IDENTIFYING ANCESTRAL WHEAT INTROGRESSIONS AND TRAITS FOR IMPROVED TOLERANCE TO HOSTILE SOILS

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Abstract

Wheat is the third most widely consumed crop after rice and maize globally. The Green Revolution increased the Indian wheat production tremendously since the 1960s using semi-dwarf wheat varieties and subsequent trait-based breeding under non-hostile soils. In addition to grain yield, wheat is an important source of dietary zinc (Zn) and other mineral elements in many countries. Dietary Zn deficiency is widespread, especially in developing countries, and there are wide scale efforts to breed wheat with increased grain Zn concentrations in South Asia. It is not clear if further grain yield and quality traits such as grain Zn concentration improvements can be sustained due to 1) narrow genetic diversity in modern wheat, and 2) limited land availability e.g., many soils are marginal due to salinity, alkalinity, acidity and mineral nutrient imbalances.

The first aim of this thesis was to quantify grain yield and yield components, including juvenile root traits, and grain Zn concentration of a panel of 36 Indian diverse wheat genotypes to explore the potential for site specific trait selection for hostile soils and characterise the baseline effect of genotype (G), site (E), and genotype x site interaction (G*E) under a wide range of soil conditions. Mean grain yields ranged from 1.0 to 5.5 t ha^{-1} at hostile and non-hostile sites, respectively. G*E interactions affected many yield and component traits, which support the value of site-specific traits selection for hostile soils. The mean grain Zn concentration of 36 genotypes ranged from 25 to 35 mg kg^{-1}. Despite a relatively small overall contribution of G to the overall variation in grain Zn concentration, biofortifying wheat through breeding is likely to be effective at scale given that some genotypes (e.g. Kharchia 65) performed consistently

across diverse soil types. Root angle and lateral root traits were associated with grain yield and some mineral composition traits.

The second aim of this thesis was to study the performance of eight amphidiploids derived from *Thinopyrum bessarabicum*, a tall wheat grass, for yield, yield components and grain Zn concentration under saline soils. Reduction in GYD in amphidiploids were less than in Indian genotypes under saline soils and grain Zn concentration ranged from 36-43 mg kg^{-1}.

The third aim of this thesis was to explore wild wheat relatives, non-relatives and their derivatives to increase the genetic diversity for grain Zn concentration. The mean grain Zn concentration of 225 wild wheat accession ranged from 47 to 178 mg kg^{-1}. Notably, *Amblyopyrum muticum*, derived amphidiploids and double haploid lines could be useful sources of grain Zn variation that can be used in breeding programmes to increase the grain Zn concentration in modern wheat varieties to alleviate the dietary Zn deficiency.

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Abbreviations

Abbreviation	Description with unit
Al	Aluminium
ANOVA	Analysis of variance
ARRT	Angle related root traits
As	Arsenic
Ba	Barium
BYD	Biological yield, g
Ca	Calcium
Cd	Cadmium
CHCRX	Centre of mass of convex hull, X-axis (cm)
CHCRY	Centre of mass of convex hull, Y-axis (cm)
CMRX	Centre of mass of the root system, X-axis (cm)
CMRY	Centre of mass of the root system, Y-axis (cm)
CRM	Certified reference material
Cs	Caesium
Cu	Copper
DAS	Days after sowing
DBT	Department of Biotechnology, India
DTA	Days to anthesis
DTM	days to maturity
E	Site
FAO	Food and Agriculture Organisation of the United Nations
Fe	Iron
G	Genotype
G*E	Genotype x site interaction
GNS	Grain number per spike
GS	Growth stage
GWS	Grain weight per spike, g
GYD	Grain yield (t ha^{-1})
HI	Harvest index, %
HTP	High throughput phenotyping
ICAR	Indian Council of Agricultural Research
ICP-MS	Inductively coupled plasma- mass spectrometry
IIWBR	Indian Institute of Wheat & Barley Research
K	Potassium

Abbreviation	Description with units
LOD	Limit of detection
LRM	Laboratory reference material
LRN	Lateral root number
LRRT	Length related root traits
LSD	Least significant difference
MDR	Maximum depth of the root system (cm)
Mg	Magnesium
MLAR	Average length of all roots (cm)
MLLR	Average length of all lateral roots (cm)
MLPR	Average length of primary roots (cm)
Mn	Manganese
Mo	Molybdenum
MWR	Maximum width of the root system (cm)
NDUA&T	Narendra Deva University of Agriculture and Technology
NEPZ	North Eastern Plains Zone
NWPZ	North Western Plains Zone
ORT	Other root traits
P	Phosphorus
PEA 1001	Emergence angle between the outermost pair of primary roots measured at root tips, degree
PEA 1002	Emergence angle between the second inner pair of primary roots measured at root tips, degree
PEA 251	Emergence angle between the outermost pair of primary roots measured at 25% length of root, degree
PEA 252	Emergence angle between the second inner pair of primary roots measured at 25% length of root, degree
PEA 301	Emergence angle between the outermost pair of primary roots measured at 30 pixel (px), degree
PEA 302	Emergence angle between the second inner pair of primary roots measured at 30 pixel (px), degree
PEA 501	Emergence angle between the outermost pair of primary roots measured at 50% length of root, degree
PEA 502	Emergence angle between the second inner pair of primary roots measured at 50% length of root, degree
PEA 751	Emergence angle between the outermost pair of primary roots measured at 75% length of root, degree
PEA 752	Emergence angle between the second inner pair of primary roots measured at 75% length of root, degree

Abbreviations	Description with units
PEA 951	Emergence angle between the outermost pair of primary roots measured at 95 pixel (px), degree
PEA 952	Emergence angle between the second inner pair of primary roots measured at 95 pixel (px), degree
PHT	Plant height at maturity
PRN	Primary root number
R	Residual
Rb	Rubidium
RCH	Root convex hull, the smallest area of the convex covered by root system (cm^2)
S	Sulphur
SD	Standard deviation
Se	Selenium
Sr	Strontium
TAG	Trace analysis grade
TGW	1000 grain weight, g
Ti	Titanium
TLAR	Total length of all roots (cm)
TLLR	Total length of all lateral roots (cm)
TLPR	Total length of all primary roots (cm)
UBKV	Uttar Banga Krishi Viswavidyalaya
UK	United Kingdom
V	Vanadium
WDR	Ratio of maximum width and depth of the root system (MWR/MDR)
Zn	Zinc

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CHAPTER 1. INTRODUCTION

1.1 Background, objectives and thesis structure

Wheat is a widely consumed cereal crop and accounts ~20% of overall direct energy intake for the world's population (Shiferaw *et al*., 2013; Fischer *et al*., 2014). It also makes significant contribution to livestock feed and expected to reach 147 Mt in 2016-17 which is ~20% of global wheat production (USDA, 2017a). In India, which is the focus of this thesis, it accounts for more than 50% of the direct energy intake (www.dwr.in). Need to increase production due to population increases and wheat consumption for animal feed. More than 5 Mt wheat was consumed for animal feed in 2017 in India (USDA, 2017b). Further, hostile soils, for example, saline, alkaline and acidic soils, constrain potential increase in wheat production areas. In India, 6.7 Mha area is salt affected, of which ~5.6 Mha is distributed in 15 states which contribute ~97% of national wheat production. Approximately 25 Mha area is affected by soil acidity, including ~30% of current area under cultivation (Mandal *et al*., 2010; Sharma *et al*., 2012; www.dwr.in).

In addition to grain yield, grain quality is important because it affects the protein and micronutrients (e.g. zinc) intake in human diet. Zinc is an essential element for plants and people (Broadley *et al*., 2007). It is an important component of many enzymes and proteins which performs different structural and regulatory function in human body (Andreini *et al*., 2006). Hostile soils also affect the uptake of nutrients from soil through roots, and grain micronutrients concentrations, particularly, zinc (Zn). Wheat is an important dietary source of Zn (Black *et al*., 2013), approximately 20% people at global scale are not getting

sufficient Zn in their diets and which linked to diarrhoea, respiratory infection and stunting in children (Hess *et al*., 2009; King *et al*., 2016; Kumssa *et al*., 2015; Gregory *et al*., 2017). It supply ~50% Zn of daily needs in Indian population (Kumssa *et al*., 2015).

This thesis focuses on studying 36 widely adapted Indian wheat genotypes, and amphidiploids derived from a salt tolerant wheatgrass, *Thinopyrum bessarabicum*. Grain yield, yield components, and grain mineral composition traits were studied under a wide range of hostile soils in India. In addition, grain Zn concentration and the grain ionome was studied in a wider range of wild wheat relatives, non-relatives and their derivatives.

There are three broad objectives of this thesis:

1) to study the 36 Indian wheat genotypes to characterise baseline effect of genotype (G), site (E), and genotype x site interaction (G*E) on grain yield, yield components, grain Zn concentration and the grain ionome under a wide range of soil conditions in India and further test the relationships between juvenile root traits and grain yield, yield components and mineral composition traits under different hostile environments. Chapters 2, 3 and 4.
2) to study the performance of eight amphidiploids derived from *Thinopyrum bessarabicum* for grain yield, yield components, grain Zn concentration and the grain ionome under normal and saline Indian soils. Chapter 5.

3) to study 225 wild wheat accessions representing 40 wild wheat species belonging to wheat wild relatives and non-relatives, and 17

amphidiploids derived from wild wheat species, for grain Zn concentration and the grain ionome. Chapter 6.

In brief, Chapter 1 provides a general introduction to the thesis. It describes the significant role of green revolution and provides a history of wheat breeding programmes in India. It further provides an overview of how hostile soils affect wheat grain production and grain quality traits, including strategies to improve the wheat grain yield, yield components and grain quality traits under different hostile soil environments and importance of root traits in improving the yield and uptake of nutrients from soils. In terms of grain quality, it specifically focuses on the impact of dietary Zn deficiency on human population and importance of wheat to alleviate the dietary Zn deficiency, particularly, India, and provides the importance of wild wheat relatives and non-relatives in the development of better wheat varieties for grain yield and quality traits.

Chapter 2 is published in a peer reviewed journal (Khokhar *et al*., 2017) and evaluated the 36 widely adapted Indian genotypes at six sites (pH from 4.5 to 9.5) in India to characterise the effect of genotype (G), site (E) and genotype x site interaction (G*E) on grain yield and yield components and explored the importance of site specific trait selection for hostile soils. Site (E) had the largest effect on yield and component traits, however, G*E affected most traits to a greater extent than genotype alone. Some genotypes performed better under hostile soils, with site-specific relationships between yield and component traits which supports the value of ongoing site-specific trait selection activities. Chapter 3 is under-review in peer reviewed journal (Khokhar *et al*., submitted) and evaluated the 36 Indian wheat genotypes to characterise the effect of G, E

and G*E interaction on grain Zn concentration and the grain ionome under a wide range of soil conditions in India. Although there was a relatively small overall contribution of G to the overall variation in grain Zn concentration, it showed that some varieties did perform consistently which is promising for wider biofortification programmes to address dietary Zn deficiency in India. In Chapter 4, the hypothesis that juvenile root architecture traits correlate with grain yield, yield components and grain mineral composition traits of 36 Indian wheat genotypes under a wide range of hostile soil types in India. Narrow root angle could be a useful proxy trait for screening juvenile germplasm for improved grain yield. Lateral root and shallow root traits could potentially be used to improve grain Zn, Fe and S concentrations. In Chapter 5, the performance of eight amphidiploids derived from *Thinopyrum bessarabicum*, a salt tolerant wheatgrass, was studied under normal and saline soils for grain yield, yield components and mineral composition traits. Amphidiploids for example, EC 787011 to EC787014, had greater GYD and grain Zn concentration under saline soils. In Chapter 6, 225 wild wheat accessions, 17 amphidiploids derived from wild wheat species and 51 double haploid lines derived from *Amblyopyrum muticum* were evaluated for grain Zn concentration and the grain ionome. Grain Zn concentration of 225 wild wheat accessions varied from 47 to 178 mg kg^{-1}. The derivatives of *Amblyopyrum muticum* present themselves useful sources to increase the grain Zn concentration in breeding programmes.

1.2 Global wheat production and challenges to food security

Wheat is the world's third most widely consumed crop after rice and maize. It accounts directly for ~20% of overall energy intake for the world's population (Ortiz *et al*., 2008; Shiferaw *et al*., 2013). The total global area under wheat

production in 2016 was 222 million hectares which produced 754 Mt (7.54 x 10^8 metric tonnes), giving a world average wheat yield of 3.39 t ha^{-1} (USDA, 2016a). Approximately 20% (147 Mt) of global wheat production was used for animal feed in 2016-17 (USDA, 2017a). Since 1960, wheat grain production has increased three times while area under cultivation increased marginally (**Figure 1.1**).

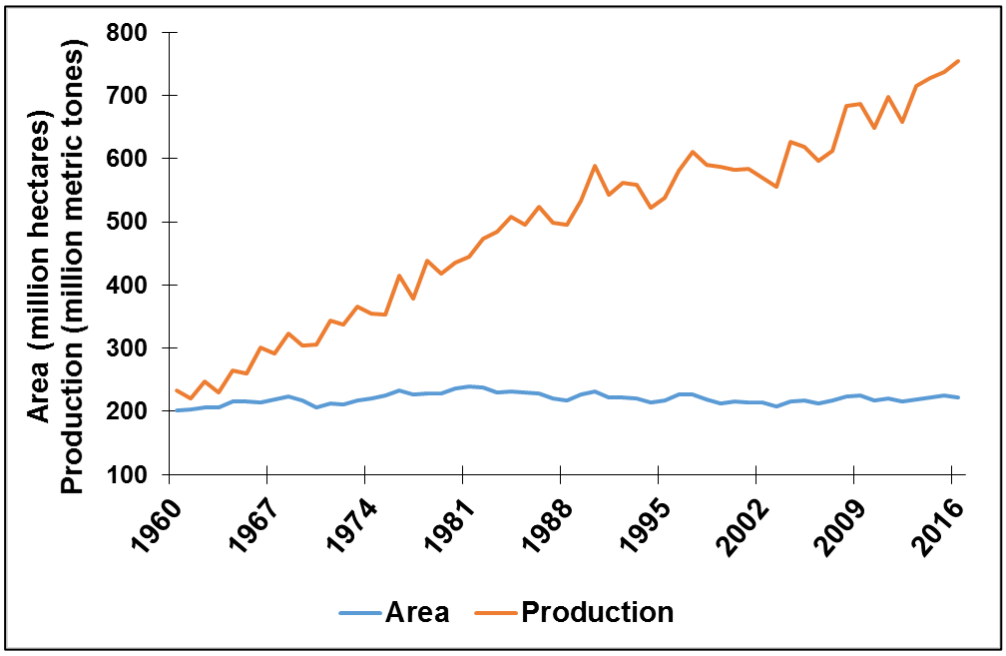


Figure 1.1 World wheat area and production from 1960-2016 (USDA, 2016a).

According to current predictions, it is estimated that the world population is likely to reach nine billion by 2050, with food production needing to increase by 70-100% from its present level (Whitford *et al.*, 2013). Presently, wheat production is increasing at 0.9% yearly, however, an annual increase of 2.4% per year would be needed to double global production by 2050 (Ray *et al.*, 2013).

