



Elemental toxicities – adaptive traits governing waterlogging tolerance in wheat (*Triticum aestivum*) under sodic soils

NEERAJ KULSHRESHTHA*, ASHWANI KUMAR, K R K PRASAD, MONIKA SINGH, RAJESH KUMAR, NIRMALENDU BASAK, N P S YADUVANSHI, P C SHARMA and S K SHARMA

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001, India

Received: 27 April 2018; Accepted: 02 September 2019

ABSTRACT

Wheat (*Triticum aestivum* L.) is one of the most intolerant crops to soil waterlogging, so to evaluate the response of 10 wheat varieties to waterlogging stress under sodic soils, a pot experiment was conducted during 2011-12, 2012-13 and 2014-15 at ICAR-CSSRI, Karnal. Critically important physiological data on increase in element concentrations of Fe, Mn, Al and B in shoots indicated key mechanisms of tolerance under waterlogging condition in sodic soils. Concentrations of Fe, Mn, Al and B in wheat genotypes were greater under waterlogging in normal and sodic conditions. However, uptakes of these elements also varied. Mean concentrations of 327, 434, 541 and 624 mg/kg for Fe; 38.3, 48.9, 48.4 and 72.9 mg/kg for Mn; 47, 147, 217 and 226 mg/kg for Al and 5, 22, 48 and 51 mg/kg for B were recorded in pH 8.2, pH 8.2 +WL, pH 9.4 and pH 9.4 +WL treatments, respectively. Besides Mn, the elements concentration in wheat was 3-6 times greater than critical limit for the above mentioned elements. Genotype HD 2189, was the best performer and showed minimum increase in shoot Fe, Mn, Al and B concentration both under higher pH and waterlogging, whereas Brookton showed maximum increase. KRL 3-4 performed better despite high Fe and Mn indicating higher tissue tolerance. These observations point towards identification of considerable genetic diversity for Fe, Mn, Al and B in wheat.

Key words: Elemental toxicity, Sodicty, Waterlogging, Wheat

Waterlogging adversely affects 10-15 million ha of wheat production annually on a global level (Sayre *et al.* 1994). India has an area of 6.73 million ha with salt-affected soils (Singh and Sharma 2015). In the Indo-Gangetic plains of northern India, 2.5 million ha of sodic soils planted with wheat may experience saturated or temporary waterlogging conditions due to unseasonal rainfall in every year (Sharma and Swarup 1988). Such problems become more acute when the cultivated fields are not leveled or irrigation is followed by unprecedented or excess rain (Gill *et al.* 1992). The adverse effects of waterlogging on plants are due to reduced aeration and accumulation of phyto-toxins (Armstrong and Armstrong 2001). Oxygen deficiency inhibits plant respiration, resulting in severe energy deficiency and subsequently death (Greenway and Gibbs 2003).

Waterlogging tolerance is a complex trait that could affect many morphological and physiological traits. In addition, waterlogging leads to a significant increase in the availability of nutrients (Poonamperuma 1972, 1984; Lobo and Joly 1998), e.g. iron (Fe) and manganese (Mn). Increase in concentration of these micronutrients in soil and subsequently in shoots may affect crop due to waterlogging.

There is now increasing evidence of elemental toxicities affecting plants in soils during waterlogging. Elemental accumulation particularly Fe, Mn, Al and B is the one of the most pronounced adaptive trait associated with waterlogging tolerance and the findings of tolerance against waterlogging along with elemental accumulation across the available genotypes highlight tremendous opportunities for wheat improvement programmes. Keeping this in view, an experiment was conducted to evaluate the response of 10 wheat varieties to waterlogging stress under sodic soils.

MATERIALS AND METHODS

A pot experiment was conducted at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, India during 2011-12, 2012-13 and 2013-14 to evaluate the response of wheat genotypes under waterlogging conditions. Ten wheat (*Triticum aestivum* L.) genotypes, viz. HD 2189, KRL 19, NW 1014, Schomburgk, BT-Schomburgk, HD 2009, Ducula 4, HD 2329, Brookton and KRL 3-4 were grown in 20 kg pots filled with normal soil (pH 8.2) and sodic soil (pH 9.4) with or without waterlogging. Ten seeds per pots were sown in the month of November having appropriate temperature and sunlight for plants grown under natural conditions. Waterlogging treatments were imposed after 25 days of sowing by saturating soils in each pot with

