat stress, photo inhibition, etc.) or to the early phases of leaf senescence. Measurements of the slow and the fast chlorophyll fluorescence kinetics have been observed to be sensitive to drought stress. The decrease of effective PS-II quantum yield (FPSII) and ETR in drought-stressed leaves as compared to well-hydrated leaves is mainly due to lack of CO_2 inside the leaf caused by stomatal closure. The chlorophyll fluorescence has also exhibited positive correlation with grain yield under terminal heat stress condition (Pandey et al. 2014). Chlorophyll fluorescence tool could reveal that spikes of durum wheat are more tolerant to desiccation in relation to bread wheat (Rane, unpublished).

Pollen Viability The efficiency of pollen transfer and viability of the pollen grains determine the reproductive success in plant species. It has been reported that the viability of pollen grains under field conditions is highly variable indicating that differences in micro-environments may have a profound effect on pollen viability. Drought and heat stresses limit crop pollination by reducing pollen grain production, increasing pollen grain sterility and decreasing pollen grain germination and pollen tube growth (Al-Ghzawi et al. 2009). Drought stress also reduces the megagametophyte fertility and decreases the setting of seed and its development.

Stem Reserve Mobilization Stem reserves are sugars such as fructans, sucrose, glucose and fructose which get accumulated in the stem as reserves. Water soluble carbohydrates (WSC) accumulate up to anthesis time and are partitioned to the stem from where they are later available as a reservoir for remobilization to the developing grains. These reserves are an important source of carbon for grain filling as demand frequently exceeds current assimilation, potentially contributing 10–20% of the grain yield under favourable conditions. Stem reserve mobilization has been shown to be adaptive for drought, heat and/or disease tolerance when current assimilation during grain filling causes a greater demand for stem reserves during grain filling. When wheat plants were shaded during grain filling, up to 0.93 g of grain was produced per gram of assimilates exported from the stem (Kiniry 1993). Genetic variability for stem reserve mobilization exists in wheat, and it can be explored for improvement of productivity under high temperature and water deficit environments (Nagarajan et al. 1998; Rane et al. 2003; Nagarajan and Rane 2002).

14.4 Phenotyping Strategies

Over the past few decades, rapid developments have taken place for phenotyping the tolerance to abiotic stresses. The focus has been mainly on the traits that contribute to plant survival under stress conditions, e.g. root architecture, transpiration efficiency/carbon isotope discrimination, stomatal conductance, canopy temperature, osmotic adjustment, stay green habit, etc. Phenotyping for evaluating the impact of both drought and heat stress conditions in wheat is usually done by comparison with the irrigated condition. For studying heat stress in open fields, late sowing of the crop complemented with recommended number of irrigations is used. The late sowing under irrigated condition enables plants to experience high temperature stress without suffering any drought stress. However, both drought and heat stresses are difficult to be simulated precisely at the field scale. Multilocation testing in the target environments is another option towards phenotyping stresses since they help to obtain response to the stresses under varied natural conditions (Rane et al. 2007). There is lack of screening techniques which are sufficiently rapid, simple, repeatable, not environment dependent with a good predictive value of yield under stress and also applicable in the field. The severity, duration and timing of stress, as well as responses of plants after stress removal and interaction between stress and other factors are extremely and equally important.

Abiotic stresses at a given growth phase are likely to affect the proper development of plant organs leading to a reduction in the yield. The reproductive phase is usually considered to be the most stress-sensitive stage of wheat. Drought causes impaired germination and poor crop stand establishment. Early vigour and rapid ground covering have been proposed as important traits for screening for early drought tolerance. During drought stress, morphological traits including leaf (shape, expansion, area, size, senescence, pubescence, waxiness and cuticle tolerance) and root (dry weight, density and length) are affected. Early maturity, reduced plant height and leaf area are related to the intensity of drought stress. Late onset and/or a slower rate of leaf senescence have an advantage in overcoming water stress. Water stress at pre-anthesis stage reduces the time taken for anthesis, while at post-anthesis stage, it shortens the duration of grain filling. Post-anthesis drought stress is detrimental to grain yield regardless of the severity of stress. Following heading, drought has little impact on the rate of kernel development, but it reduces the weight of grains by shortening the duration of grain development (Jain et al. 2013).