However, increasing urbanisation, limited agriculture land, global warming, water scarcity, increasing salinity and alkalinity of soils, nutrient deficiencies in soil and other biotic stresses are imposing serious problems on the global wheat production (Gregory *et al*., 2005; Khokhar *et al*., 2017). Even intensive agricultural practices have been destroying the soil health. For example, excessive use of nitrogen based fertilisers in wheat cultivation deteorating the soil condititions due to low nitrogen use efficiency of modern wheat cultivars (Foulkes *et al*., 2009). Therefore, there is a need to develop high yielding wheat varieties with more efficient nutrient uptake mechanism and can perform better even under hostile soil conditions. Many approaches are being used by researchers for wheat crop improvement, for example, adopting better soil management practices and involvement of wheat wild relatives in breeding programmes to use the un-tapped genetic reservoir of genetic variation for grain yield, component traits, grain quality traits and other traits of agronomic importance in breeding programmes (King *et al*., 2013).

1.3 Wheat evolution and domestication

Wheat (*Triticum* spp.) belongs to the grass family (*Poaceae*), the 4th largest family of the flowering plants (angiosperms). It is thought that the *Poaceae* emerged 50-70 million years ago (Kellogg, 2001). The basic chromosome number of the common ancestors of the *Poaceae*, due to duplication events, range from 5-12 chromosomes (Gaut, 2002). The sub family *Pooideae* which includes wheat, barley and oats is thought to have evolved ~20 million years ago (Inda *et al*., 2007). Bread wheat (*Triticum aestivum* L*)* is likely to have arisen

recently (<10,000 years ago) from progenitor species of varying cytogenetic classifications (from diploid to hexaploid), originating from the 'Fertile Crescent' area known previously as Mesopotamia, around the Tigris and Euphrates rivers, and representing current countries including Iran, Iraq, Israel, Jordan, Syria and Turkey. Alphonse de Candolle believed that wheat then moved to China, Egypt and other parts of the world (Candolle de, 1883).

Triticum aestivum is a hexaploid species (2n=6x=42), comprising A, B and D genomes (AABBDD). It is known that *Triticum urartu* (2n=2x=14; Genome A^uA^u) has contributed A^u genome to all tetraploid and hexaploid wheats (Dvorak *at al.*, 1993) species. *Aegilops speltoides* (2n=2x=14; genome SS) is believed to be the closest relative of B genome ancestor. The hybridization of *T. urartu* and *Ae. speltoides* is likely to have led to the appearance of wild emmer wheat (*T. dicoccoides*, 2n=4x=28; genome A^uA^uBB) (Huang *at al*., 2002; Dvorak and Akhunov, 2005) (**Figure 1.2**). Tetraploid wheat domestication began ~10,000 years ago, by hunter-gatherers, with subsequent selection of cultivated emmer/durum wheats (*T. dicoccum / T. turgidum*; 2n=4x=28; genome A^uA^uBB).

Tetraploid wheats are thought to have hybridized spontaneously with D genome donor wild diploid species, *Aegilops tauschii* (2n=4x=14; genome DD) ~9000 years ago, around the Southern Caspian Sea to produce an early hexaploid species, spelt (*T. spelta*; 2n=6x=42; Genome A^uA^uBBDD) (Dvorak *et al*., 1998; Matsuoka and Nasuda 2004). Consequently, natural mutations thought to have changed emmer and spelt wheat into modern, free threshing, durum wheat and bread wheat, respectively (Dvorak *et al*., 2006; 2011).

The domestication of *T. monococcum* (Einkorn wheat) is thought to have begun in the Karacadag mountain range in south-east Turkey ~10,000 years ago. This crop was a main crop for thousands of years, however, einkorn wheat has been largely replaced by modern durum and bread wheats, and is now limited to mountains regions of Turkey, Italy and Spain as an animal feed crop (Nesbitt and Samuel, 1996; Heun *et al.*, 1997).

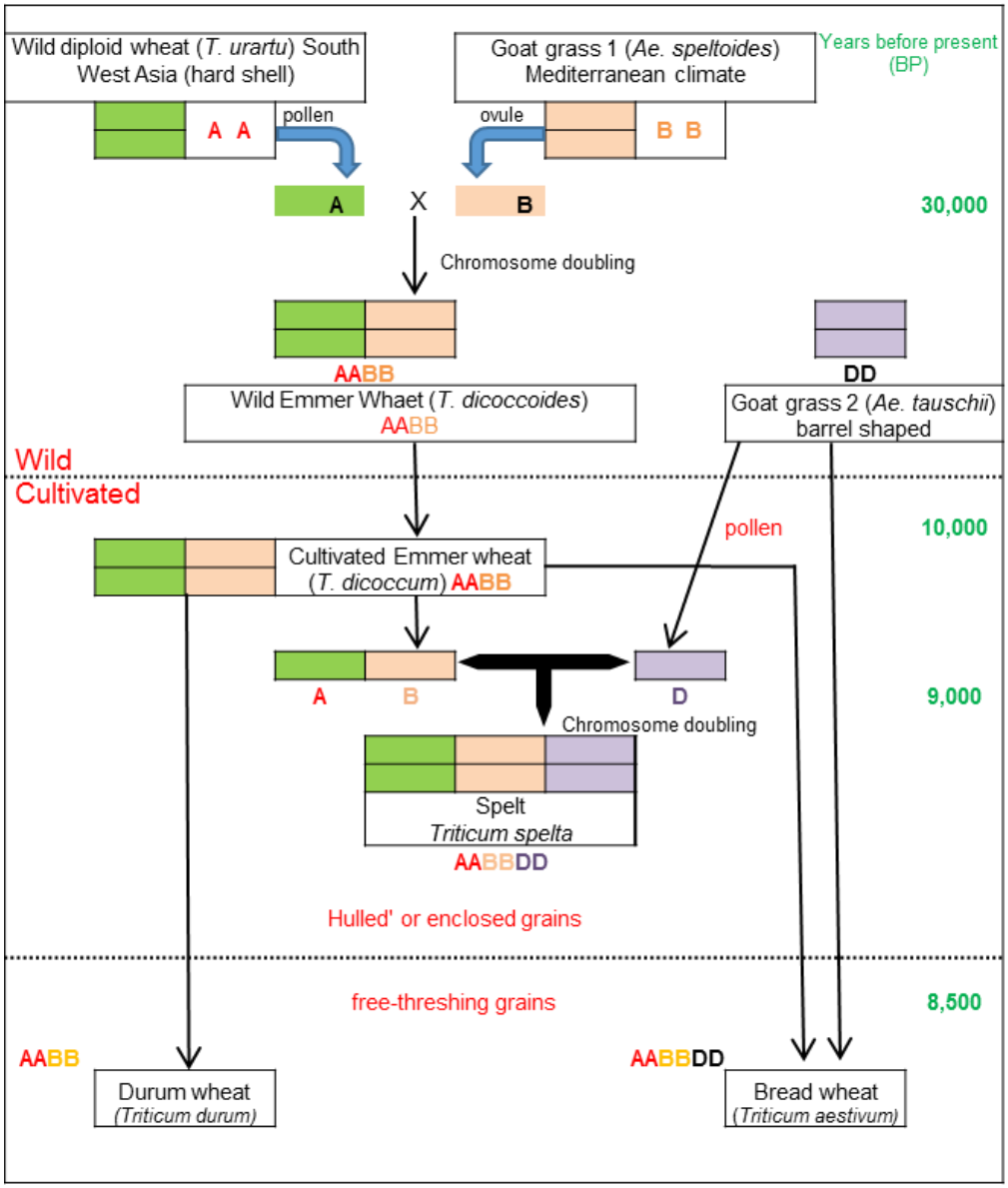


Figure 1.2 The evolution of wheat from prehistoric Stone Age grasses to modern durum wheat and bread wheat (reproduced from www.newhallmill.org.uk/wht-evol.htm).

The wild tetraploid species *T. dicoccoides* has played a crucial role in bread wheat domestication (Dvorak *et al.*, 2011). Emmer wheat (*T. dicoccum*) is the domesticated form of *T. dicoccoides*. Ozkan *et al.*, 2011, proposed a "dispersed-specific" domestication model based on geographical distribution and molecular data, which assumes pre-adaptation of a wild emmer race for cultivation, as proposed previously for einkorn wheat. Archaeo botanical findings suggested that Southern Levant (comprising Israel, the Palestinian territories, Jordan and the southern part of Lebanon) and Northern Levant (comprising Lebanon, western and southern Syria and a part of Turkey) might be independent centres of cultivation of wild emmer wheat. Thus domesticated emmer wheat contains the gene for non-brittleness and free-threshability, most likely developed as a polymorphic population and currently, emmer wheat cultivation is found in just a few traditional farming communities in Russia and Ethiopia. Durum wheat (*T. durum*) has replaced *T. dicoccum* and is cultivated globally (Feldman and Kislev, 2007).

1.4 Wheat improvement in India- from deficit to surplus

Wheat is the major food crop of India, especially in northern India, where people have preference for *chapatti* style unleavened breads. Wheat production in India accounted for 13% of global wheat production in 2016, making India the 2nd largest wheat producing nation after China (USDA, 2016b). Surpluses of wheat (31 Mt), comprising 2.6 Mt of exports and 28.4 Mt in stocks in 2014, contrasts with deficits of 1.8 Mt in the 1980s (FCI, 2015). During these periods of deficit,

India was dependant on wheat imports to fulfil country demand and growing traditional Indian varieties producing low yield on high fertile soils.

Globally, demand for wheat has increased substantially in the past 50 years and more area of land are being used for wheat cultivation as compared to other major crops like rice, maize etc. (Clay, 2004). Significant increase in wheat production in 1960s was due to the green revolution, which involved the adoption of new high-yielding varieties of wheat (Singh & Kohli, 1997) with dwarfing gene which eliminate the photoperiod response and make them high yielding in the environment of developing world. The dwarfing genes *Rht* 1 and *Rht2* shortened the plant height and makes wheat varieties tolerant to lodging and increase the harvest index. These varieties are more responsive to higher dose of fertilisers (Trethowan *et al.,* 2007), hence increased overall production. In India, wheat production increased from 11 Mt to 94 Mt from 1961 to 2016 (DACFW, 2016; **Figure 1.3**), due to selective breeding for high yielding semi-dwarf varieties.

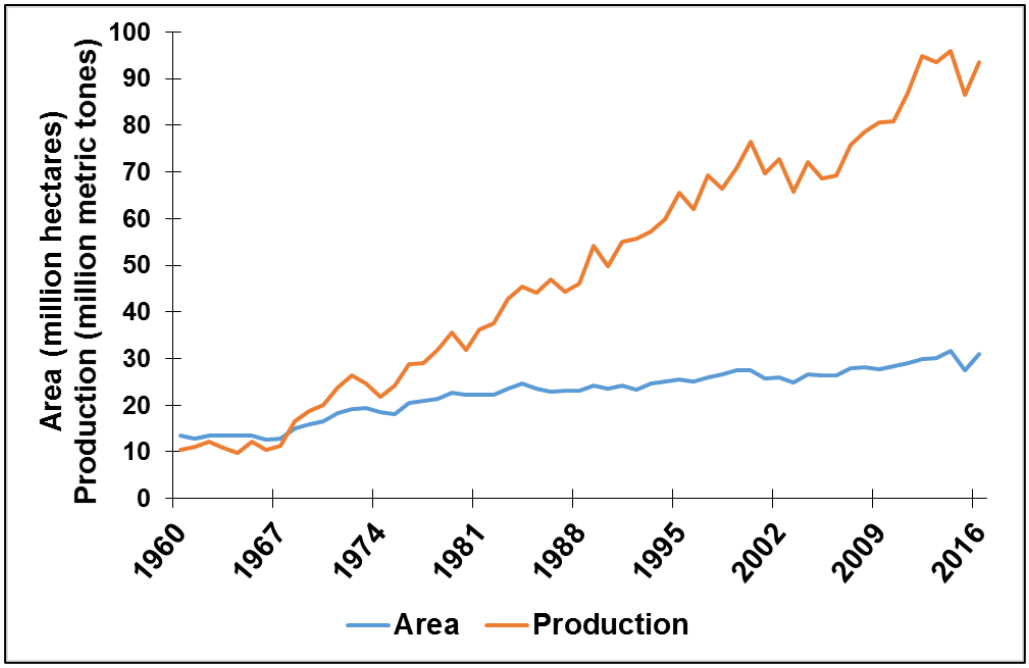


Figure 1.3 Wheat area and production in India from 1960 to 2016 (DACFW, 2016).

Three species of wheat are cultivated in India are, (1) *T. aestivum*, (2) *T. durum*, (3) *T. dicoccum* (**Table 1.1**). Around 99.5% of the total wheat production of India is comes from major wheat producing states, for example, Uttar Pradesh (UP), Punjab (PB), Haryana (HR), Madhya Pradesh (MP), Rajasthan (RJ), Bihar (BH), Gujrat (GJ), Karnataka (KN), Uttarakhand (UK), Himachal Pradesh (HP), and Jammu & Kashmir (J&K) while 0.5% are contributed by Jharkhand (JH), Assam, Chhattisgarh and other North Eastern states of the India (Source: DWR Perspective Plan Vision 2025, www.dwr.in).

Table 1.1 Proportion of different wheat species cultivated in India.

Species	**Production (%)**	**Growing areas (states)***
T. aestivum	95	Uttar Pradesh, Punjab, Haryana, Rajasthan, Bihar, West Bengal, Assam, Madhya Pradesh, Himachal Pradesh, Jammu & Kashmir
T. durum	4	Madhya Pradesh, Maharashtra, Gujrat, Rajasthan, Punjab
T. dicoccum	1	Karnataka, Maharashtra, Tamil Nadu

*ranked by production

1.5 Wheat improvement strategies to ensure food security in India

1.5.1 History of wheat breeding institutes

In India, 'spring-type' *Triticum aestivum* L (bread wheat), *T. durum* (durum wheat) and *T. dicoccum* (emmer wheat) have been cultivated since pre-historic times. Systematic wheat breeding in India began in 1905, under British colonial rule, after Sir Albert Howard's appointment as Imperial Botanist at Pusa (Bihar). The Indian Agriculture Research Institute (IARI) in Delhi played a crucial role for the development of the wheat research and later on the Indian Council of Agricultural Research (ICAR) established in 1929, became the main funding agency and promotor of wheat research activities in India. The All India Coordinated Wheat Improvement Project (AICWIP) was established in 1965 by the Indian Government and which proved a very important step toward the wheat research in India. It was coincidence that the emergence of dwarf wheat and establishment of the AICWIP happened simultaneously in the same year 1965. The AICWIP was uplifted to the status of the Directorate of Wheat Research

(DWR) in 1978 and in 1990, with the addition of barley network, it was renamed as All India Coordinated Wheat and Barley Improvement Project (AICW&BIP), it shifted from IARI, New Delhi, to its present site at Directorate of Wheat Research (DWR) which is now Indian Institute of Wheat & Barley Research (IIWBR) at Karnal, 130 km north of Delhi along with two regional stations located at Flowerdale, Shimla and Dalang Maidan (Lahul valley), both in HP state.

The mission of IIWBR is *"to ensure Food Security of India by enhancing the productivity and profitability of wheat and barley on an ecologically and economically sustainable basis and making India the world leader in wheat production"*. The IIWBR is the nodal institution for the coordinating multi-locational testing of wheat and barley technologies under AICW&BIP with the support from 31 funded centres located in different State Agricultural Universities (SAUs) and voluntary centres spread across six cultivation zones of the country. Since the establishment of AICW&BIP, there have been major developments in yield potentials, productivity and sustainability of wheat in India. For example, the area, productivity and production of wheat increased by 123%, 226% and 630%, respectively, in 2006-07, compared to 1965-66 (www.dwr.in).