*Corresponding author e-mail: Kulshreshthan@yahoo.co.in

water (5 cm above the soil surface). Five replicated pots were used for each genotype as control (pH 8.2), control + waterlogging, sodic (pH 9.4) and sodic + waterlogging treatments. Plants were waterlogged for 10 days. Redox potential (Eh) was determined in the wet soils from the day after the imposition of treatments and during the recovery periods. Electrodes were inserted vertically into the soils, and measurements were taken at a depth of 5 cm. Plant samples were collected after 10 days of recovery and analyzed following di-acid (HNO_3 ; $HClO_4$) digestion using ICP (Inductive Coupled Plasma Emission, SHI ICPE 9000 Shimadzu) for elemental analyses (Fe, Mn, Al and B). The data were analyzed statistically using randomized block design and the significance was tested at 5% level of critical difference using 'ANOVA'.

RESULTS AND DISCUSSION

Waterlogging limited wheat yield in all the genotypes and greater reductions were observed in sodic soils and waterlogged sodic soils. However, the reduction varied among the genotypes which might be due to the different tolerance mechanisms against waterlogging. Applied stress of waterlogging with sodicity caused significant reduction in the biomass and grain weight in all the wheat genotypes relative to control. Phenotypic performance of KRL 3-4, BT-Schomburgk and HD 2189 was better than other varieties under waterlogging (Fig 1). In normal soil, maximum reduction in grain weight due to waterlogging

was observed in Brookton (59.6%) followed by HD 2009 (55.0%) and Schomburgk (52.8%), whereas minimum reduction was observed for KRL 3-4 (29.7%) followed by HD 2189 (30.9%) and BT-Schomburgk (32.7%). Maximum reduction in grain yield was observed in sodic waterlogged soil. It might be due to poor aeration for root respiration under waterlogging. Our results also are in line with earlier findings (Sharma and Swarup 1988, Setters and Waters 2003, Setter *et al.* 2008, Sharma *et al.* 2018). Yield declined due to waterlogging are associated with reduced production and limited survival of tillers, few and small fertile tillers, and small grain size (Sharma and Swarup 1988, Condom and Giunta 2003). Sayre *et al.* (1994) also described that there is usually a strong correlation between the total above ground biomass and grain yield in waterlogging treatments. Further, excess water caused a sharp decrease in soil redox potential, resulting in very significant changes to the elemental profile (Marschner 1991). Waterlogging causes oxygen deficiency and prevents root and shoot growth, reduces the accumulation of dry matter and results in failure of yield (Sharma and Swarup 1988).

Uptake of both manganese and iron increased due to soil waterlogging, although re-oxidation of the soil affected iron more than manganese (Iu *et al.* 1982). These results are in conformity with the findings of Khabaz-Saberi *et al.* (2006) who reported increase in shoot Al, Mn, Fe and Na above toxicity concentrations when wheat was grown under waterlogged conditions (49 d) in acidic soil. Under



Fig 1 Impact of waterlogging after recovery period under normal (pH 8.2) and sodic (pH 9.4) soils on Ducula-4, KRL 3-4, HD 2009 and HD 2189 genotypes.

waterlogging, oxidized forms Fe^{3+} and Mn^{4+} convert to reduced forms Fe^{2+} and Mn^{2+} (Samad *et al.* 2001, Steffens *et al.* 2005, Bailey-Serres and Voesenek 2008), leading to an increase in concentration of Fe and Mn beyond the plant nutritional requirements, which results in poor plant growth and performance. Importantly, genotypes showing superior Mn and Fe tolerance under drained conditions tolerated waterlogging much better, outperforming intolerant genotypes by 30–50% (Khabaz-Saberi and Rengel 2010).