The size of the root system in wheat can be a selection target for drought and heat tolerance. Deeper roots enable plants to explore higher soil volumes and thus remain hydrated under drought and permit cooling of the canopy under heat stress. The evaluation of grain yield performance in areas of frequent stress remains the most widely applied criterion for characterizing adaptation of genotypes under stressful conditions. However, in stress environments, yield *per se* is not always the most suitable selection trait. However, an approach based on evaluation of some physiological traits involved in stress tolerance would be a better option. Thus, increasing grain weight and grain size might be a way worthy to be followed to improve grain yield, especially in case of early water stress which affects mainly spikelet and floret initiation, thereby limiting the grain number per unit area, whereas grain weight is affected by terminal drought. Grain-filling duration under drought and heat stress may be reduced, but it might be partly compensated by a higher grain-filling rate if abundant carbohydrates are available from the leaf photosynthesis or from stem or leaf reserves. The grain-filling rate may be slightly increased, and the duration strongly decreases with heat stress (Garg et al. 2013).

The important target traits which have been used as indicators of stress tolerance include reduced plant height which is associated with high harvest index; reduced number of days to anthesis and maturity which enables the crop to evade terminal

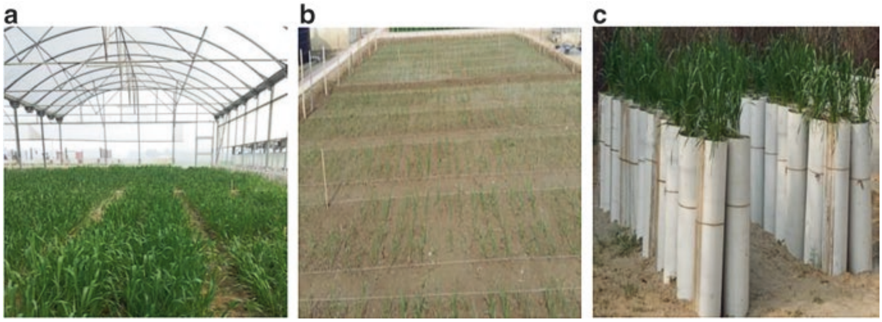

Fig. 14.2 Rainout shelter deployed at IIWBR, Karnal (**a**). Precise phenotyping for drought stress in ROS. (**b**) Screening of genotypes for root traits in large >1.5 m PVC pipes (**c**)

stress; root architectural traits such as even distribution and root length density which enable effective water uptake; seedling traits associated with vigorous seedling establishment such as coleoptile length and early ground cover which reduces evaporative losses; and traits associated with reduced evaporative losses and photo-assimilate production such as leaf rolling, flag leaf persistence, stomatal conductance and canopy temperature. However, these traits should have a positive correlation with yield under stress condition. The ultimate criteria for selection of a genotype should be the capability to integrate its adaptive mechanisms to optimize yield without falling on a single trait. A range of stress tolerance indices including yield, morphological, and physiological traits has been suggested for use in screening wheat genotypes under stress conditions.

14.4.1 Precision Field Phenotyping for Drought Tolerance

The precision phenotyping for drought stress is done under rainout shelter (ROS) to identify the real drought-tolerant wheat genotype. Lack of uniformity of plant stand while conducting a field experiment can substantially contribute to errors in the prediction of association between plant phenotypic traits and the genotypes. Among the several factors that can contribute to experimental errors, inconsistent seed depth and plant spacing often occur due to lack of precision when seeds are sown by hand or seed drills. An improved planting method was devised for sowing of field experiments as well as in ROS. The method involved a tool designed for dibbling seeds and a protocol to place seeds uniformly in the soil (Fig. 14.2) (Sharma et al. 2016). We studied advantage of the new methods over conventional methods of sowing, viz. seed drill and by hand. Compared with conventional methods, the new method improved the consistency in plant spacing and depth substantially as indicated by reduction in standard deviation at least by three times (unpublished). The germplasm accessions and mapping populations for drought tolerance are being evaluated based on root characters, delayed senescence, canopy temperature, chlorophyll content, relative water content, 1000-grain weight and grain yield in comparison to irrigated conditions. The *ex situ* root phenotyping precisely can be done using

Fig. 14.3 Direct root coring to phenotype deep roots

>1.5 m long PVC pipes both under stress and control conditions. The in situ root phenotyping is done by using root corer, extracting the roots, washing the roots and later scanning using root scanner WinRhizo (Fig. 14.3).

14.4.2 Precision Phenotyping for Heat Tolerance

Various attempts have been made to understand traits associated with high temperature tolerance in wheat through experiments conducted both in the field and under controlled environmental facilities. Many of these attempts were not conclusive due to lack of sufficient precision in simulating the ambient temperature dynamics and micro-environments prevailing in the field or due to lack of repeatability of results in the field, often featured by inconsistent exposure of genotypes to desired level of temperature during evaluation. These bottlenecks severely affect the prediction of the relationship between plant phenotype and genes. Hence, we attempted to develop a method for phenotyping wheat genotypes for high temperature tolerance by integrating a novel design of temperature-controlled phenotyping facility (TCPF) as a novel inexpensive tool to ensure uniform crop stand. The novel TCPF has been designed that allows screening of several wheat genotypes in larger plot size (as in the fields) at a desired temperature at any stage of crop growth while allowing plants to grow in the natural environment during the rest of the period (Fig. 14.4).