1.5.2 Wheat germplasm bank to develop better wheat varieties

The Germplasm Resource Unit (GRU) at IIWBR maintains >11,000 lines of wheat which includes indigenous core collections, donated stocks, and wild relatives/species. It also includes germplasm from other countries including USA, Canada, Australia, China, Syria, UK and South Africa. The IIWBR

organizes the evaluation of new germplasm entries for yield and contributing traits, including for various biotic and abiotic stresses, through the national nurseries. All the SAUs and other breeders can utilise these germplasm stocks in their breeding programmes. A breeder's work involves selecting two individual for crossing, each of which have specific traits or characteristic of interest. During crossing, genes are exchanged between the parents so that a wide range of diverse individuals is observed in the progeny of future generations. So, breeders first create the variation which is the basis of every selection and then go for selection of individuals which contain the best features of both the parents and then breed further (McCouch, 2004). In India, breeders develop new improved wheat varieties through a systematic testing procedure under the coordination of IIWBR. This involves grain multiplication and varietal evaluation trials for yield and yield contributing traits. Each year, ~500 accessions/entries developed by the wheat breeding centres are tested in ~450 varietal trials at about 130 locations.

1.5.3 National wheat germplasm nurseries

In India, there are six national nurseries which supply germplasm to different collaborating centres for further screening and hybridization.

1.5.3.1 National Genetic Stock Nursery (NGSN)

Elite germplasm for improved yield and disease resistance are supplied to breeding centres for use in hybridization programmes. Genotypes showing better performance than reference/check materials are identified for further development.

1.5.3.2 Yield Component Screening Nursery (YCSN)

Various bread wheat and durum wheat entries are supplied to centres for trait specific screening in the different growing zones. Yield components include 1000-grain weight, grain yield, days to maturity and tillers/plant.

1.5.3.3 Short Duration-cum-late Heat Tolerance Screening Nursery (SDSN)

Genotypes showing better performance than reference/check materials for heat tolerance are identified for further development.

1.5.3.4 Drought and Heat Tolerance Screening Nursery (DHTSN)

Genotypes showing better performance than reference/check materials for drought and heat tolerance are identified for further development for the different growing zones.

1.5.3.5 Salinity/Alkalinity Tolerance Screening Nursery (SATSN)

Genotypes showing better performance than salinity/alkalinity tolerant checks, e.g. Kharchia 65, KRL 3-4, KRL 19, HD 4530 and KRL 210, are identified for further development for the different growing zones.

1.5.3.6 Quality Component Screening Nursery (QCSN

Genotypes are evaluated and analysed for various quality traits (e.g. protein and starch contents, grain hardiness) and promising lines identified for further development for the different growing zones.

1.5.4 Elite international germplasm nurseries (EIGNs)

Genotypes performing well at international nurseries and other national trials in India are multiplied at two nurseries. One is the Elite International Germplasm

Nursery for bread wheat (EIGN-1), the other is the Elite International Germplasm Nurseries for durum wheat (EIGN-II). In total, 441 promising lines are identified for further development for the different growing zones. IIWBR, Karnal also run the directorate Shuttle Breeding Programme (SBH) for eastern India and the shuttle breeding programme for warmer areas of the country. In programmes, advanced lines and F2 segregating materials are screened successively at different sites, for specific traits.

1.5.5 Pre-breeding systems to screen genetic material for desirable traits

Pre-breeding is required to transfer desirable traits from primary and tertiary genepools to well adapted wheat cultivars. An example area of pre-breeding activity is in crop protection, which is supported by various disease/pest evaluation nurseries at various locations under natural and artificial inoculated conditions. At IIWBR Karnal, the Initial Plant Pathological Nursery (IPPSN) and Plant Pathological Screening Nursery (PPSN) are the main nurseries which screen thousands of entries every year. Selected genotypes are then evaluated in Primary Yield Trials (PYTs) and Advanced Yield Trials (AVTs). Selected genotypes are then released. Other pre-breeding activities at IIWBR include screening for improving processing and nutritional quality traits (www.dwr.in).

1.5.6 Crop conservation and extension activities at IIWBR, Karnal

Conservation practices are also tested at IIWBR to improve the sustainability of agricultural production system. Practices including altered seed rates, sowing depths, spacing and fertiliser doses are recommended for different growing zone of country time to time. Zero-tillage technologies have recently been developed and promoted for low cost wheat production in North Western Plane Zone

(NWPZ) and North Eastern Plane Zone (NEPZ) farmers by this institute. Other technologies which are promoted by IIWBR and which can be adopted by farmers in future are Rotary-Till drill, Strip Till Drill and Rotary Disc Drill. The adoption of conservation agriculture can help to improve the sustainability of soil and water resources by avoiding crop residue burning. New varieties and technologies are disseminated to farmers by various extension activities and frontline demonstrations. These include exhibitions, farmer's days, seed days, travelling seminars, TV talks and training programmes helps in promoting of new varieties and other resource conservation technologies to the farmers (www.dwr.in). A newsletter, *"Wheat Crop Health Newsletter*", is released each month on the basis of survey and surveillance of wheat disease during the crop season and it advises the farmers on disease control measures at any stage in which they occur.

1.6 Approaches to transfer desirable traits into modern wheat

1.6.1 Traditional breeding and constraints

Conventional plant breeding has supported increases in human population of the world. This technique remains consistent in providing improved cultivars which can increase the yields of major crops around the world (Fedoroff, 2010). Mainly, in traditional plant breeding, screening of available diversity and selection is based on phenotypic evaluation. Those genes which have large effect on phenotype can be selected but many favourable alleles with small effects cannot be detected and will not be included intentionally in breeding programmes (Morgante and Salamini, 2003). Similarly, the masking effect of

different environments can decrease phenotypic selection efficiency, which can lead to the loss of desirable alleles and can further hamper traditional breeding efficiency (Araus *et al.*, 2008).

1.6.2 Genetic modification (GM) and constraints

Genetic modification (GM) is the process of transferring genes from one organism or genome into another genome by using artificial techniques rather than using natural crossing and recombination. Through the latest transfer techniques, a target gene (typically ~10 kb DNA) can be transferred into a crop plant genome (~1 Gb DNA), thereby the resulting plant will remain 99.999% similar to its parents (Jones, 2011). Such approaches can hasten breeding by eliminating 'linkage drag', which is a major drawback of tradition breeding (Gust *et al.,* 2010). Four genetically modified crops are grown widely worldwide: maize, cotton, canola and soybean. These GM crops are dominated by two traits: the *Bt* (*Bacillus thuringiensis*) endotoxin for resistance against lepidopteran insect pest, and glyphosate herbicide tolerance. Around 148 Mha of GM crops were grown globally in 2010 (Peng, 2011). USA ranked first in production of GM crops followed by Brazil, Argentina, India and Canada (James, 2010). There are many technologies which can be used to develop GM products (Lusser *et al*., 2012). However, there remains a widespread perception that GM crops might have negative effects on environment and health (Durant and Lindsey, 2000). For example, it has been reported that secondary pest population, e.g. mirid bugs in cotton, can increase after growing *Bt* crops in China (Chen and Lin, 2013; Lu *et al*., 2010). In wheat, there is no GM cultivar available commercially and GM wheat is likely to be met with resistance.

1.6.3 Wild wheat introgression

The domestication process caused the reduction in genetic diversity at genomic level. For example, Haudry *et al*., 2007 reported an 84% and 69% reduction in diversity from wild to cultivated durum and bread wheat, respectively, based on nucleotide diversity at 21 loci. So, harnessing beneficial alleles and exploiting genetic diversity from wild species and exotic germplasm through introgression of desired traits for abiotic and biotic stresses can be used to develop high yielding and disease tolerant varieties. For the purposes of wide crosses, three gene pools of *T. aestivum* can be considered. The primary (1°) gene pool includes *T. turgidum, T. urartu, Ae. tauschii* and landraces of wheat which have A genome in common. Traits from this gene pool can be transferred into cultivated wheat through homologous combination during hybridization (Fribe and Gill, 1996). The secondary (2°) gene pool includes species which share one homologous genome with *T. aestivum*, e.g. B genome diploid, *Ae. speltoide* and D genome polyploid *Aegilops* species. The tertiary (3°) gene pool comprises those species of *Triticeae* which contain genomes other than A, B, and D, for example, *Secale* (RR) and *Thinopyrum* (EE) species. Gene transfer is not feasible by direct homologous recombination from this gene pool (Feuillet and Salse, 2009).

The introgression of DNA from wild species to cultivated wheat can increase the genetic diversity within wheat, but it is difficult process due to crossing barriers. Introgression involves the transfer of genes from wild species into cultivated wheat genome by sexual hybridization and homologous or homoeologous recombination, followed by many backcrosses of a hybrid to its parents to eliminate deleterious genes introduced through linkage drag

(Anderson and Hubricht, 1938). Strategies include the production of chromosomal addition or substitution lines, however, the development of addition or substitution lines can carry the gametocidal genes which preclude the transfer of alien chromosomes through both male and female gametes (Endo, 1978). Gametocidal genes have been reported in *Aegilops geniculate*, *Ae. triuncialis*, *Ae. caudate*, *Ae. cylindrical*, *Ae. sharonensis* and *Ae. speltoides* and removal of gametocidal genes is necessary for introgression of genes into modern wheat from wild wheat relatives (Niranjana, 2017).

Thus, agronomically desired traits can be transferred from wild species to cultivated wheat by developing translocation lines, however translocation can reduce the yield (Friebe *et al.*, 1996). Radiation can be used to generate random chromosome breakages during this process (Sears and Gustafson, 1993). In addition to translocation lines, genetic diversity in cultivated wheat can also be increased through the development of 'amphidiploid' lines by hybridization, for example, crossing between cultivated wheat and *Aegilops, Secale, Thinopyrum* and *Triticum spp*. Resulting hybrids from these crosses are usually sterile, but can be converted into fertile lines by with colchicine/caffeine treatments which double the chromosome numbers (**Figure 1.4**). The amphidiploid lines can be screened under hostile soil conditions for a range of traits, including responses to biotic and abiotic stresses (Nemeth *et al.*, 2015).

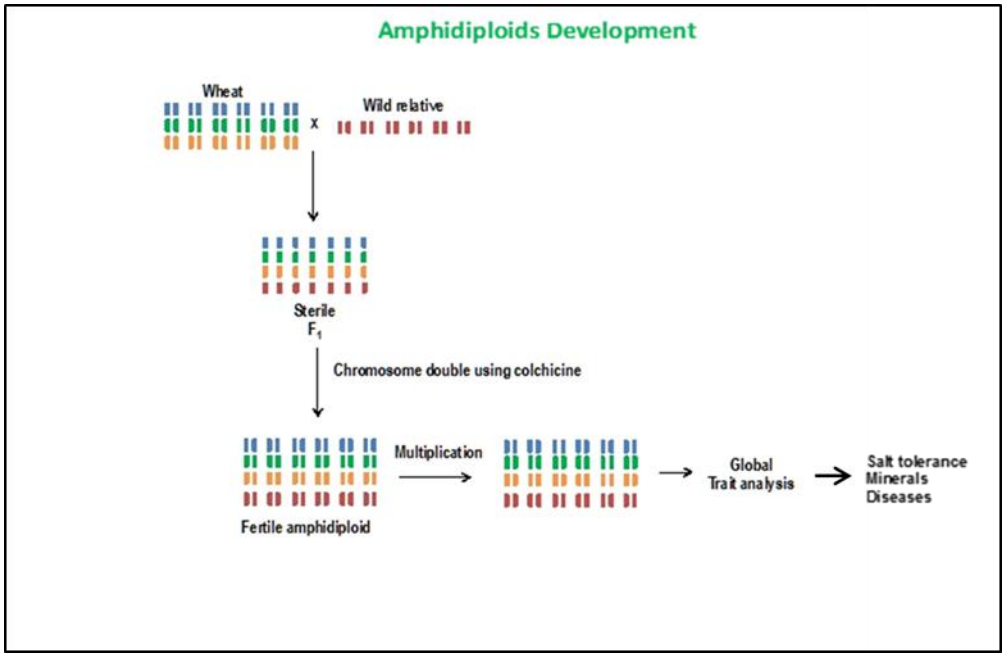


Figure 1.4 Systematic development of amphidiploids and screening for different traits (redrawn from, Nemeth *et al*., 2015).

1.7 Impact of hostile soils on global wheat production

There are several major abiotic constraints to increasing wheat production globally and in India. Soil stresses, for example, acidic soil, saline/alkaline soils are widespread. Soil acidity is the result of excessive amount of free H^+ ions in the soil solution which further adversely affect the availability of soil nutrients. Globally, it is estimated that ~4000 Mha of arable agriculture land is suffering from soil acidity and 38% area affected in Southeast Asia, 31% in Latin America, 20% in East Asia and 56% in Sub Saharan Africa (cross ref. Bian *et al*., 2013). In India, soil acidity affects 25 Mha of soils, including 30% of current areas under cultivation (Sharma *et al*., 2012). Crops grown on soil with pH<5.5 typically suffer from aluminium (Al) toxicities and deficiency of phosphorus (P), boron (B), molybdenum (Mo) and other nutrients (Singh, 2009).

On the other hand, salt affected soils where excessive amount of salt in the soil affect the plant growth and consequently reduce the grain yield. Salt affected soils can be classified into saline and sodic soils, depending upon the concentration and types of salts present in the soil. It is estimated that more than 950 Mha of global area is affected by salt, of which, ~350 Mha are suffering from salinity and 600 Mha from sodicity (FAO, 2015). In India, 6.7 Mha land area is salt affected, of which 3 Mha by salinity and 3.7 Mha by sodicity/alkalinity, distributed across 15 of 29 states (Mandal *et al*., 2010; Sharma *et al*., 2012). Saline and sodic soil conditions adversely affect the uptake of water and nutrient from the soil and imposes the significant effect on reduction in grain yield (Tavakkoli *et al*., 2012) which is studied in Chapter 2.

1.8 Strategies to improve wheat production under hostile affected soils

Improving crop production under saline/sodic soils can achieved through both soil chemical and mechanical management practices, and through traditional breeding approaches (Genc *et al*., 2016). In India, soil chemical and mechanical management has been adopted to increase the wheat production under salt affected soils. For example, land levelling, farm yard manure (FYM) and green manure (Biswas and Biswas, 2014) and around 180,000 ha area of alkali soils have been reclaimed using gypsum ($CaSO_4$) which contributes 12-15 Mt of wheat annually (Sharma and Gupta, 2010). Liming is the most economical and widely used method to reclaim acidic soils in India. Typically, ground limestone from calcite ($CaCO_3$), dolomite ($CaCO_3$, $MgCO_3$) is used to neutralize acidic soils. Generally, lime is broadcast on the soil surface and mixed with soil during

tillage (Fageria and Baligar, 2008). Soil liming can increase the crop-availability of phosphorus (P) and other nutrients in the soil (Osundwa *et al*., 2013). However, chemical and mechanical management of hostile soils increase input costs and, where farmers have small land holdings is likely to require subsidies. There is therefore a need to screen the modern high yielding wheat genotypes under different hostile soil conditions to identify the site specific salt tolerant genotypes (Chapter 2) and with the involvement of salt tolerant wild species to widen the genetic diversity for salt tolerance in the modern wheat cultivars.

1.8.1 Development of salt tolerant wheat using wheat wild relatives

Several approaches have been adopted to develop salt tolerant wheat by using conventional breeding, wide crosses using wheat wild relatives, and using biotechnological approaches (Munns *et al*., 2006; Waters *et al.*, 2013). Salt tolerant wheat varieties for example, KRL 1-4, KRL 19, KRL 210 and KRL 213 have been obtained from conventional breeding efforts in India (Sharma and Gupta, 2010).