Iron concentration in all the wheat genotypes significantly raised under waterlogging. Mean concentrations of 327, 434, 541 and 624 mg/kg were observed for Fe in pH 8.2, pH 8.2 + WL, pH 9.4 and pH 9.4 + WL treatments, respectively. Iron concentration varied among different wheat genotypes. KRL 3-4 accumulated the highest and HD 2189 the lowest Fe concentration in leaf tissues among all the genotypes across all the treatments. Iron in shoot are 3-6 times greater than the critical concentrations (>100 mg/kg) for toxicity (Khabaz-Saberi and Rengel 2010). Per cent increase in Fe concentration observed over the control was the highest in Brookton (72.7) and the lowest in NW 1014 (26.2). Element toxicities were pronounced in the leaves subjected to waterlogging for 10 d at pH 8.2 and 9.4. Element toxicity continued even following drainage after WL (recovery period of 10 days). Concentrations of elements (Fe, Mn, Al and B) increased with increase in pH from 8.2 to 9.4 and waterlogging in all the genotypes. Significant increase in concentration of Mn occurred in waterlogged vs. control treatment in all the genotypes except HD 2189 and HD 2329, which showed 17.2 and 33.3% reduction at pH 8.2 + WL. Mean values of 38.3, 48.9, 48.4 and 72.9 mg/kg were recorded at pH 8.2, pH 8.2 + WL, pH 9.4 and pH 9.4 + WL treatments, respectively. KRL 3-4 and Brookton showed the highest accumulation of Mn concentration (113 and 117 mg/kg) while HD 2189 and HD 2329 showed the lowest accumulation (49 and 51 mg/kg) at pH 9.4 + WL and the values for the later cases were below the critical concentrations for toxicity (>100 mg/kg shoot dry weight) (Reuter *et al.* 1997, Singh and Rao 1995). It was found that per cent increase in concentration was

29.4 (HD 2329) to 72.6 (Brookton). Wheat is an intolerant crop to soil waterlogging and the plants that are intolerant to waterlogging may suffer from Fe or Mn toxicity (Horst 1988). Plants such as wheat and barley are not able to oxidize Fe and Mn so toxicity of Mn and Fe may occur under waterlogged conditions (Drew 1988).

Similar mean values were observed for Al, *i.e.* 47, 147, 217 and 226 mg/kg, respectively. These were 3-4 fold greater than the critical concentrations (>50 mg/kg) for toxicity (Ma *et al.* 2003). Results presented in Fig 2, showed HD 2189, accumulated minimum, and Brookton and KRL 19 genotypes accumulated maximum Al concentration at pH 9.4 and waterlogging treatments. A marked increase (4-5 fold) in shoot B concentration was observed over the control and the mean concentrations of 5, 22, 48 and 51 mg/kg were observed for B at pH 8.2, pH 8.2 + WL, pH 9.4 and pH 9.4 + WL treatments, respectively (Fig 3). Critical concentration for B toxicities in wheat shoots was >10–20 mg/kg (Mortveld 1972, Ascher-Ellis *et al.* 2001). The highest B uptake was found in the shoot tissues of Schomburgk and Brookton (71 and 80 mg/kg) and the lowest uptake was in HD 2189 (20 mg/kg).

Varietal variation in concentrations of Fe, Mn, Al and B in shoots was observed in waterlogged sodic soil compared with normal soil indicating considerable genetic diversity for these elements in sodic soils in wheat. The observed increases in elements seem to have serious implications for plants growing in sodic soils, when exposed to waterlogging. Plants continue to be exposed to toxic concentrations even after standing water is drained off after 10 days of waterlogging treatment and are recovering from the effects of waterlogging. These effects are probably the result of reduced energy status of roots under waterlogging and the partial loss of root selective permeability and exclusion and accompanied by reduced redox potential of soil which aggravated the toxicity (Setter *et al.* 2008, Khabaz-Saberi *et al.* 2006, Khabaz-Saberi and Rengel 2010, Sharma *et al.* 2018).

This study revealed that genotypes grown under waterlogging in normal and sodic soils induced Fe, Mn, Al

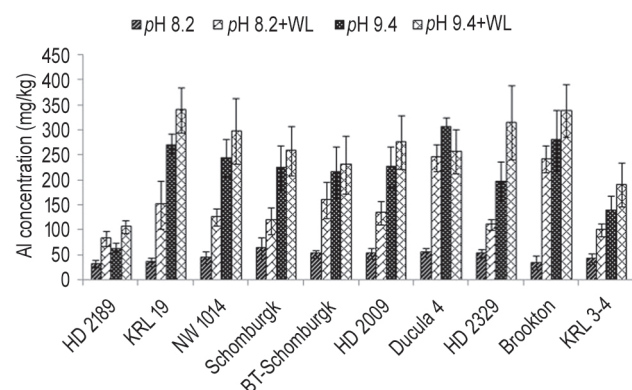


Fig 2 Aluminum concentration (mg/kg) in shoot tissues of wheat genotypes grown in normal and sodic soil subjected to waterlogging for 10 days.