The size of the structure is approximately 100 ft. by 35 ft. Motorized control units of this unique system allows roofs and walls to slide down to open the structure during initial growth stages allowing the plants to respond according to the prevailing open environment conditions. The structure is closed with the help of sliding roof and windows to seal the whole unit so that the genotypes can be screened at any desired temperature and at any desired crop growth stage. For increasing temperature, a boiler-based heating system is utilized in which warm water runs through a network of pipelines hanging from the roof with several inlets and outlets to avoid formation of temperature gradient from one end to another end in the structure. The temperature regulation in the structure is precise and is linked to ambient temperature so that desired difference between the temperature inside and outside the structure is maintained in relation to the diurnal cycle during the heat stress

Fig. 14.4 Temperature-controlled phenotyping facility

treatment. Cooling is done using split air conditioners integrated and automatically governed by the control panel. Desired humidity level is maintained through mist system that releases fine water droplets, and the desired soil moisture is obtained through drip irrigation system. The structure allows the termination of required temperature stress treatment to expose the crop again to natural environment conditions.

Studies clearly revealed the advantage of the integrated method over conventional methods in differentiating high temperature responses of a large number of genotypes of wheat. The reduction in error and the lowest coefficient of variation (CV) for the plant traits measured in the new method relative to other methods indicated possibility of enhancing precision in phenotyping responses of plants under field condition. The repeatable assessment of plant response to stress in terms of growth, physiology and productivity supported the view that the novel tool developed for ensuring uniform crop establishment and the TCPF together can enhance the precision of phenotyping crop genotypes. There was high consistency in grouping heat tolerant and susceptible wheat genotypes in TCPF as against late sown field screening.

14.4.3 Characterization of Wheat for Waterlogging Tolerance

The problem of waterlogging becomes more acute if the fields are not properly levelled and normal irrigation schedules are followed by unseasonal heavy rainfall. Waterlogging occurring at any growth stage in case of wheat usually causes degradation of chlorophyll in leaves and also protein content in wheat grains. It also decreases the concentrations of nitrogen, phosphorous and potassium in the shoot of wheat plants. Waterlogging also causes reductions in biomass accumulation in both shoot and root and hence affects final grain yield.

14.4.4 Traits for Characterization of Preharvest Sprouting Tolerance

PHS-resistant/PHS-tolerant wheat cultivars and land races have been identified globally, and both red- and white-seeded spring wheat cultivars are known to carry resistance to PHS. There are a number of methods to measure the PHS. The falling number (FN) is most commonly used approach to quantify PHS which indirectly measures the activity of the enzyme α-amylase that breaks down starch in germinating grains. Two other important traits for the characterization of PHS are GI (germination index) and SI (susceptibility index). GI values are deduced from seed germination tests in petri dishes and constitute a direct measure of seed dormancy. The SI values obtained via artificial wetting of intact wheat spikes help in detecting dormancy and properties of the inflorescence that affect PHS (DePauw et al. 2012).

14.5 Genetic Understanding of Traits

The use of selection indices is more efficient than direct selection for grain yield alone, and the relative efficiencies could be better when two or more traits are merged than using each of the single traits independently. Correlation studies also increase the possibility of indirect selection for different traits. High estimates of broad sense heritability for tillers per plant, plant height, spike length, grains per spike, grain yield and 1000-grain weight, root length and shoot length indicate the occurrence of additive gene effects. Among the variability parameters, estimates of PCV were generally higher than that of GCV for most of the traits, indicating thereby the role of environment in total variability. Under stress conditions, tillers m^{-2} and 1000-grains weight have expressed positive correlation with grain yield. Path analysis indicated that 1000-grain weight had the highest direct effect on grain yield followed by tillers m^{-2} under both stress and non-stress conditions. Based on positive direct effect along with positive genotypic correlation with grain yield, 1000-grain weight may be considered to be a suitable selection trait under irrigated and rainfed conditions. Genotypic correlation study showed the importance of tillers and 1000-grain weight under drought stress conditions (Sareen et al. 2014). Grain yield is correlated to biomass and number of fertile tillers per unit area. Significant positive correlations with grain yield were also observed for early as well as late ground cover, dry matter yield and number of fertile tillers per unit area.