Using molecular tools such as marker assisted selection (MAS) and quantitative trait loci (QTL) mapping, breeders can pyramid salt tolerance traits into the new germplasm (Genc *et al.*, 2010). Many QTL have been found for Na^+ exclusion in wheat, rice and barley. It is reported that introgression of two genes, *Nax1* and *Nax2* which are likely to control sodium transport, from *Triticum turgidum* to *Triticum aestivum*, showed 60% reduction of Na^+ in leaf blades (James *et al*., 2011). Similarly, a salt tolerant gene, *TaSC* (*Triticum aestivum* Salt-tolerant Correlative), cloned from a salt tolerant wheat line and its expression in *Arabidopsis thaliana* showed increased salt tolerance. It is believed that this

gene may enhance the salt tolerance in plants through an effect on the calcium-dependent protein kinase (CDPK) pathway (Huang *et al*., 2012). It has been found that higher concentration of K^+ in the leaves sometimes have positive correlation with the salinity tolerance in wheat and barley and could be used as a salinity tolerance parameter (Chen *et al.*, 2007; Cuin *et al*., 2008). However, approaches based on single genes have not yet been widely deployed, because salt tolerance trait is very complex trait and their effect on yield/biomass has not been fully characterized genetically and physiologically (Flowers, 2004; Placido *et al.*, 2013; Flowers and Colmer, 2015).

Some work has been done to introgress salt tolerance into bread wheat from wheat wild relatives. The wild relative of wheat, for example, *Aegilops tauschii* (DD) and *Triticum urartu* (AA) and their derivatives have already shown tolerance to salinity under salt solution cultures (Gorham, 1990; Gorham *et al*., 1991). However, wild wheat species from the tertiary gene pool (species not share genome with wheat genotypes), particularly, *Thinopyrum bessarabicum*, which grows in coastal regions of the Crimea, showed high level of salt tolerance and better agronomic traits in saline hydroponic culture (Gorham *et al*., 1985; King *et al*., 1997a).

Thinopyrum bessarabicum (2n=14; JJ), a tall wheat grass from tribe *Triticeae*, possesses genes for salt tolerance, disease resistance and quality traits and can be used to develop the salt tolerant genotypes (King *et al*., 1997a; Qi *et al*., 2010). *Thinopyrum bessarabicum* and their derivatives have been shown to exhibit greater salt tolerance under different salt solution cultures (Gorham *et al*., 1986; King *et al*., 1997b). Amphidiploids derived from *Th. bessarabicum*

have shown better performance than wheat parents under normal soil condition (Hassani *et al*., 2000). However, amphidiploids have not yet been tested for grain yield, yield components and mineral composition traits under saline soil field conditions. Therefore, performance of eight amphidiploids derived from *Th. bessarabicum* was studied for grain yield, yield components and grain mineral composition traits under hostile soil conditions (Chapter 5).

1.9 Micronutrients deficiency and impact on human health

A healthy human diet requires a balanced intake of energy, protein and nutrients for an active and healthy life (Welch and Graham, 2004). Micronutrients (vitamins and minerals) are required in smaller quantity for normal human body functioning and cannot be synthesized in body and of which main source is different types of foods (FAO and WHO, 2001). Dietary deficiency of nutrients including, iron (Fe), zinc (Zn), calcium (Ca), magnesium (Mg), potassium (K), selenium (Se), iodine (I) and vitamins are affecting population globally (Broadley and White, 2010; Muthayya *et al*., 2013; Joy *et al*., 2015; Rahal and Shivay, 2016). Deficiency of micronutrients is also called 'hidden hunger' where people cannot feel the lack of micronutrients and their consequences immediately (Stein, 2010). Inadequacy of mineral elements occurs due to insufficient supply by diet, low bioavailability from ingested food and other co-factors which impaired the adsorption of nutrients in human body (WFP, 2017; Petry *et al*., 2014).

Globally, more than 800 million people are not getting enough calories from their food (undernourished) and 2-3.5 billion people are affected by deficiency

of one or more micronutrients in their diets (FAO *et al*. 2015; Kumssa *et al*., 2015), particularly Fe and Zn (Gregory *et al*., 2017). Micronutrient deficiencies impair human health throughout their lives. For example, Fe deficiency affects ~1.6 billion people, resulting in anaemia, maternal mortality, premature birth and low birthweight. Vitamins A affecting ~190 million children below five years of age and causing blindness, increased risk of diarrhoea and measles and 19 million pregnant women which are at risk of night blindness and death during delivery (Allen, 2006; Stein, 2010). In India, more than 58% children below 5 years age, 53% women and 23% men are anaemic and 57% of preschool children and their mothers are suffering from vitamin A deficiency, and due to malnutrition, Indian losses more than 1% of its gross domestic product (GDP), annually (Kotecha, 2008; NFHS, 2016). Zinc is an essential element for plants and human beings (Broadley *et al*., 2007; Graham *et al*., 2012). Dietary Zn deficiency is linked to diarrhoea, respiratory infections and stunting (low height to weight ratios) in children (Hess and King, 2009; King *et al*., 2016). Approximately 20% of world population is at risk of having insufficient Zn in their diets, based on food supply, with much greater proportions at risk in sub-Saharan and South Asian countries (Wessels and Brown, 2012; Kumssa *et al*., 2015; Gregory *et al*., 2017).

1.10 Approaches to improve wheat grain Zn concentration

Over the past 20 years, agronomic and breeding based approaches (agronomic and genetic biofortification) have been developed to increase the Zn concentration of wheat grain (Cakmak, 2008; White and Broadley, 2009; Joy *et al*., 2015; Gregory *et al*., 2017).

Agronomic biofortification which involves the application of appropriate micronutrients fertilisers to increase their bioavailable quantity in food crops. Zinc fertilisers in granular and foliar form are widely used to increase the crop yield and Zn concentration in edible grain under Zn deficient soils (Joy *et al*., 2015; Ram *et al*., 2016). In Turkey, Zn fertiliser use had shown many fold increase in wheat grain yield (Cakmak, 2004). Zinc is used either in zinc-sulphate (ZnSO4) or zinc-oxide forms in Zn-fertilisers and can be applied with nitrogen (N) fertilisers to save the extra cost of application. The most effective agronomic approaches to increasing wheat grain Zn concentrations involve foliar applications of $ZnSO_4$ in the presence of adequate nitrogen (Kutman *et al*., 2010). Foliar application of Zn fertilisers is more effective in the improvement of grain Zn concentrations in cereals, particularly in wheat and less expensive than Zn flour fortification (Joy *et al*., 2015). Extra cost of foliar application of Zn fertilisers can be avoided by spraying it with pesticides (Wang *et al*., 2016; Ram *et al*., 2016). In addition to increase in grain Zn concentration, Zn-fertilisers also inhibit the uptake of cadmium (Cd) from soil to grain which is non-essential toxic metal to human health (Jiao *et al*., 2004). In India, coating of Zn with urea had shown increase in the grain yield and grain Zn concentration in rice-wheat cropping system (Shivay *et al*., 2008). This approach is likely to be cost-effective in terms of yield and health benefits but may require changes to current farming practices (Joy *et al*., 2015, Joy *et al*., 2017; Wang *et al*., 2016).

Breeding for increased grain Zn concentration (genetic biofortification) is likely to be a more cost-effective approach in the longer term provided there is adequate plant-available Zn in the soil (Stein *et al*., 2007; Joy *et al*., 2017). Genetic biofortification can provide a cost effective, long term and sustainable

solution to fight with hidden hunger in the rural communities in developing countries who have limited access to diverse diets, supplements and fortified foods. Many crops have been bred and released for increased minerals and vitamins in many developing countries. For example, orange sweet potato, cassava, maize, pumpkin, rice with higher pro-vitamin A concentrations released in many developing and under developing countries with the involvement of national and international research institutes. Similarly, high Fe and Zn wheat, rice, pearl millet, sorghum, lentil, cowpea and beans have been released for consumption (Saltzman *et al*., 2013). The 'HarvestPlus' programme is developed and deploying new wheat varieties with higher grain Zn concentrations in South Asia (Singh and Velu, 2017). It is likely that optimal grain Zn concentrations will ultimately be achieved using a combination of crop improvement and agronomy (Joy *et al*., 2015, 17; Manickavelu *et al*., 2017). However, little work has been reported baseline relative contribution of genotype (G), environment (E) and G*E interactions on wheat grain Zn concentration under field conditions. Therefore, a panel of 36 Indian wheat genotypes have been studied to quantify the baseline variation in grain Zn concentration under wide range of soils in India and simultaneously the grain concentration of a wide range of elements was also determined (Chapter 3). However, wild wheat progenitors and non-progenitors wheat species and their derivatives have been screened under field and glasshouse conditions and showed greater grain Zn concentration and the grain ionome than the modern wheat cultivars (Chapters 5 and 6).

1.11 Root architecture and its importance

Root architecture of plants describes the spatial configuration of root system in soil. Roots play important roles in exploring the rhizosphere around the root for water and other nutrients which are key component in plant growth and development (Lynch, 2007; Gewin, 2010; Smith and Smet, 2012). Roots secrete some hormones in root zone and change the soil chemical property, encourage the growth of essential microorganism and their symbiosis for better plant growth and inhibit the growth of weed plants. For example, formation of root nodules in many legume crops by symbiosis of nitrogen fixing microorganisms (Walker *et al*., 2003; Downie *et al*., 2010).

1.11.1 Wheat root systems and traits to improve grain yield and quality

Wheat roots can be divided into two main root types, the primary root (seminal) system and the secondary root system (adventitious/nodal or crown roots). The primary root emerge as the first root to develop from coleorhiza followed by further primary roots (3-8 stated in Chapter 4). In mature plants, the primary root system constitute up to 10% of the total root system (Hoad *et al*., 2001). Adventitious roots emerge from basal node of coleoptile and stem and their numbers increases with the increase in the number of leaves and tillers (Hoad *et al*., 2001). The relative root distribution of winter wheat cultivars were measured in 17 field experiments, sampling by soil coring between anthesis and harvest up to 1 meter depth, total root length was calculated and it ranged from 3 to 18 km m^{-2}, and different soil environmental conditions, such as soil pH, soil texture, water level and other environmental stresses effect the root spatial configuration in soil (White *et al*., 2015). The Green Revolution increased the grain production

tremendously based on selection of shoot traits, including semi-dwarf wheat varieties (Khush, 2001). Root traits have not been used directly in wheat breeding. Interestingly, modern wheat varieties which have root biomass less than two-third of the mean of wheat landraces (Waines and Ehdaie, 2007).

A 'steep, cheap and deep' root system has been proposed to make plants more efficient in water and nutrient uptake from deeper layers of soil, even under less fertile and drought conditions (Lynch, 2013). Root traits of many crop species were studied under soil conditions using different approaches, for example, soil coring (Wasson *et al*., 2014), shovelomics (Trachsel *et al*., 2011; White *et al*., 2015) and rhizotrons (Nagel *et al*., 2012; Shrestha *et al*., 2014) to quantify the length and angle related root traits. However, studying root traits in field condition is very challenging, therefore many researchers have deployed high throughput phenotyping (HTP) systems to screen wheat seedling root traits and tested their relationships with grain yield and component traits measured in normal field conditions. For example, a germination paper based 'cigar roll' system was used to grow 199 double haploid wheat near isogenic lines (NILs) for 11 days to screen the seedling root traits. They reported no correlation of primary root length and lateral root length with matured plant height measured in field (Bai *et al*., 2013). Similarly, narrow root angle between the primary pair of seminal roots of 14 days old seedlings grown in root boxes not correlated with grain yield measured in field of 52 wheat genotypes (McDonald, 2010). A 'pouch & wick' germination paper based approach was used to grow 94 double haploid wheat lines in nutrient solution for nine days to study the root architectural traits by Atkinson *et al*., 2015. They reported no correlation between seedling root traits and grain yield and plant height, measured in field

experiments with high nitrogen and low nitrogen treatments. Similarly, Xie *et al*., 2017 also grew 226 wheat recombinant inbred lines in 'pouch & wick' system for 13 days and reported positive significant relationships of seedling root traits with grain yield and yield components measured under normal soil field trials in United Kingdom (UK).

It is evident that indoor screening of juvenile root traits on artificial growing medium have shown associations with grain yield and yield component traits measured in normal growing field conditions, however, juvenile root traits have not been tested for correlation with field traits measured under different hostile soils. Therefore, juvenile root traits of 36 Indian wheat genotypes and eight amphidiploids, derived from *Th. bessarabicum*, have been quantified in 'pouch & wick' growth system and association between juvenile root traits and grain yield, yield components and mineral composition traits measured in a wide range of soil environments were studied (Chapter 4 and Chapter 5).

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CHAPTER 2. CHARACETERISING VARIATION IN WHEAT TRAITS UNDER HOSTILE SOIL CONDITIONS IN INDIA

2.1 Authors contribution

JSK, SS, BST, GS, SDY, IPK and MRB designed the study. AKY, TD and VS managed the experiments at Pundibari, Malda and Kumarganj sites, respectively. JSK collected and compiled the data and carried out data analysis and prepared the original draft of the manuscript. All the authors contributed in reviewing and editing the manuscript.

2.2 Abstract

Intensive crop breeding has increased wheat yields and production in India. Wheat improvement in India typically involves selecting yield and component traits under non-hostile soil conditions at regional scales. The aim of this study is to quantify G*E interactions on yield and component traits to further explore site-specific trait selection for hostile soils. Field experiments were conducted at six sites (pH range 4.5-9.5) in 2013-14 and 2014-15, in three agro-climatic regions of India. At each site, yield and component traits were measured on 36 genotypes, representing elite varieties from a wide genetic background developed for different regions. Mean grain yields ranged from 1.0 to 5.5 t ha^{-1} at hostile and non-hostile sites, respectively. Site (E) had the largest effect on yield and component traits, however, interactions between genotype and site (G*E) affected most traits to a greater extent than genotype alone. Within each agro-climatic region, yield and component traits correlated positively between hostile and non-hostile sites. However, some genotypes performed better under hostile soils, with site-specific relationships between yield and component traits, which supports the value of ongoing site-specific selection activities.

2.3 Introduction

2.3.1 Wheat breeding in India

Wheat is the world's third most widely consumed crop after rice and maize. It accounts directly for ~21% of energy intake for the world's population (Shiferaw *et al*., 2013; Ortiz *et al*., 2008) and more than 50% of the energy intake in the Indian population (www.dwr.in). In India, wheat production increased from 11 Mt to 94 Mt from 1961 to 2016 (USDA, 2014; DACFW, 2016) due to selective breeding for high yielding semi-dwarf varieties. Seeds of varieties including Sonara 63, Sonara 64, Mayo 64 and Lerma Rojo 64 along with 613 segregating lines were introduced in India from the International Maize and Wheat Improvement Center (CIMMYT) and led to the release of five commercial varieties (PV 18, Kalyan Sona, Sonalika, Choti Lerma and Safed Lerma) which led to the Green Revolution in India (Singh and Kohli, 1997) (www.dwr.in). At present, wheat breeding programmes in India are co-ordinated by the IIWBR (Indian Institute of Wheat & Barley Research), formerly DWR (Directorate of Wheat Research), based at Karnal, through the All India Coordinated Wheat & Barley Improvement Programme (AICW&BIP). Since the establishment of AICW&BIP, there have been major developments in yield potentials, productivity and sustainability of wheat in India. For example, the area, productivity and production of wheat increased by 123%, 226%, and 630%, respectively, in 2006-07, compared to 1965-66 (www.dwr.in).