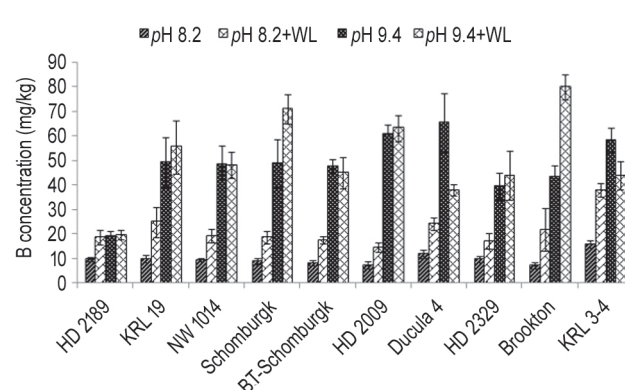


Fig 3 Boron concentration (mg/kg) in shoot tissues of wheat genotypes grown in normal and sodic soil subjected to waterlogging for 10 days.

Table 1 Correlations among element concentrations in wheat genotypes under waterlogging in normal and sodic soils

Particulars	Fe	Mn	Al	B
Fe	1.00	0.847**	0.43**	0.597**
Mn		1.00	0.45**	0.55**
Al			1.00	0.83**
B				1.00

*, ** denote significant at 5 and 1% level of significance, respectively

and B accumulation. These finding were further confirmed by estimating Pearson's correlation coefficient on the effects of waterlogging on shoot elements concentrations of wheat genotypes shown in Table 1. Among these ions, highest significant correlation was found between Fe and Mn ($r = 0.84^{**}$) as well as between Al and B ($r = 0.83^{**}$). All these showed positive correlation among themselves but the significance was less between Fe and Al, Mn and Al. These results also confirmed the greater uptake of these microelements during waterlogging.

Wheat genotypes showed element toxicities of Al, B, Mn and Fe which could be the reason for a yield plateau or decline in grain yields observed for many locations under waterlogged sodic soils and even in drained soils in India. These findings also relate to opportunities for improving crop management.

ACKNOWLEDGEMENTS

Authors are thankful to the Australian Council of International Agricultural Research (ACIAR), Canberra and the Indian Council of Agricultural Research (ICAR), New Delhi for financial and administrative support for the project "Wheat improvement for waterlogging, salinity and element toxicities". Authors are also grateful to the Director, Central Soil Salinity Research Institute, Karnal for encouragement and Dr T L Setter, Department of Agriculture and Food, Western Australia for scientific interaction.

REFERENCES

Armstrong J and Armstrong W. 2001. An overview of the effects of phytotoxins on *Phragmites australis* in relation to die-back. *Aquatic Botany* **69**: 251–68.

Ascher-Ellis J S, Graham R D, Hollamby G J, Paull J, Davies P and Huang C. 2001. Micronutrients. *Application of Physiology in Wheat Breeding*, pp. 219–240. Reynolds M P, Ortiz-Monasterio J I, McNab A (Eds). CIMMYT, Mexico.

Bailey-Serres J and Voesenek L A C J. 2008. Flooding stress: acclimations and genetic diversity. *Annual Review of Plant Biology* **59**: 313–39.

Condon A G and Giunta F. 2003. Yield response of restricted-tillering wheat to transient waterlogging on duplex soils. *Australian Journal of Agriculture Research* **54**(10): 957–67.

Drew M C. 1988. Effects of flooding and oxygen deficiency on plant mineral nutrition. *Advances in Plant Nutrition* **3**: 115–59.

Gill K S, Qadar A and Singh K N. 1992. Effect of wheat (*Triticum aestivum*) genotypes to sodicity in association with waterlogging at different stages of growth. *Indian Journal of Agricultural*

Sciences **62**: 124–8.

Greenway H and Gibbs J. 2003. Mechanisms of anoxia tolerance in plants. II. Energy requirements for maintenance and energy distribution to essential processes. *Functional Plant Biology* **30**: 999–1036.

Horst W J. 1988. The physiology of manganese toxicity. *Manganese in Soils and Plants*, pp 175–188, Graham R D, Hannam R J and Uren N C (Eds). Kluwer Academic Publishers, Dordrecht, The Netherlands.