The additive-dominance model is inadequate to account for the inheritance of most of the traits and the environmental conditions. Additive, additive x additive and additive x dominance gene effects were higher than the dominance and dominance x dominance gene effects, proving the important role of additive gene effects for most studied traits. Polygenes with mainly additive effects were involved in the control of stem diameter which was also positively correlated under both drought and drought plus heat stress with stem weight and stem density. Stem diameter was significantly associated with 1000-kernel weight and grain yield per spike in three environments. Such strong association of stem diameter with single-grain mass and grain yield per spike under stress indicated the important role this character plays in sustaining grain filling through provision of greater capacity for assimilation in the stem before mobilizing it to grains (Sallam et al. 2014). Early vigour is genetically fixed and positively related to large kernel size. Moreover, physiological traits are prone to variation within a trial and between environments, therefore having only intermediate heritability.

In a study involving diverse wheat germplasm which were screened under alkaline and waterlogged soils in ten environments over 2 years at three locations in India (IIWBR, CSSRI & NDUAT), the performance of genotypes (plant height, tillers, 1000-grains weight and grain yield) over years, conditions and locations was adversely influenced by alkalinity and waterlogging (unpublished). Genotype x environment interaction was evident from the negligible genetic correlation between the grain yields observed at CSSRI and the same at NDUAT under waterlogged conditions for both the years ($r^2 = 0.00–0.01$). However, the pattern of reduction in grain yields of different genotypes due to waterlogging was consistent over the years at same location as evident from the genetic correlation values ($r^2 = 0.80–0.90$ for CSSRI and 0.50 for NDUAT). At NDUAT, where waterlogging resulted in the most severe reduction in grain yield, there was no significant difference in the pattern of genetic variability observed under waterlogged and non-waterlogged conditions indicating that enhanced efforts are needed for genetic improvement of tolerance to waterlogging (Singh et al. 2014).

14.6 Molecular Approaches

It is being realized that the success of molecular markers depends on the phenotyping methods used to characterize the plant responses. This can only be achieved by repeated experiments and increasing replications within the experiments, particularly when the genotypes are evaluated under field condition. This may often be considered an impractical task when a large number of genotypes have to be characterized with conventional methods. There is little or no evidence that a single phenotyping approach, whether conducted in pots, glasshouse or laboratory, is effective for germplasm improvement related to abiotic stresses. Trethowan et al. (2005) and Rebetzke et al. (2014) have strongly advocated the use of field-based screening in environments rigorously controlled for the timing and amount of water availability. Therefore, the importance of accurate phenotyping for drought tolerance has been realized.

The traits associated with improved performance of wheat under drought have complex genetic control with each trait controlled by many genes, each gene having small effect. QTLs in large number have already been reported for several traits associated with drought tolerance including coleoptile length, CID or Δ, water soluble carbohydrates, root system, grain yield and related traits recorded under water stress (Sheoran et al. 2015a, b). Most QTLs for drought tolerance in wheat have been identified through yield and yield component measurements under water-limited conditions. Genetic analysis has led to the identification of two major QTLs for grain yield under water-limited condition, including a QTL each on chromosomes 4AL and 7AL. The QTL on 4AL was co-localized with QTLs for spike density, grains per m^{-2}, grain-filling rate and biomass production (Kirgwi et al. 2007), while QTL for 7A was co-localized with QTLs for grain weight per ear, flag leaf chlorophyll content and flag leaf width (Quarrie et al. 2005). The genome-wide association mapping approach has been applied recently for QTL detection in wheat. Although the development of gene-based molecular markers and genome sequencing in wheat should accelerate positional cloning, the genomic regions associated with individual QTL are still very large and are usually unsuitable for screening in a breeding programme.

Development of functional markers for useful alleles utilizing DREB genes is crucial for crop improvementstrategies. ASM developed for distinguishing drought tolerance in bread wheat (Sareen et al. 2015) was validated in 21 wheat accessions already field phenotyped. Bi-allelic variation with this primer was observed in genotypes IC36761A, IC57586, IC30276A and IC28665. On the basis of drought susceptibility index analysis, linear regression between AS-PCR and the phenotypic traits like GY, TGW and GW was found to be 1.8%, 41.5% and 20.4%, respectively. The highest correlation was observed between SNP and TGW.

Tolerant lines identified would thus lead to higher production and productivity under abiotic stress situations that adversely affect the wheat crop. These lines may also be utilized in hybridization programme for developing next-generation mapping (MAGIC and NAM) populations for identification of fine stress tolerance QTLs. Thus, the strategy involving trait-specific germplasm, precision phenotyping and the selection criteria based upon indices will be rewarding for increasing grain yield in wheat under harsh environments (Pandey et al. 2015).