New wheat varieties are developed in India through a systematic testing procedure. The IIWBR coordinates multi-location testing of wheat and barley varieties and technologies at 31 centres located in State Agricultural Universities

(SAUs) and other centres across six agro-climatic zones for wheat cultivation. These zones are: 1. Northern Hill Zone (NHZ), 2. North-Western Plains Zone (NWPZ), 3. North-Eastern Plains Zone (NEPZ), 4. Central Zone (CZ), 5. Peninsular Zone (PZ), 6. Southern Hills Zone (SHZ). Variety trials, grain multiplication and the field evaluation trials involves evaluation for yield and contributing traits, disease incidence, agronomic practices and grain quality traits. Each year, ~500 accessions/entries are tested in ~450 varietal trials at ~130 locations (www.dwr.in)**Error! Hyperlink reference not valid.**.

2.3.2 Marginal soils are widespread in India and can contribute to sustainable intensification

There are several major abiotic constraints to further increases in wheat production in India, including widespread soil stresses. In India, 6.7 Mha land under wheat cultivation is affected by salt including 3 Mha by salinity and 3.7 Mha by sodicity/alkalinity, distributed across 15 of the 29 states. Out of these 15 states, eight contribute ~97% of national wheat production and have ~5.6 Mha affected by salt. Soil acidity affects 25 Mha of Indian soils, including ~30% of current areas under cultivation (Mondal *et al*., 2010; Sharma *et al*., 2012). The IIWBR has a Salinity/Alkalinity Screening Nursery (SATSN) programme which runs at a small number of locations each year. However, soils at most locations used for screening new varieties are classified as 'normal' within each cultivation zone and trials on marginal soils (e.g. saline, sodic, low pH) are not routinely conducted.

Saline soils are defined as having an electric conductivity (EC_e) >4 dS m^{-1}, an Exchangeable Sodium Percentage (ESP) <15, a Sodium Adsorption Ratio

(SAR) <13 and a pH <8.2 (Bower *et al*., 1952; Singh, 2005). Saline soils are typically dominated by chloride and sulphate ions and are associated with arid and semiarid climates. Sodic soils have a higher pH (>8.2), ESP >15 and are also referred as alkaline soils (Dey and Gupta, 2011). Sodic soils are dominated by sodium ions, and carbonate and bicarbonate of sodium on exchange sites. These salts are responsible for the poor physical condition of the soil and give the soil black colour due to dispersion of organic matter and clay (Singh *et al*., 2010; Krishnamurthy *et al*., 2016). Excessive salt in soil and water affects plants morphological, physiological and biochemical properties; resulting in reduction of crop growth and productivity (Koca *et al*., 2007). Salinity may cause osmotic stress, ionic toxicity through osmotic and biochemical processes and nutritional imbalances through reduced uptake of essential elements (Ashraf *et al*., 2008; Munns and Tester, 2008; Lenis *et al*., 2011. Considerable fundamental knowledge has been gained in plant biology under salt stressed conditions at cellular and tissues level (Munns and Tester, 2008; Genc *et al*., 2016; Munns and Gilliham, 2015). However, to our knowledge, new salt tolerant varieties have yet to be adopted following the targeting of specific physiological processes. Crops grown on acidic soils with pH <5.5 typically suffer from aluminum (Al) toxicities and deficiencies of phosphorus (P), boron (B) and molybdenum (Mo) (Singh, 2009).

Small-scale programs to screen for varieties within improved salt tolerance use a limited number of genotypes at a few sites in India. However, it is not yet clear which traits from main breeding programs under ‘normal’ soils will have value in breeding programs on hostile soils, which limit the deployment of trait-based selection. The aim of this study is therefore to quantify the contribution of

environmental and genotypic sources of variation on grain yield and component traits in Indian wheat, using a common reference panel of diverse wheat genotypes. These data could help to identify which traits might be more amenable for crop improvement for marginal soils, based on site-specific selection.

2.4 Materials and methods

2.4.1 Experimental sites

The study was carried out at six field sites in major wheat growing areas of India, during *rabi* (winter) seasons in 2013/14 and 2014/15. Two sites were selected from within an agro-climatic region of the North Western Plains Zone (NWPZ); four sites were selected from the North Eastern Plains Zone (NEPZ), two sites from each of two different agro-climatic regions in NEPZ. Within each region, one site was selected to represent a 'normal' soil, the other a 'hostile' soil (**Table 2.1**). The NWPZ sites were, (1) IIWBR, Karnal, Haryana (HR); (2) IIWBR, Hisar (HR); NEPZ were, (3) Narendra Deva University of Agriculture and Technology (NDUA&T), Kumarganj, Faizabad, Uttar Pradesh (UP), reclaimed site; (4) NDUA&T, Kumarganj, Faizabad (UP), sodic site; (5) Uttar Banga Krishi Viswavidyalaya (UBKV), Pundibari, Cooch Behar, West Bengal (WB); (6) UBKV, Regional Research Sub-Station (RRSS), Mathurapur, Malda (WB). Sites (2), (4) and (5) represent 'hostile' soils (pH range 4.5-9.5), and sites (1), (3) and (6) represent 'normal' soils (pH range 7.2-8.3). Site 3 was reclaimed using heavy applications of Farm Yard Manure (FYM), >10 years ago. The experiments were conducted at research farms of IIWBR, Karnal; NDUA&T,

Kumarganj and UBKV, Pundibari with their research director's permission and study received the permission from Indian Council of Agricultural Research (ICAR) and Department of Biotechnology (DBT) under a collaborative project between India and University of Nottingham, UK, grant number BT/IN/UK/12/IS/2012.

Table 2.1. Sowing dates and cropping pattern of field experiments.

Site	Growing zone[a]	Grid	Sowing	Harvesting	Year	Soil type	Cropping pattern
IIWBR, Karnal	NWPZ	29.70° N	20.11.13	20.04.14	2013/14	Normal	Rice-Wheat
		76.99° E	26.11.14	23.04.15	2014/15		
IIWBR, Hisar	NWPZ	29.18° N	21.11.13	24.04.14	2013/14	Hostile	Cotton-Wheat
		75.70° E	19.11.14	22.04.15	2014/15		
NDUA&T, Kumarganj-reclaimed	NEPZ	26.43° N	28.11.13	26.04.14	2013/14	Normal	Rice-Wheat
		82.17° E	09.12.14	23.04.15	2014/15		
NDUA&T, Kumarganj-sodic	NEPZ	26.43° N	02.12.13	04.05.14	2013/14	Hostile	Rice-Wheat
		82.17° E	09.12.14	23.04.15	2014/15		
RRSS, Mathurapur, Malda	NEPZ	25.57° N	04.12.13	04.04.14	2013/14	Normal	Rice-Wheat
		87.10° E	25.11.14	08.04.15	2014/15		
UBKV, Pundibari	NEPZ	26.32° N	25.11.13	01.04.14	2013/14	Hostile	Rice-Wheat
		89.45° E	26.11.14	03.04.15	2014/15		

[a]NEPZ, North Eastern Plain Zone; NWPZ, North Western Plain Zone

2.4.2 Germplasm

A panel of elite wheat genotypes comprising *Triticum aestivum* L. (n=34) and *Triticum durum* L. (n=2) were selected, represented a diverse genetic background and adaptations to a range of climatic and soil environments (**Table 2.2**).

Table 2.2 Wheat genotypes used in field trials during 2013/14 and 2014/15.

Variety	Pedigree	Date of release	Adoption Area[a]	Production Condition[b]
Kharchia-65	Kharchia Local/EG 953	1970	All zones	TS,IR
HD-2009	LR 64 A / NAI 60	1975	NWPZ	TS,IR
UP-262	S 308/BJ 66	1978	NEPZ	TS,IR
KRL 1-4	Kharchia 65/WL 711	1990	All zones	TS,IR
HI-8498	CR 'S'-GS'S'//A-9-30-1/Raj 911	1999	CZ	TS,IR
HW-2044	HD 226*5/Sunstar*6/C-80-1	1999	SHZ	TS,IR
KRL-19	PBW 255/KRL 1-4	2000	All zones	TS,IR
HD-2733	Attila/3/Tui/Carc//Chen/Chto/4/Atila	2001	NEPZ	TS,IR
GW-322	PBW 173/GW 196	2002	CZ,PZ	TS,IR
DBW-14	Raj 3765/PBW 343	2002	NEPZ	LS,IR
NW-1067	TR 380-16-3-614/chat'S'	2004	UP	TS,IR
DBW-16	Raj 3765/WR 484//HUW 468	2006	NEPZ	TS,IR
K-0307	K 8321/UP 2003	2007	NEPZ	TS,IR
DBW-17	Cmh79a.95/3*Cno79//Raj 3777	2007	NWPZ	TS, IR
WH-1021	Nyot 95/Sonak	2007	NWPZ	LS,IR
HD-2932	Kauz/Star//HD 2643	2008	CZ	TS,IR
CBW-38	Cndo/r143//Ente/Mexi-2/3/Ae.squarrosa(taus)/4/Weaver/5/2*Pastor	2008	NEPZ	TS,IR
DBW-39	Attila/Hui	2010	NEPZ	TS,IR
DBW-51	Site/Milan	2010	NEPZ	LS,IR
KRL-213	Cndo/r143//Ente/Mexi-2/3Aegilops squarrosa(taus)/4/Weaver/5/2*Kauz	2010	NWPZ	TS,IR
PDW-314	Ajaia12/F3Local(SEL.Ethio.135.85)//Platai 13/3/Somat3/4/Sooty/Rascon37	2010	NWPZ	TS,IR
KRL-210	PBW 65/2*Pastor	2010	NWPZ/NEPZ	TS,IR
MACS-6222	HD 2189*2//MACS 2496	2010	PZ	TS,IR
HI-1563	MACS 2496*2MC 10	2011	NEPZ	LS,IR
HD-2967	Ald/Coc//User/HD 2160m/HD22778	2011	NWPZ	TS,IR
DPW-621-50	Kauz//Altar84/aOS/3/Milan/Kauz/4/Huites	2011	NWPZ	TS,IR
RAJ-4238	HW 2021/Raj 3765	2012	CZ	LS,IR
RAJ-4229	HW 2048/Raj 4000	2012	NEPZ	TS,IR
NW-4018	-	2013	NWPZ	LS,IR
WH-1105	Milan/S87230//Babax	2013	NWPZ	TS,IR
DBW-71	Prinia/UP 2425	2013	NWPZ	LS,IR
RW-3684	Pastor.florkwa.1//Pastor	Stock	-	TS,RF
NW-4092	Site/MO/Milan/3/PBW 343	Stock	NWPZ	LS,IR
KRL 3-4	HD 1982/Kharchia 65	[c]Stock (2009)	All zones	TS,IR
BH-1146	Eonta ponta grossa 1//Fretes/Martin	Stock (1987)	-	-
DBW-46	PBW 343/Inq21	Stock (2011)	-	-

[a]NEPZ, North Eastern Plain Zone; NWPZ, North Western Plain Zone; CZ, Central Zone; PZ, Peninsular Zone; SHZ, Southern Hills Zone

[b]TS, Timely Sown; LS, Late Sown; IR, Irrigated; RF, Rain fed

[c]Stock refers to advanced breeding line used in breeding programme

2.4.3 Field management

Wheat was sown in *rabi* (winter) season in November/December and harvested during April/May in 2013/14 and 2014/15, at all the sites (**Table 2.1**). After

conventional operations, including field preparation, fertilizing, disking, levelling and furrowing, seeds were manually placed in four rows per plot at 25 cm spacing between rows. The plot length was 2.5 m. The number of seeds sown for each genotype was the same for each plot (~624 seed). The plots were arranged in a simple lattice design (6x6) with two replicates according to standard IIWBR practices.

Fertilisers were applied at a rate of 150 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1} as urea, triple super phosphate (TSP) and muriate of potash (MOP), respectively. All fertilisers, including one third of the N, were applied uniformly in the field during final land preparation. One third of the N was top dressed at nodal root initiation (NRI) stage, ~21 days after sowing (DAS), and the remaining N was applied at the time of second irrigation, ~45 DAS. Experiments were irrigated when required to avoid water stress to the plants, typically on three occasions, to bring the soil moisture close to the field capacity during NRI, booting and grain filling stages. Weeds were controlled manually at 30 DAS by hand weeding and then crops were protected from pests and disease as required. Crops were harvested at maturity, sun-dried and then threshed.

2.4.4 Traits scored

Pre-harvest traits, for example, Grain number per spike (GNS); Grain weight per spike (GWS, g) and Plant height at maturity (PHT, cm) were recorded on five randomly selected plants per plot, which were tagged for subsequent measurements at maturity, alongside plot-scale measurements. Data were recorded on the following traits: Grain yield per plot at 12-13% dry weight (GYD, g); GNS; GWS; 1000 grain weight (TGW, g); Productive tillers per

meter (PTM); Biological yield per plot (BYD, g); Harvest index (HI, %); Days to 75% heading (DTH, d); Days to anthesis (DTA, d); Days to 75% maturity (DTM, d); PHT.

2.4.5 Statistical analysis

Variance components were calculated for all yield and component traits using Residual Maximum Likelihood (REML) analyses. Two-way analysis of variance (ANOVA) was used to test for differences in yield and yield component trait due to genotype and site factors, for each year, within each of the three agro-climatic regions. Means of yield and yield component traits were compared using Least Significant Difference (LSD). Differences between sites and genotypes for grain yield were considered significant at $P<0.01$. Pearson correlation coefficients were calculated to explore correlations among yield and component traits, for each site in each year. A principal component analysis (PCA) on data variates was performed to construct a biplot for grain yield to study the effect of genotype, and genotype by environment interaction, to explore the adaptation of genotypes to the specific sites. All data analyses were conducted using GenStat 17th Edition (VSN International Ltd, Hemel Hempstead, UK).

2.5 Results

2.5.1 Contribution of G, E and G*E interaction to yield and components traits

Primary data are provide in S2.2 Table (https://doi.org/10.1371/journal.pone.0179208.s002). Site accounted for most of the variation in yield and component traits in both years. For example, 76% and 70% of the variation in GYD was due to site factor in 2013/14 and 2014/15, respectively. Site also accounted for most of the variation in DTA (81 and 91%) and DTM (90 and 92%) in 2013/14 and 2014/15, respectively. In 2013/14, PHT was controlled by E (76%) factor to a larger extent than G (16%); in 2014/15 both G and G*E interaction affect PHT similarly (40 and 49 % respectively). G and G*E interaction factors had a much greater influence on TGW, GWS, HI and PHT than on GYD, DTA and DTM during both the years.

2.5.2 Variation in yield and component traits under normal and hostile soils

2.5.2.1 Trait comparisons between Karnal (normal) and Hisar (saline) sites

Yield and component traits were typically greater at Karnal than Hisar. The GYD was greater at Karnal than at Hisar in both years (**Figure 2.1**a, b). In 2013/14, GYD was 5.5 and 4.4 t ha^{-1} at Karnal and Hisar, respectively (LSD=0.44). In 2014/15, GYD was 5.3 and 2.9 t ha^{-1} at Karnal and Hisar, respectively (LSD=0.34). The marginal and substantial yield reductions at Karnal and Hisar, respectively, in 2014/15 were due to heavy later rains (post-heading) (S2.1 Table; https://doi.org/10.1371/journal.pone.0179208.s001). The TGW did not differ significantly between Karnal and Hisar in 2013/14 but was

greater at Karnal in 2014/15 (**Figure 2.1**c, d). In 2013/14, TGW was 39.4 and 39.6 g at Karnal and Hisar, respectively (LSD=1.87). In 2014/15, TGW was 44.5 and 39.8 at Karnal and Hisar, respectively (LSD=1.76). Conversely, the GWS was slightly lower at Karnal than Hisar in 2013/14 (**Figure 2.1**e, f). In 2013/14, GWS was 1.9 and 2.1 g at Karnal and Hisar, respectively (LSD=0.12). In 2014/15, GWS was 2.2 and 1.8 g at Karnal and Hisar, respectively (LSD=0.15).