Iu K L, Pulford I D and Duncan H J. 1982. Influence of soil waterlogging on subsequent plant growth and trace metal content. *Plant Soil* **66**(3): 423–7.

Khabaz-Saberi H and Rengel Z. 2010. Aluminum, manganese, and iron tolerance improves performance of wheat genotypes in waterlogged acidic soils. *Journal of Plant Nutrition and Soil Science* **173**: 461–8.

Khabaz-Saberi H, Setter T L and Waters I. 2006. Waterlogging induces high to toxic concentrations of iron, aluminium and manganese in wheat varieties on acidic soil. *Journal of Plant Nutrition* **29**: 899–912.

Lobo P C and Joly C A. 1998. Tolerance to hypoxia and anoxia in neotropical tree species. *Ecophysiological strategies of xerophytic and amphibious plants in the neotropics. Series Oecologia Brasiliensis*, Vol IV, pp 137–156. Scarano F R and Franco A C (Eds). Rio de Janeiro, Brazil.

Ma G, Rengasamy P and Rathjen A J. 2003. Phototoxicity of aluminium to wheat plants in high pH solutions. *Australian Journal of Experimental Agriculture* **43**: 497–501.

Marschner H. 1991. Mechanisms of adaptation of plants to acid soils. *Plant Soil*. **134**: 1–20.

Mortvedt J J. 1972. *Micronutrients in Agriculture*. Book Series No. 4, Soil Science Society of America, Madison WI.

Ponnamperuma F N. 1972. The chemistry of submerged soils. *Advances in Agronomy* **24**: 29–96.

Ponnamperuma F N. 1984. Effects of flooding on soils. *Flooding and Plant Growth*, pp 9–45. Kozlowski T T (Eds). Academic Press, London.

Reuter D J, Edwards D G and Wilhelm N S. 1997. Temperate and tropical crops. *Plant Analysis: An Interpretation Manual*, pp 81–284. Reuter D J and Robinson J B (Eds). CSIRO Publishing, Collingwood, Australia.

Samad A, Meisner C A, Saifuzzaman M and Van Ginkel M. 2001. Waterlogging Tolerance. *Application of Physiology in Wheat Breeding*, pp. 136–144. Reynolds M P, Ortiz-Monasterio J I and McNab (Eds). CIMMYT, Mexico.

Sayre K D, Van Ginkel M, Rajaram S and Ortiz-Monasterio I. 1994. Tolerance to waterlogging losses in spring bread wheat: Effect of time on onset of expression. *Annual Wheat Newsletter* **40**: 165–71.

Setter T L and Waters I. 2003. Review of prospects for germplasm improvement for waterlogging tolerance in wheat, barley and oats. *Plant Soil* **253**: 1–34.

Setter T L, Waters I, Sharma S K, Singh K N, Kulshreshtha N, Yaduvanshi N P S, Ram P C, Singh B N, Rane J, McDonald G, Khabaz-Saberi H, Biddulph T B, Wilson R, Barclay I, McLean R and Cakir M. 2008. Review of wheat improvement for waterlogging tolerance in Australia and India: the importance of anaerobiosis and element toxicities associated with different soils. *Annals of Botany* **137**: 1–15.

Sharma D K and Singh A. 2015. Salinity research in India: achievements, challenges and future prospects. *Water Energy International* **58**(6): 35–45.

- Sharma D P and Swarup A. 1988. Effect of short-term flooding on growth, yield and mineral composition of wheat on sodic soil under field conditions. *Plant Soil* **107**: 137–43.
- Sharma S K, Kulshreshtha N, Kumar A, Yaduvanshi N P S, Singh M, Prasad K R K and Basak N. 2018. Waterlogging effects on elemental composition of wheat genotypes in sodic soils. *Journal of Plant Nutrition* **41**(1): 149–56.
- Singh M V and Rao A S. 1995. Manganese research and agricultural production. *Micronutrient Research and Agricultural Production*, pp 82–114. Tandon H L S (Eds). FDCO, New Delhi.
- Steffens D, Hütsch B W, Eschholz T, Lošák T and Schubert S. 2005. Water logging may inhibit plant growth primarily by nutrient deficiency rather than nutrient toxicity. *Plant Soil Environment* **51**: 545–52.