PHS tolerance is a complex trait, and its genetics needs to be dissected using modern methods of QTL analysis. One facet of this complex trait deals with the balance of plant growth regulators, abscisic acid (ABA), gibberellic acid (GA) and their control to α-amylase enzyme activity. The level of *viviparous-1* (*Vp-1*) gene expression in immature embryos positively regulates ABA sensitivity and promotes seed dormancy (Kumar et al. 2015). Molecular studies for PHS indicated that chromosomes 3A, 3B, 3D and 4A have been considered potential region for PHS tolerance/dormancy. PHS resistance could be improved in spring wheat by pyramiding PHS resistance QTLs from different sources. Furthermore, identification and incorporation of genetic factors underlying resistant genotypes are keys to improve resistance/tolerance to preharvest sprouting in future cultivars (McCaig and DePauw 1992; Flinthan 2000; Mares et al. 2005; DePauw et al. 2012).

Modern plant science is dominated by genomics, and it has tremendous capacity to provide deep insights into the genetic makeup of plants. However, this needs complementation by precise characterization of response of plants to stresses which is now encompassed in the emerging field of phenomics. In addition, other components of *omics* science such as proteomics and metabolomics with bioinformatics as tool for integration of all these sciences are in place for genetic improvement of abiotic stress tolerance. These are equally applicable in important crops like wheat.

14.6.1 Transcriptomics

With the advent of microarray, DNA chip technologies, subtraction libraries, cDNA-AFLP, serial analysis of gene expression (SAGE) and RNA sequencing (RNA-seq), genome-wide transcript profiling has been widely used to identify drought-responsive genes in wheat. Next-generation transcriptome sequencing is also used for analysis of gene expression, the structure of genomic loci and sequence variation present at expressed gene loci. The expression profile of transcription factors involved in abiotic stress has been studied in wheat. The differential contributions of homeologous genes to abiotic stress response in hexaploid wheat on a genome-wide scale have been observed wherein large proportion (68.4%) of wheat homeologous genes exhibited partitioned gene expression in a temporal and stress-specific manner when subjected to heat stress, drought stress and their combination (Liu et al. 2015). Activity of antioxidant enzymes, viz. superoxide dismutase (SOD), ascorbate peroxidase (APX) and catalase (CAT), and the expression of their genes were studied in wheat genotypes under controlled severe drought (Sheoran et al. 2015a, b). The results indicated a unique pattern of activity and gene expression of antioxidant enzymes suggesting existence of genetic variation in drought responses of wheat at molecular and biochemical level.

14.6.2 Proteomics

The key proteins/enzymes and metabolic pathways identified from drought-tolerant wheat lines could be potentially targeted for designing drought-tolerant varieties of wheat. A series of proteomic experiments have been carried out in wheat to elucidate differential stem proteome patterns in two divergent wheat landraces (N49 and N14) under terminal drought stress. The tolerant landrace (N49) was more efficient at remobilizing stem reserves than the sensitive landrace (N14). The maximum number of differentially expressed proteins was noted at 20 days after anthesis in N49 when active remobilization of dry matter was recorded, thus suggesting potential participation of these proteins in efficient stem reserve remobilization (Bazargani et al. 2011).

14.6.3 Metabolomics

Plants react to abiotic stresses by altering the composition and concentration of metabolites so that they can acclimatize to adverse environmental changes.

Metabolic profiling has accelerated discovery of stress signal transduction molecules and compounds that are integral part of plant response to abiotic stresses. To accelerate the trait-based analysis of complex biochemical process, it is necessary to assess metabolic profiling along with NGS techniques, transcriptomics and proteomics underlying cellular biochemical events across diverse conditions. The metabolite profiling of given mapping population can be combined with the genetic linkage makeup maps to obtain greater insights into the genetic map of complex traits, thereby rendering metabolomics particularly relevant to crop breeding. Experiments have identified multiple metabolite QTLs in wheat under drought stress and pinpointed some genomic segments that control both agronomic traits and specific metabolites.