The HI was greater at Karnal than at Hisar in both years (**Figure 2.1**g, h). In 2013/14, HI was 33 and 30.5 % at Karnal and Hisar, respectively (LSD=2.32). In 2014/15, HI was 33.2 and 26.5 % at Karnal and Hisar, respectively (LSD=1.74). The PHT did not differ significantly between Karnal and Hisar in either year (**Figure 2.1**i, j). In 2013/14, PHT was 101.9 and 99.2 cm at Karnal and Hisar, respectively (LSD=3.76). In 2014/15, PHT was 88.3 and 91.4 cm at Karnal and Hisar respectively (LSD=3.06).

Crop development was slightly faster at Karnal than Hisar. Thus, the phenological stages DTM and DTA were earlier at Karnal than at Hisar in both years (Figure 2.1k-n). In 2013/14, DTM was 136 and 143 days at Karnal and Hisar, respectively (LSD=0.81). In 2014/15, DTM was 133 and 141 days at Karnal and Hisar, respectively (LSD=1.03). In 2013/14, DTA was 101 and 105 days at Karnal and Hisar, respectively (LSD=1.18). In 2014/15, DTA was 95 and 103 days at Karnal and Hisar, respectively (LSD=1.07).

Two-way analysis of variance (ANOVA) was used to assess the variation in traits due to genotype and site factors across both years, showed that most of the yield and component traits differed significantly between sites, except PHT (P=0.8) (S2.3 Table; https://doi.org/10.1371/journal.pone.0179208.s003).

2.5.2.2 Trait comparisons between Kumarganj-reclaimed (normal/saline) and Kumarganj-sodic (sodic) sites

Yield and component traits were greater at the Kumarganj-reclaimed than the Kumarganj-sodic sites. The GYD was greater at the reclaimed than at the sodic site in both years. In 2013/14, GYD was 1.8 and 0.9 t ha^{-1} at reclaimed and sodic sites, respectively (LSD=0.13). In 2014/15, GYD was 3.1 and 1.4 t ha^{-1} at reclaimed and sodic sites, respectively (LSD=0.19) (**Figure 2.1**a, b). The TGW was greater at the reclaimed site than at the sodic site in both years. In 2013/14, TGW was 34.5 and 29.1 g at reclaimed and sodic sites, respectively (LSD=1.15). In 2014/15, TGW was 37 and 32.3 g at reclaimed and sodic sites, respectively (LSD=1.65) (**Figure 2.1**c, d). However, the GWS was greater at the reclaimed site than at the sodic site in both years. In 2013/14, the GWS was 1.8 and 1.2 g at reclaimed and sodic sites, respectively (LSD=0.11). In 2014/15, GWS was 1.5 and 1.4 g at reclaimed and sodic sites, respectively (LSD=0.09) (**Figure 2.1**e, f).

The HI did not differ significantly between reclaimed and sodic sites in 2013/14, but was greater at the sodic site in 2014/15. In 2013/14, HI was 39.9 and 39.3 % at reclaimed and sodic sites, respectively (LSD=1.15). In 2014/15, HI was 36.5 and 39.5 % at reclaimed and sodic sites, respectively (LSD=2.25) (**Figure 2.1**g, h). The PHT was higher at the reclaimed site than at the sodic site in both years. In 2013/14, PHT was 74.4 and 63.8 cm at reclaimed and sodic sites, respectively (LSD=3.1). In 2014/15, PHT was 86.7 and 72.8 cm at reclaimed and sodic sites, respectively (LSD=2.87) (**Figure 2.1**i, j).

Crop development was slightly slower at the reclaimed site than at the sodic site. Thus, DTM was greater at the reclaimed site than at the sodic site in both years. In 2013/14, DTM was 130 and 127 days at reclaimed and sodic sites, respectively (LSD=0.67). In 2014/15, DTM was 120 and 115 days at reclaimed and sodic sites, respectively (LSD=0.58) (**Figure 2.1**k, l). However, The DTA did not differ significantly between reclaimed and sodic sites in either year. In 2013/14, DTA was 91 and 90 days at reclaimed and sodic sites, respectively (LSD=1.08). In 2014/15, DTA was 79 days at both reclaimed and sodic sites (LSD=1.11) (**Figure 2.1**m, n).

Two-way ANOVA showed that all of the yield and component traits differed significantly between the Kumarganj-reclaimed and Kumarganj-sodic sites, except for HI (*P*=0.06) and DTA (*P*=0.24) (S2.3 Table).

2.5.2.3 Trait comparisons between Malda (normal) and Pundibari (acidic) sites

The GYD was lower at Malda than Pundibari in 2013/14 while in 2014/15 Malda had greater GYD than Pundibari (**Figure 2.1**a, b). In 2013/14, GYD was 3.1 and 3.4 t ha^{-1} at Malda and Pundibari, respectively (LSD=0.21). In 2014/15, GYD was 4.8 and 4.1 t ha^{-1} at Malda and Pundibari, respectively (LSD=0.29). The TGW and GWS did not differ significantly between Malda and Pundibari sites in 2013/14 but were greater at Pundibari than at Malda in 2014/15. In 2013/14, TGW was 40.4 and 40.5 g at Malda and Pundibari, respectively (LSD=1.52). In 2014/15, TGW was 36.7 and 43.4 g at Malda and Pundibari, respectively (LSD=1.58) (**Figure 2.1**c, d). In 2013/14, GWS was 1.9 and 1.8 g at Malda and Pundibari, respectively (LSD=0.14). In 2014/15, GWS was 1.5 and 2.1 g at Malda and Pundibari, respectively (LSD=0.09) (**Figure 2.1**e, f).

The HI did not show consistent differences between Malda and Pundibari sites between years. In 2013/14, HI was 37.5 and 41.3 % at Malda and Pundibari, respectively (LSD=2.13). In 2014/15, HI was 30.8 and 22.3 % at Malda and Pundibari, respectively (LSD=1.73) (**Figure 2.1**g, h). The PHT did not differ significantly between Malda and Pundibari sites in 2013/14 but was greater at Malda than at Pundibari in 2014/15. In 2013/14, PHT was 115.2 and 117.6 cm at Malda and Pundibari, respectively (LSD=4.23). In 2014/15, PHT was 109.6 and 91.2 cm at Malda and Pundibari respectively (LSD=4.82) (**Figure 2.1**i, j).

Crop development did not show overall consistent differences between sites, between each year. The DTM differed significantly between Malda and Pundibari in 2013/14 but not in 2014/15. In 2013/14, DTM was 112 and 127 days at Malda and Pundibari, respectively (LSD=1.23). In 2014/15, DTM was 112 and 111 days at Malda and Pundibari, respectively (LSD=1.79) (**Figure 2.1**k, l).In 2013/14, DTA was 76 and 77 days at Malda and Pundibari, respectively (LSD=1.46). In 2014/15, DTA was 84 and 78 days at Malda and Pundibari, respectively (LSD=2.12) (**Figure 2.1**m, n).

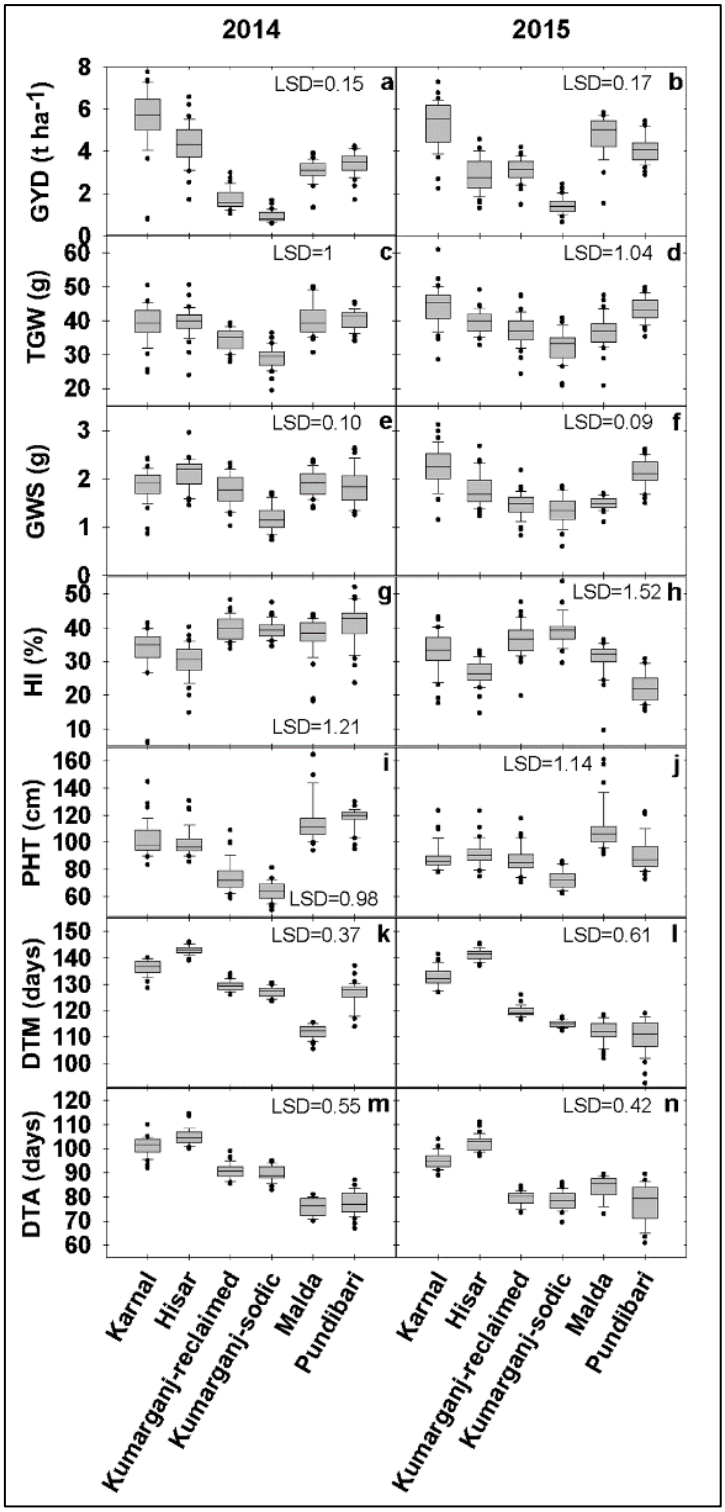


Figure 2.1 Yield and component traits at the six sites during 2013/14 and 2014/15. Data represent two replicate plots per site of a panel of 36 elite genotypes (n=72). Boxes represent the two quartiles with the median drawn; whiskers are the 95% confidence limits plus outliers. Traits: GYD (grain yield, t ha^{-1}), TGW (1000 grain weight, g), GWS (grain weight per spike, g), HI (harvest index, %), PHT (plant height at maturity, cm), DTM (days to maturity, days), DTA (days to anthesis, days).

2.5.3 Variation in grain yield in panels of 36 genotypes under normal and hostile soils

In general, there were positive relationships in grain yield between years across all sites within an agro-climatic region (**Figure 2.2**). However, there is the potential for some genotypes to perform better at specific sites, i.e. the highest and lowest yielding genotypes were not usually consistent between sites.

2.5.3.1 Yield comparison of different genotypes between Karnal (normal) and Hisar (saline) sites over two seasons

There was a strong positive relationship in GYD between Karnal and Hisar in both 2013/14 ($r=0.65$; $P<0.001$) and 2014/15 ($r=0.51$; $P<0.01$). At Karnal, the highest yielding genotype was RW 3684, which had the highest GYD in 2013/14 (7.8 t ha^{-1}) and 2014/15 (7.3 t ha^{-1}) (**Figure 2.2**c, d). At Hisar, RW 3684 was the 9th highest GYD producing genotype in 2013/14 (5.1 t ha^{-1}) and 8th in 2014/15 (3.6 t ha^{-1}) (**Figure 2.2**e, f). The lowest yielding genotype at Karnal was KRL 3-4 in 2013/14 (0.8 t ha^{-1}) and 2014/15 (2.2 t ha^{-1}). At Hisar, KRL 3-4 was the 4th and 16th lowest yielding genotype in 2013/14 (3.1 t ha^{-1}) and 2014/15 (2.7 t ha^{-1}), respectively.

At Hisar, the highest yielding genotype was KRL 210, which had the highest GYD in 2013/14 (6.6 t ha^{-1}) and 2014/15 (4.6 t ha^{-1}). At Karnal, KRL 210 was the 6th and 2nd highest GYD producing genotype in 2013/14 (6.9 t ha^{-1}) and 2014/15 (6.8 t ha^{-1}), respectively. The lowest yielding genotype at Hisar was Kharchia 65 in 2013/14 (1.7 t ha^{-1}) and KRL 19 in 2014/15 (1.3 t ha^{-1}). At Karnal, Kharchia 65 and KRL 19 were the 2nd and 8th lowest yielding genotypes in 2013/14 (0.8 t ha^{-1}) and 2014/15 (4.3 t ha^{-1}), respectively.

2.5.3.2 Yield comparisons between Kumarganj-reclaimed (normal/saline) and Kumarganj-sodic (sodic) sites over two seasons

There was a weak and non-significant relationship in GYD between reclaimed and sodic sites in both 2013/14 (r= 0.25; P=0.141) and 2014/15 (r=0.19; P=0.267). At the reclaimed site, the highest yielding genotypes were DPW 621-50 and KRL 213, which had the highest GYD in 2013/14 (2.9 t ha^{-1}) and 2014/15 (4.2 t ha^{-1}), respectively (**Figure 2.2**g, h). At the sodic site, DPW 621-50 and KRL 213 were the 1st and 4th highest GYD producing genotypes in 2013/14 (1.7 t ha^{-1}) and 2014/15 (2 t ha^{-1}), respectively (**Figure 2.2**i, j). The lowest yielding genotype at the reclaimed site was WH 1105 in 2013/14 (1 t ha^{-1}) and Kharchia 65 in 2014/15 (1.5 t ha^{-1}). At the sodic site, WH 1105 and Kharchia 65 were the 18th and 9thth lowest yielding genotypes in 2013/14 (0.8 t ha^{-1}) and 2014/15 (1.2 t ha^{-1}), respectively.

At the sodic site, the highest yielding genotypes were DPW 621-50 and Raj 4238, which had the highest GYD in 2013/14 (1.7 t ha^{-1}) and 2014/15 (2.5 t ha^{-1}), respectively. At the reclaimed site, DPW 621-50 and Raj 4238 were the 1st and 29th highest GYD producing genotypes in 2013/14 (2.9 t ha^{-1}) and 2014/15 (2.6 t ha^{-1}), respectively. The lowest yielding genotype at the sodic site was MACS 6222 in 2013/14 (0.6 t ha^{-1}) and PDW 314 in 2014/15 (0.7 t ha^{-1}). At the reclaimed site, MACS 6222 and PDW 314 were the 12th and 2nd lowest yielding genotypes in 2013/14 (1.4 t ha^{-1}) and 2014/15 (2.2 t ha^{-1}), respectively.

2.5.3.3 Yield comparisons between Malda (normal) and Pundibari (acidic) sites over two seasons

There was a strong positive relationship in GYD between Malda and Pundibari sites in 2013/14 ($r=0.71$; $P<0.001$) and a weak and non-significant relationship in 2014/15 ($r=0.256$; $P=0.132$).

At Malda, the highest yielding genotypes were DBW 39 and KRL 213, which had the highest GYD in 2013/14 (3.9 t ha^{-1}) and 2014/15 (5.8 t ha^{-1}) respectively (**Figure 2.2**k, l). At Pundibari, DBW 39 and KRL 213 were the 6th and 1st highest GYD producing genotypes in 2013/14 (3.9 t ha^{-1}) and 2014/15 (5.4 t ha^{-1}), respectively (**Figure 2.2**m, n). The lowest yielding genotype at Malda was Kharchia 65 in 2013/14 (1.1 t ha^{-1}) and KRL 3-4 in 2014/15 (1.5 t ha^{-1}). At Pundibari, Kharchia 65 and KRL 3-4 were the 1st and 18th lowest yielding genotypes in 2013/14 (1.7 t ha^{-1}) and 2014/15 (4.1 t ha^{-1}), respectively.

At Pundibari, the highest yielding genotypes were HD 2967 and KRL 213, which had the highest GYD in 2013/14 (4.3 t ha^{-1}) and 2014/15 (5.4 t ha^{-1}), respectively. At Malda, HD 2967 and KRL 213 were the 9th and 1st highest GYD producing genotypes in 2013/14 (3.4 t ha^{-1}) and 2014/15 (5.8 t ha^{-1}), respectively. The lowest yielding genotype at Pundibari was Kharchia 65 in 2013/14 (1.7 t ha^{-1}) and HI 8498 in 2014/15 (2.9 t ha^{-1}). At Malda, Kharchia 65 and HI 8498 were the 1st and 8th lowest yielding genotypes in 2013/14 (1.3 t ha^{-1}) and 2014/15 (4.2 t ha^{-1}), respectively.

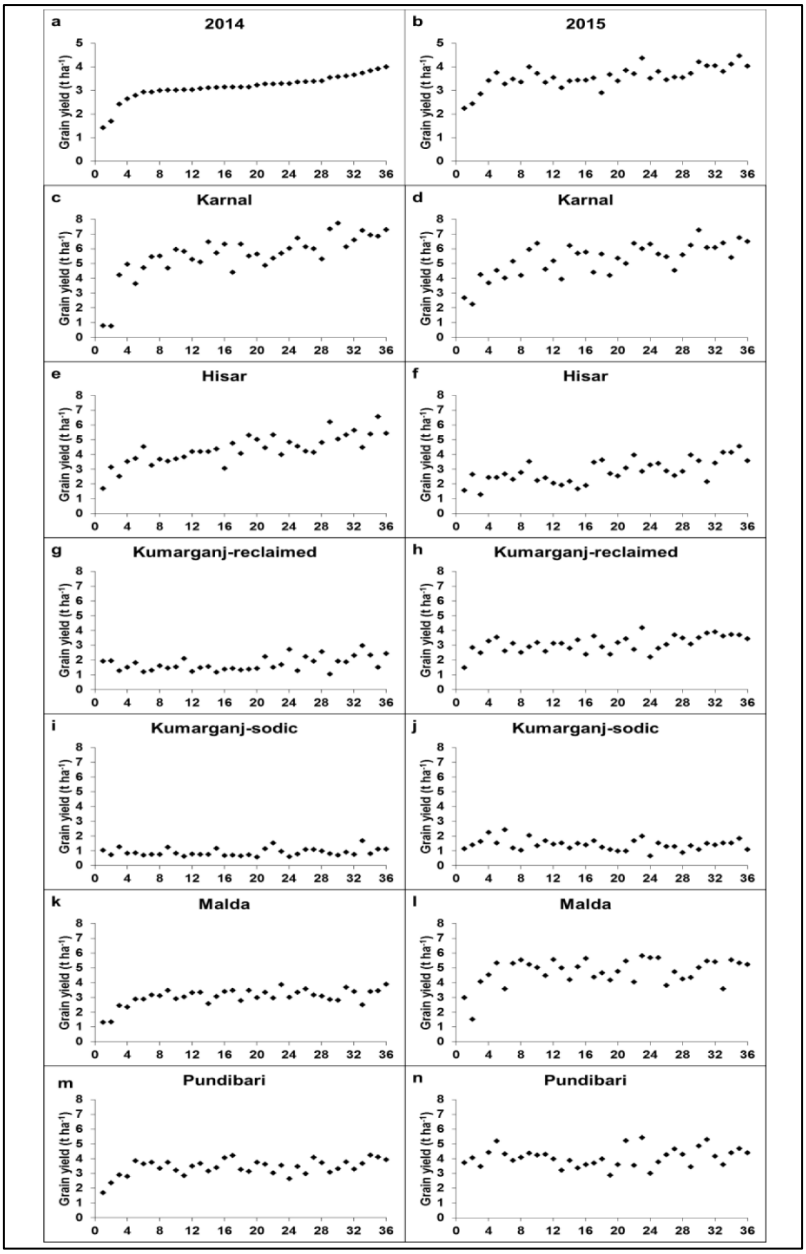


Figure 2.2 Mean grain yield of wheat harvested in 2013/14 (a,c,e,g,i,k,m) and 2014/15 (b,d,f,h,j,l,n) at six sites. In panels (a) and (b), data are means of each genotype at all sites. For all other panels, data are means of two replicate plots per site each year. Genotypes 1-36 are labelled in the same order on the x-axis as: (1) Kharchia-65; (2) KRL 3-4; (3) KRL 19; (4) BH 1146; (5) UP 262; (6) Raj 4238; (7) DBW 14; (8) Raj 4229; (9) HD 2932; (10) NW 4092; (11) HD 2009; (12) GW 322; (13) HI 1563; (14) NW 4018; (15) HW 2044; (16) KRL 1-4; (17) HD 2733; (18) HI 8498; (19) DBW 51; (20) MACS 6222; (21) DBW 16; (22) NW 1067; (23) KRL 213; (24) PDW 314; (25) WH 1021; (26) DBW 46; (27) K 0307; (28) DBW 17; (29) WH 1105; (30) RW 3684; (31) DBW 71; (32) CBW 38; (33) DPW 621-50; (34) HD 2967; (35) KRL 210; (36) DBW 39.

2.5.4 Biplot analysis for grain yield

The genotype and genotype by environment effects were visualised using a biplot (**Figure 2.3**). The biplot explained 82.4% of total variation with the contribution of 69.6% from principal component-1 (PC-1) and 12.8% from principal component 2 (PC-2). The genotypes G4 (DBW 16), G5 (DBW 17), G7 (DBW 46), G8 (DBW 51), G26 (MACS 6222) and G15 (HD 2967) which have the PC1 value >0 and PC2 value near to zero being considered the more stable genotypes across all the sites (**Figure 2.3**). Genotypes which are closest to specific sites indicates that they are likely to be better suited to that particular site (for grain yield). For example; G23 (KRL 210), G36 (WH 1105) and G10 (DPW 621-50) showed higher grain yield at Hisar site. Similarly, G21 (KRL 1-4), G24 (KRL 213), G3 (DBW 14), G11 (GW 322) and G29 (NW 4092) are better suited for Malda site in terms of grain yield.

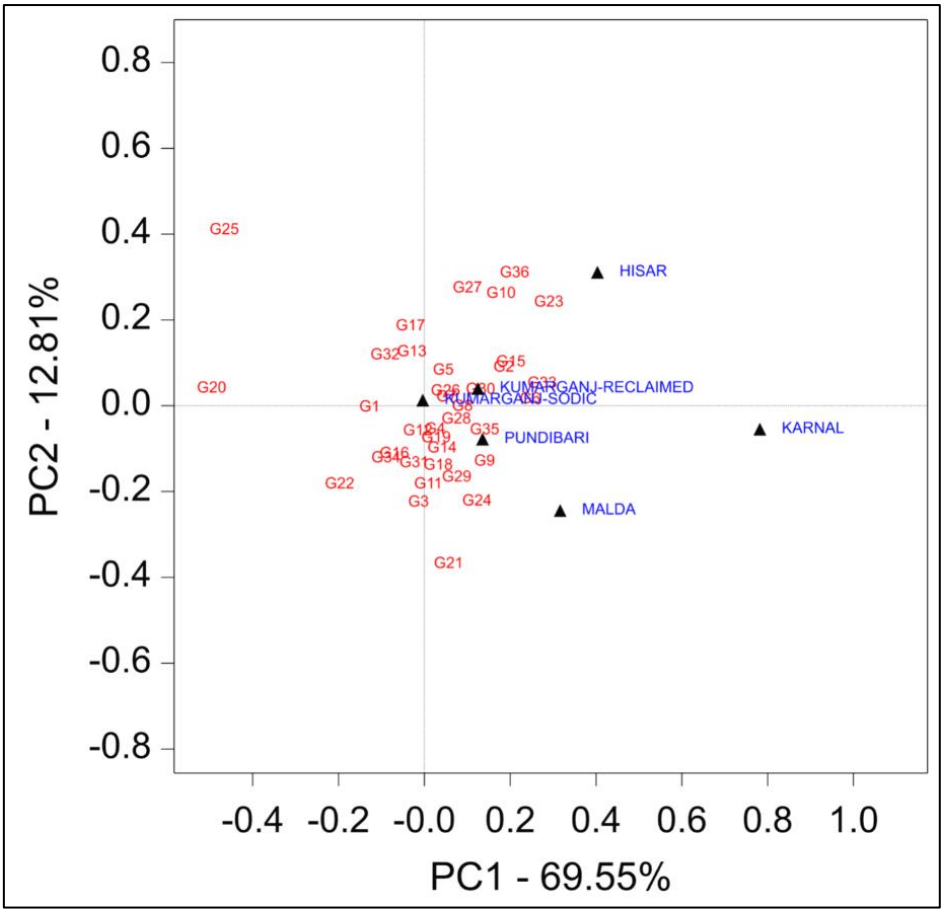


Figure 2.3 Biplot for grain yield of 36 genotypes evaluated at 6 sites over two years. Genotypes G1-G36 are as: G1 (BH 1146); G2 (CBW 28); G3 (DBW 14); G4 (DBW 16); G5 (DBW 17); G6 (DBW 39); G7 (DBW 46); G8 (DBW 51); G9 (DBW 71); G10 (DPW 621-50); G11 (GW 322); G12 (HD 2009); G13 (HD 2733); G14 (HD 2932); G15 (HD 2967); G16 (HI 1563); G17 (HI 8498); G18 (HW 2044); G19 (K 0307); G20 (Kharchia 65); G21 (KRL 1-4); G22 (KRL 19); G23 (KRL 210); G24 (KRL 213); G25 (KRL 3-4); G26 (MACS 6222); G27 (NW 1067); G28 (NW 4018); G29 (NW 4092); G30 (PDW 314); G31 (Raj 4229); G32 (Raj 4238); G33 (RW 3684); G34 (UP 262); G35 (WH 1021); G36 (WH 1105).

2.5.5 Correlations among yield and contributing traits

There were significant positive correlations between GYD and BYD at all the sites. There were also positive significant correlations between GYD and TGW at all the sites except Malda and Pundibari (**Figure 2.4**). Among other

quantitative traits, there was a positive significant correlation between TGW and GWS, between GNS and GWS, and between DTM and DTA at all sites. There was a positive significant correlation between GNS and HI at all the sites except for Kumarganj-sodic and Pundibari sites.

2.5.5.1 Correlations among yield and component traits at Karnal (normal) and Hisar (saline) sites

At Karnal, there was a significant positive correlation between GYD and TGW, GWS, HI, BYD and GNS, but GYD did not correlate with PHT, DTM, DTA and PTM (**Figure 2.4**a). At Hisar, there was a significant positive correlation between GYD and all of the traits except PHT (**Figure 2.4**b).

2.5.5.2 Correlations among yield and component traits at Kumarganj-reclaimed (normal/saline) and Kumarganj-sodic (sodic) sites

At the reclaimed site, there was a significant positive correlation between GYD and TGW, PHT, BYD and PTM, and a significant negative correlation between GYD and DTM, DTA and GNS (**Figure 2.4**c). At the sodic site, there was a significant positive correlation between GYD and TGW, GWS, PHT, BYD, GNS and PTM, and a significant negative correlation between GYD and DTM and DTA (**Figure 2.4**d). GYD did not correlate with HI at either site.

2.5.5.3 Correlations among yield and component traits at Malda (normal) and Pundibari (acidic) sites

At Malda, there was a significant positive correlation between GYD and DTA and BYD, and a significant negative correlation between GYD and GWS and PHT (**Figure 2.4**e). However, GYD did not correlate with TGW, HI, DTM or

GNS. At Pundibari, there was a significant positive correlation between GYD and BYD and PTM, and a significant negative significant correlation between GYD and DTM (**Figure 2.4**f). However, GYD did not correlate with TGW, GWS, HI, PHT, DTA or GNS.

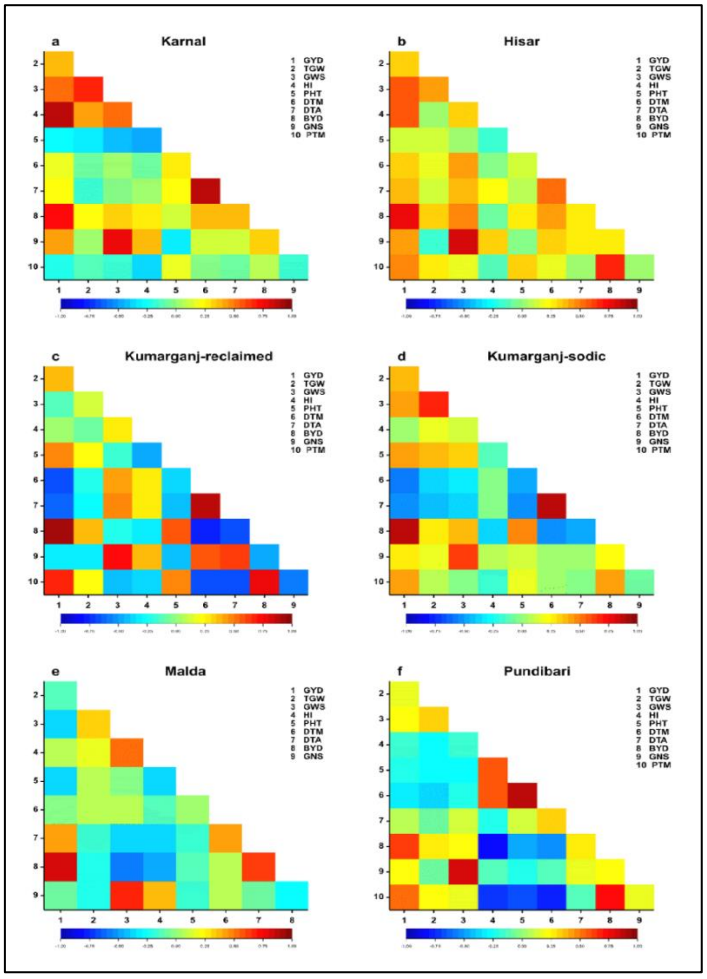


Figure 2.4 Correlation coefficients among yield and component traits of a panel of elite 36 wheat genotypes grown at six sites in India in 2013/14 and 2014/15. Colour represents strength of correlation from strongly negative (dark blue) to strongly positive (dark red). Traits measured 1-10 are labelled as: (1) grain yield (GYD); (2) 1000 grain weight (TGW); (3) grain weight per spike (GWS); (4) harvest index (HI); (5) Plant height at maturity (PHT); (6) Days to maturity (DTM); (7) Days to anthesis (DTA); (8) biological yield (BYD); (9) grain number per spike (GNS); (10) Productive tillers per meter (PTM).