14.6.4 Identification and Validation of Stress-Induced Micro-RNA

Micro-RNAs (miRNAs) are a class of short endogenous non-coding small RNA molecules of about 18–22 nucleotides in length. Computational predictions have raised the number of miRNAs in wheat significantly using an EST-based approach. Hence, a combinatorial approach which is amalgamation of bioinformatics software and PERL script was used to identify new miRNA to add to the growing database of wheat miRNA. Identification of miRNAs was initiated by mining the EST (expressed sequence tags) database available at the National Center for Biotechnology Information. Pandey et al. (2013) investigated that as many as 4677 mature miRNA sequences belonging to 50 miRNA families from different plant species were used to predict miRNA in wheat. These authors further identified five abiotic stress-responsive new miRNAs. Also four previously identified miRNAs, i.e. *Ta-miR1122*, *miR1117*, *Ta-miR1134* and *Ta-miR1133*, were predicted in newly identified EST sequence, and 14 potential target genes were subsequently predicted, most of which seem to encode ubiquitin-carrier protein, serine/threonine protein kinase, 40S ribosomal protein, F-box/kelch-repeat protein and BTB/POZ domain-containing protein, transcription factors which are involved in growth, development, metabolism and stress response. Among the predicted miRNAs, expression of *miR855* in wheat for salt tolerance has been validated (Pandey et al. 2013). The result has increased the number of miRNAs in wheat, which should be useful for further investigation into the biological functions and evolution of miRNAs in wheat and other plant species. In order to understand the differential regulatory mechanism in wheat genotype C-306, expression profile of selected abiotic stress-responsive miRNAs involved in adaption to drought was examined. The drought-stressed C-306 genotype resulted in differential expression of six miRNAs. The accumulation of *miR393*, *miR1029* and *miR172* was significantly higher; however, drought had no major effect on the expression profiling of *miR529* as compared to mock-treated plants. These findings indicate that a diverse set of miRNAs could play an important role in mitigating drought stress responses in wheat. Using NGS, 30 novel miRNAs have been mined and work on further validation of selective drought-specific miRNAs, and their targets are being explored in wheat genotypes exhibiting contrasting responses to drought (unpublished).

14.6.5 Transformation of Abiotic Stress Genes for Imparting Stress Tolerance

Wheat is a less explored cereal crop for the development of transgenics. For the development of transgenic wheat, there is a necessity for having a robust regeneration and transformation protocol. Most of the earlier reported transformation systems are in Chinese spring and Bobwhite genotypes, and they are highly genotype dependent. Hence, at ICAR-IIWBR a robust wheat transformation system was developed in recently released Indian wheat genotypes with a transformation efficiency of 14% (unpublished). The first wheat transformation was reported by Cheng et al. (1997) using marker gene *uidA* through *A. tumefaciens*. The HDR77 wheat variety was transformed with *AtCBF3* gene using particle bombardment method and T_1 plants showed tolerance under moisture stress conditions (Kasirajan et al. 2013). The overexpression of *TaNF-YB4* gene enhanced the grain yield in wheat (Yadav et al. 2015). In the last few years, a number of attempts have been made to generate salt-tolerant genotypes. The *Vigna aconitifolia*_1-pyrroline-5-carboxylate synthetase '*P5CS*' gene-encoding enzyme required for the biosynthesis of proline was delivered into wheat, and the resultant transgenics showed significant salinity tolerance (Sawahel and Hassan 2002). The overexpression of transcription factor *TaNAC69* driven under barley drought-inducible *HvDhn4s* promoter enhanced shoot and root biomass of transgenic lines under combined mild salt stress and drought conditions (Xue et al. 2011).

14.7 Mitigation of Abiotic Stresses

14.7.1 Role of Phytohormones in Stress Amelioration

Hormones play an important role in plant adaptations to adverse environmental conditions. Crosstalk in hormone signalling reflects the ability to integrate different inputs and respond appropriately. There are six main groups of hormones, namely auxin, cytokinin (CK), gibberellic acid (GA), abscisic acid (ABA), ethylene and brassinosteroids.

Among all plant hormones, ABA is the most critical and hence termed as 'stress hormone'. Stress-induced senescence and abscission are the key processes mediated by ABA. Under water deficit conditions, ABA-modified root architecture contributes to the development of deeper root system along with enhancing hydraulic conductivity in plants, maintenance of cell turgor which finally contributes to desiccation tolerance. Other hormones, such as auxin, ethylene and cytokinins (CKs) , may alter the effect and biosynthesis of ABA. Under water and temperature stress, ethylene regulates root growth and development by limiting organ expansion. The higher ABA concentration ingrains might result from autosynthesis within the grain and partly by the translocation from leaves and roots during drying. ABA increases the endogenous content of proline under drought conditions. CKs play a supportive role during water deficit conditions by stimulating osmotic adjustment. Auxin is positively associated, and ABA is negatively correlated with the activity of *expansin* protein under oxidative stress condition. The ability of 28-homo-brassinolide to confer resistance to soil moisture stress in wheat is also established (Sairam 1994).

Hormonal homeostasis, stability, content, biosynthesis and compartmentalization are altered under heat stress. Brassinosteroids are considered as hormones with pleiotropic effects as they influence varied developmental processes like growth, germination of seeds, rhizogenesis, flowering and senescence. Brassinosteroids also confer resistance to plants against various abiotic stresses**.** They increase the tolerance to high temperature in wheat leaves (Seeta-Ram et al. 2002). The tolerance in plants to high temperature due to application of brassinosteroids is associated with the induction of *de novo* polypeptide (heat shock protein) synthesis. In a dwarf wheat variety, high temperature-induced decrease in cytokinin content was found to be responsible for reduced kernel filling and its dry weight (Wilkinson and Davies 2010). The external application of salicylic acid (SA) under field condition alleviates terminal heat stress in wheat (Mamrutha et al. 2015; Ratnakumar et al. 2016).

The ABA concentration increases in different plant parts in response to stress under salinity. ABA acts as the main signalling molecule under salinity stress. Pre-sowing treatment of wheat seeds with growth regulators (IAA, GA) inhibits the effect of salinity. It has been reported that plant growth-stimulating compounds like gibberellic acid, zeatin and ethephon also help to alleviate the impact of salinity (Afzal et al. 2005). It was hypothesized that CKs could increase salt tolerance in wheat plants by interacting with other plant hormones, especially auxins and ABA. Exogenous application of kinetin overcame the effects of salinity stress on the growth of wheat seedlings. Gibberellic acid (GA_4) has been reported to be helpful in enhancing wheat growth under saline conditions (Parasher and Varma 1988). Exogenously applied phytohormones act as bioactivators of carbohydrates and alleviate the salt stress by acting as an osmoregulator. Salicylic acid (SA)-induced resistance of seedlings against salinity was associated with increase in chlorophyll content because SA is linked with the enhanced activity of photosynthetic pigments like Chl*a*, *b* and carotenoids in salt-stressed plant leaves. SA also provides a pool of compatible osmolytes under saline conditions. Exogenous applications of SA enhanced the accumulation of sugars and hence contribute towards yield enhancement in wheat. Proline also plays a supportive role by osmotic modifications along with SA-mediated defence-related role under salinity stress in wheat. SA action against salinity stress includes the development of antistress programmes and acceleration of normalization of growth processes even after the period of stress. SA can protect enzymes like nitrate reductase critical for nitrogen assimilation in wheat (Rane et al. 1995; Ratnakumar et al. 2016).

The plant hormones are of interest to produce shorter (2–15 cm), thicker and stronger stems which reduce lodging mainly by altering plant's biosynthesis GA (chlormequat chloride) or ethylene (ethephon). Changes in internode lignin content accompanied by those in cytokinin, IPA and t-zeatin suggest the role of CKs in the regulation of lignin deposition in wheat under waterlogging condition. The accumulated lignin contributes to mechanical strength/resistance to lodging, tolerance to biotic and abiotic stresses and feedstock quality of wheat straw (Nguyen et al. 2016).

14.7.2 Agronomic Interventions

While genetic improvement is often prioritized for addressing abiotic stresses, the agronomic techniques are also helpful in the management and mitigation of abiotic stresses. Though many of the factors causing stress remain beyond control, these can be alleviated to some extent for obtaining high productivity. Wheat yields in warm environments can be raised significantly by modifying agronomic practices involving conservation agriculture which involves significant reductions in tillage, surface retention of adequate crop residues and adopting diversified and economically viable crop rotations. The main longer-term productivity benefit of conservation agriculture practices comes from its potential to reverse the widespread and chronic soil degradation that threatens yields in the intensive wheat-based cropping systems. Resource-conserving practices like zero tillage (ZT) allow early sowing of wheat after rice harvest so that the crop is able to fill the grains before the hot weather ensues. As average temperatures in the region rise, early sowing will become even more important for wheat (Ortiz-Monasterio et al. 1994).

The agronomic interventions and management options for mitigating various abiotic stresses are briefly discussed hereunder.

Heat Stress Using sprinkler irrigation to cool down the canopy in the afternoon whenever the temperature goes beyond 30 °C improves productivity. For addressing the early heat stress at tillering stage, need-based light irrigation can be applied. In addition, adopting conservation agriculture practices helps in mitigating the temperature stress by moderating temperature variations, conserving soil moisture and improving soil organic matter status. Early sowing or timely sowing of the crop helps in escaping terminal heat stress and also leads to saving water required for pre-sowing irrigation in wheat crop by utilizing the residual moisture available in soil after harvesting the previous crop (Rane et al. 2007).

Drought Stress Scheduling irrigation according to growth stages of crop, use of efficient sowing methods like bed planting, irrigation based on soil moisture status and providing extra irrigation results in higher grain yield by mitigating the effects of moisture stress. Different methods of irrigation like furrow irrigation in furrow-irrigated raised bed (FIRB) planting system, sprinkler and drip irrigation help in efficient management of scarce water resources. These methods can also be utilized to use saline water for irrigation without its deleterious effects on the crop growth and development. Conservation agriculture practices also help significantly by reducing soil surface evaporation, moderating temperature and enhancing water availability for plant uptake, thereby mitigating the moisture stress effects.

Salt Stress Management practices for the safe use of saline water for irrigation comprise the use of land preparation methods for uniform distribution of water and to increase infiltration, leaching and removal of salts; special planting methods to minimize salt accumulation in the vicinity of the seed; irrigation to maintain a high level of soil moisture and periodic leaching of salts in the soil; and special treatments such as tillage and additions of chemical amendments, organic matter and growing green manure crops to maintain soil permeability and tilth. The use of micro-irrigation systems, such as drip and sprinklers, help in better control on salt and water distribution and thus enhance the use efficiency of saline water especially for high value crops. Saline soils are reclaimed by scraping of salts by using mechanical ways; flushing is used in crusting and low permeability soils to wash away the surface salts using good quality water to remove salts, and leaching works well on saline soils having good structure and internal drainage. Leaving crop residue at the soil surface, as in conservation agriculture, helps to reduce soil evaporation losses to decrease the accumulation of surface salts. The alkali/sodic soils are generally reclaimed by leaching of the excess sodium, deep ploughing to incorporate the calcareous subsoil into the topsoil and adding acidifying minerals like pyrite and gypsum.

Waterlogging Adopting conservation agriculture can be beneficial as addition of organic manure improves soil physical factors, reduces soil surface crusting, enhances plant rooting and alleviates the effects of pan formation on yield. Increase in organic content of soil helps in reclaiming problem of waterlogging due to increase in infiltration rate. Bed and furrow system or sprinkler irrigation on soils prone to waterlogging has been shown to reduce the problem significantly. Furrows also help to drain fields or keep a large portion of the root system out of waterlogged soils. It has been observed that adopting conservation agriculture and furrow-irrigated raised-bed planting system also helps to reduce crop lodging.

Nutrient Deficiency/Toxicity The nutrient management options like integrated nutrient management (INM), site-specific nutrient management, enhancing precision in nitrogen application based on NDVI and fertilizer application on the basis of soil test values help in mitigating nutrient deficiencies and toxicity in the soil as well as in plants (Yaduvanshi and Sharma 2008).

14.8 The Way Forward

Tolerance to abiotic stresses is essential to improve the productivity of wheat under harsh environments and reduce food insecurity threatened by climate changes. There are several reports indicating the existence of genetic variation in traits associated with tolerance to abiotic stresses. In this regard it is necessary to characterize the available germplasm and mapping populations for the known traits responsible for providing tolerance to different stresses. Assessment of the level of stress tolerance in popular cultivars not only in terms of yield and its components but also for relevant stress tolerance traits can help in fixing the targets for improvement. However, there is an urgent need for developing a database of screened germplasm and cultivars. The information on reduction in values for the traits in popular cultivars and genetic stocks when grown under optimal and suboptimal conditions in different agroecosystems should also be compiled. The rapid advances being made in genomics have to be utilized for identification of new genes and markers for genetic improvement of wheat for tolerance to drought, high temperature, waterlogging, etc. The already identified genes and markers need to be validated for their suitability in a particular genetic background. Focus is also required towards developing progenies with combination of traits rather than individual traits for different stresses and also towards finding markers so that they can be easily introgressed or tracked in breeding populations. This is essential as the future genetic gain in productivity improvement is likely to emerge from a combination of traits which can be stacked in a desired agronomic background by molecular approaches.

Since agroecologies where wheat is grown are diverse, genotypes adapted to specific locations need to be identified together with agronomic options for mitigation of stress for boosting wheat production in the future. Further, there have been promising results from experiments to identify hormones and bioregulators to alleviate abiotic stresses. The protocols for their use need to be optimized so that they can be integrated in agronomic packages for management of abiotic stresses in wheat. While this can be accomplished by experts in resource management, the desired level of resistance/tolerance to stresses in wheat genotypes can be incorporated through a close linkage between plant breeders and experts undertaking genotyping/phenotyping.

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