2.6 Discussion

Grain yield is typically the most important trait in wheat breeding programmes. It is a result of interaction of many contributing traits which affect the grain yield directly and indirectly. Although site-specific selection has long-been adopted in cereal breeding, it remains important to quantify and understand relationships between grain yield and contributing traits under as many environments as possible. The contribution of genotypic (G) and environmental (site and year, E) sources of variation on grain yield and component traits in Indian wheat was determined to identify which traits might be most useful for site-specific selection on hostile soils. Although E had the largest effect on yield and component traits, yield and component traits correlated positively between hostile and non-hostile sites within each agro-climatic region, reflecting a large contributory effect of G. However, for most traits, more of the variation was associated with interactions between genotype and site terms (G*E) than it was to G alone. Thus, some genotypes performed better under hostile soils and site-specific correlations between yield and component traits were observed.

2.6.1 Effects of site on trait variation

Given the diverse selection of hostile and non-hostile soils from within three agro-climatic regions, it is unsurprising that site accounted most of the variation in all the traits. The hostile and non-hostile soils differed considerably in their characteristics. For example, Karnal soils were pH 7.5, with an EC of 0.2, dS m^{-1}, and organic carbon (OC) content of 0.45%. In contrast, Hisar soils were pH 8.1, with an EC of 0.41 dS m^{-1} and OC of 0.58%. Grain yield averaged across

all genotypes and year ranged from 5.4 to 3.6 t ha^{-1} at Karnal and Hisar, respectively. Kumarganj-reclaimed site soils were pH 8.2, with an EC of 0.2, dS m^{-1}, and OC content of 0.43%. On contrast, Kumarganj-sodic site soils were pH 9.4, with an EC of 0.7, dS m^{-1} and OC of 0.34%. Grain yield averaged across all genotypes and year ranged from 2.4 to 1.1 t ha^{-1} at reclaimed and sodic sites, respectively. Reduction in GYD in wheat under hostile soils (saline/sodic) is consistent with studies of Munns and Tester, 2008; James *et al.*, 2008; Ashraf *et al.*, 2008, Lenis *et al.* 2011; Zhang *et al.*, 2016 and Wright and Rajper, 2000 who reported yield reduction in wheat under sodic soils were due to fewer grains per plant and reduced grain weight.

Malda soils were pH 7.7, with an EC of 0.2, dS m^{-1}, and OC content of 0.72%. Conversely, Pundibari soils were pH 5.7, with an EC of 0.2, dS m^{-1}, and OC of 0.74%. Grain yield averaged across all genotypes and year ranged from 3.9 to 3.7 t ha^{-1} at Malda and Pundibari, respectively. Reduction in GYD under acidic soils is consistent with Tang *et al.*, 2002; Tang *et al.*, 2003; Haling *et al.*, 2011 and Bian *et al.*, 2013.

Soil management has been adopted to increase wheat production under salt affected soils. For example, soil management by using gypsum (calcium sulphate, $CaSO_4$), adequate drainage, land levelling, farm yard manure (FYM) and green manure (Biswas and Biswas, 2014). Installing PVC pipes below the soil surface is also used to provide subsurface drainage to promote leaching. Approximately 50,000 ha of waterlogged saline soils have been reclaimed in India using these technologies (Sharma and Gupta, 2010). Liming is the most economical and widely used method to reclaim acidic soils in India. Typically,

ground limestone from calcite ($CaCO_3$), dolomite ($CaCO_3$, $MgCO_3$) is used to neutralize acidic soils. Generally, lime is broadcast on the soil surface and mixed with soil during tillage (Fageria and Baligar, 2008). Soil liming can increase the crop-availability of phosphorus (P) and other nutrients in the soil (Osundwa *et al*., 2013). However, chemical and mechanical management of hostile soils increase input costs and, where farmers have small land holdings is likely to require subsidies. There is therefore a need to develop varieties tolerant to hostile soils (Singh, 2009).

2.6.2 Effects of genotype on trait variation

The elite panel of 36 genotypes were selected to encompass a wide genetic diversity with extreme morphologies, including wide variations in height, maturity date, and yield. For all yield and component traits, the variation accounted for by G was less than the variation accounted for by E. Similarly, the variation accounted for by G*E interactions accounted for more variation than G alone for most yield and component traits, with the exceptions of PHT and DTA.

Genotypes showed a strong positive correlation in GYD between Karnal and Hisar sites, and between Malda and Pundibari sites. However, there was a weak and non-significant correlation in GYD between Kumarganj-reclaimed and Kumarganj-sodic sites. Thus, whilst genotypes did not perform identically on hostile and non-hostile soils, there are common traits which can be selected for hostile conditions under standard screening. Within each agro-climatic region, many yield component traits showed positive correlations between hostile and non-hostile soils. However, TGW, GWS and HI showed only weak and non-

significant correlations between Kumarganj-reclaimed and Kumarganj-sodic sites, indicating that genotypes did not perform consistently between these sites and that there is scope for site-specific selection of traits.

2.6.3 Effects of G*E on trait variation

The G*E interaction term was associated with more of the variation in TGW, GWS, HI and GYD than PHT, DTA and DTM. Therefore, there is potentially more scope for site-specific selection for these traits. In addition, within each agro-climatic region, correlations between yield and component traits differed between hostile and non-hostile soils.

2.6.3.1 Karnal (normal) and Hisar (saline) sites

There was a positive correlation between GYD and DTA, DTM and PTM at Hisar, but not at Karnal; Kharchia 65 and KRL 3-4 had greater GYD at Hisar than Karnal. Similarly, there was a significant positive correlation between TGW and BYD and PTM at Hisar but not at Karnal. Genotypes HI 1563, MACS 6222, NW 1067 and WH 1105 had greater TGW at Hisar than Karnal. There was significant positive correlation between GWS and DTM and DTA at Hisar, but not at Karnal. Genotypes HD 2967, HI 1563, Kharchia 65, KRL 210, KRL 213, KRL 3-4, Raj 4229 and Raj 4238 had greater GWS at Hisar than Karnal. Similarly, there was a positive significant correlation between BYD and TGW, PHT and PTM at Hisar, but not at Karnal; KRL 210 had greater BYD at Hisar than Karnal.

2.6.3.2 Kumarganj-reclaimed (normal/saline) and Kumarganj-sodic (sodic) sites

There was positive significant correlation between GYD and GWS and GNS at the sodic site, but not at the reclaimed site. Similarly, there was positive significant correlation between TGW and GWS and PHT at sodic site, but not at reclaimed site. Genotypes HW 2044 and KRL 210 had greater TGW at the sodic site than at the reclaimed site, however NW 4092 and HD 2932 had similar TGW at both sites. There was positive significant correlation between GWS and GYD, TGW, PHT and BYD at the sodic site, but not at the reclaimed site; HW 2044, Kharchia 65, KRL 210 and KRL 3-4 had greater GWS at sodic site than reclaimed site.

2.6.3.3 Malda (normal) and Pundibari (acidic) sites

There was positive significant correlation between GYD and PTM at Pundibari, but not at Malda; approximately, 30% of genotypes had greater GYD at Pundibari than Malda. Similarly, there was positive significant correlation between TGW and BYD at Pundibari, but not at Malda and most of the genotypes had greater TGW at Pundibari than Malda. There was positive significant correlation between BYD and TGW and PTM at Pundibari, but not at Malda and most of the genotypes had greater BYD at Pundibari than Malda. There was positive significant correlation between HI and PHT and DTM at Pundibari, but not at Malda. Genotypes DBW 14, DPW 621-50, HI 8498, HW 2044, Kharchia 65, KRL 3-4, Raj 4229, Raj 4238 and WH 1105 had greater HI at Pundibari than Malda.

2.6.4 Some traits are more amenable to site-specific selection

2.6.4.1 Saline/sodic sites

In general, salinity/sodicity reduced the GYD, TGW, GWS, GNS, HI and BYD. Reduction in TGW in wheat under salt stress was reported by Noori *et al., 2010*; Turki *et al*., 2012 and Chamekh *et al.,* 2016. Mass and Grieve, 1990 reported that high salt (NaCl) in the soil decreased spikelets per spike, thus decreasing GNS at the vegetative stage. Salinity shortened the grain filling duration which cause reduction in grain number and weight (Javed *et al*., 2003). These observations are consistent with previous studies of yield component traits under hostile soil conditions (Ranjbar *et al*., 2010; Asli and Zanjan, 2014; Gholizadeh *et al*., 2014; Akbarpour *et al*., 2015). Given that GYD correlated positively with TGW, GWS, BYD, GNS and PTM under saline and sodic soils, routine selection based on these traits could improve grain yield under hostile soils. In particular, spike associated traits like GNS and GWS could be favourable traits for selecting high performing genotypes under hostile soils, because they increase the grain yield. DTA and DTM had negative significant correlations with GYD at Kumarganj-sodic and Kumarganj-reclaimed sites (Akbarpour *et al*., 2015; Chamekh *et al*., 2016). Early flowering and maturity might favour the grain yield under hostile soils or a way to escape salt stresses (McDonald *et al*., 2013).

Notably, some genotypes performed better for yield and component traits under salt affected soils. KRL 3-4 had a greater GYD at Hisar than Karnal and KRL 210 had the similar GYD at Hisar and Karnal sites. These varieties have Kharchia 65 background, which have been selected from salt affected areas of Rajasthan, India (Munns *et al*., 2006; Setter *et al*., 2016). The better performance of these genotypes is generally due to site-specific greater TGW, GWS, GNS

and BYD. Beneficial salt tolerance mechanisms which might have been transferred into these genotypes from Kharchia 65 include high leaf K^+ and K^+:Na^+ concentrations and water content (Sairam *et al*., 2002). An ability to retain more K^+ in the leaves by excluding Na^+ and maintaining a higher K^+:Na^+ ratio helps to retain water and is the subject of extensive studies for breeding salt tolerance (Tester and Devenport, 2003; Chen *et al*., 2005; Munns and Tester, 2008; Zhu *et al*., 2016).

2.6.4.2 Acidic sites

Overall, most of the genotypes showed reduced GYD, PHT and HI at Pundibari than Malda. Genotypes KRL 210, KRL 213 and HD 2967 performed well on the acid soil by maintaining greater TGW, DTM and BYD, which might be useful targets for site-specific selection. Acidic soils affect plant growth by reducing uptake of water and essential nutrients and by increases in solubility of toxic metals in the soil solution (Chuan *et al*., 1996; Tang *et al*., 2002; Merino *et al*., 2010). Tolerant genotypes might therefore have increased Al tolerance by exudation of citrate and malate organic acids which bond to Al and form non available organic acid and prevent Al to affect root apices (Ryan *et al*., 2009; Delhaize *et al*., 1993; Kochian *et al*., 2005). Most genotypes showed increased TGW, GWS and GNS at Pundibari than Malda. This contrasts with findings of Rahman *et al., 2013*, who reported reduction in TGW, GWS and GNS under acidic soils. The presence of higher amount of organic matter in acid soils at Pundibari compared to many acid soils might offset the phytotoxicity of Al through the formation of complexes with Al which are less available to plants (Brown *et al*., 2008). Such phenomenon are likely to be important for site-specific selection, especially for low-input systems, e.g. under Conservation

Agriculture (Sharma *et al*., 2007). Durum genotypes (HI 8498 and PDW 314) showed extreme sensitivity for acidic soils and had the lowest yield at Pundibari. These observations are consistent with studies of Tang *et al*., 2003 who also showed durum wheat was sensitive for acidic soils.

2.7 Acknowledgments

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CHAPTER 3. VARIATION IN GRAIN ZN CONCENTRATION, AND THE GRAIN IONOME, IN FIELD-GROWN INDIAN WHEAT

3.1 Author's contribution

JSK, SS, BST, GS, SDY, IPK and MRB designed the study. JSK and LW processed and prepared the samples in laboratory for ICP-MS analysis. SDY and LW carried out ICP-MS analysis. JSK compiled mineral data after laboratory analysis and carried out the statistical analysis, and prepared the initial draft of the manuscript. JSK, SS, BST, GS, SDY, IPK and MRB contributed in drafting the manuscript.

3.2 Abstract

Wheat is an important dietary source of zinc (Zn) and other mineral elements in many countries. Dietary Zn deficiency is widespread, especially in developing countries, and breeding (genetic biofortification) through the HarvestPlus programme has recently started to deliver new wheat varieties to help alleviate this problem in South Asia. To better understand the potential of wheat to alleviate dietary Zn deficiency, this study aimed to characterise the baseline effects of genotype (G), site (E) and genotype by site interactions (GxE) on grain Zn concentration, under a wide range of soil conditions in India. Field experiments were conducted on a panel of 36 Indian-adapted wheat genotypes, grown on a range of soil types (pH range 4.5-9.5), in 2013-14 (five sites) and 2014-15 (six sites). Grain samples were analysed using inductively coupled plasma-mass spectrometry (ICP-MS). The mean grain Zn concentration of the genotypes ranged from 24.9-34.8 mg kg^{-1}, averaged across site and year. Genotype and site effects were associated with 10% and 6% of the overall variation in grain Zn concentration, respectively. Whilst G x E interaction effects were evident across the panel, some genotypes had consistent rankings between sites and years. Grain Zn concentration correlated positively with grain concentrations of iron (Fe), sulphur (S), and eight other elements, but did not correlate negatively with grain yield, i.e. no yield dilution was observed. Despite a relatively small overall contribution of genotype to the overall variation in grain Zn concentration, biofortifying wheat through breeding is likely to be effective at scale given that some genotypes performed consistently across diverse soil types. Notably, all soils in this study were probably Zn deficient and interactions between wheat genotypes and soil Zn availability/management (e.g.

the use of Zn-containing fertilisers) also need to be better-understood to improve Zn supply in food systems.

3.3 Introduction

Zinc is an essential element for plants and people (Cakmak *et al*., 2000; Broadley *et al*., 2007; Graham *et al*., 2012). Approximately 20% percent of the world's population is at risk of having insufficient Zn in their diets, based on food supply, with much greater proportions at risk in sub-Saharan Africa and South Asia (Wessells *et al*., 2012; Kumssa *et al*., 2015; Gregory *et al*., 2017). Dietary Zn deficiency is linked to diarrhoea, respiratory infections and stunting (low height to weight ratios) in children (Hess and King, 2009; King *et al*., 2016). Wheat (*Triticum aestivum* L.) is the third most widely consumed cereal crop by weight, after rice and maize, providing ~20 % of total global energy and protein supply (Shiferaw *et al*., 2013). This figure rises to >50% of energy in some countries, for example, in India (www.dwr.in). Wheat is an important dietary source of Zn (Black *et al*., 2013) and supplies ~50% Zn of daily needs in India (Kumssa *et al*., 2015; http://harvestplus.org/where-we-work/india). Over the past 20 years, agronomic and breeding based approaches have been developed to increase the Zn concentration of wheat grain (Cakmak, 2008; White and Broadley, 2009). The most effective agronomic approaches to increasing wheat grain Zn concentrations involve foliar applications of $ZnSO_4$ solution in the presence of adequate nitrogen (Kutman *et al*., 2010). This approach is likely to be cost-effective in terms of yield and health benefits but may require changes to current farming practices (Zhang *et al*., 2010; Joy *et al*., 2015, Joy *et al*., 2017; Wang *et al*., 2016; Guo *et al*., 2015). Breeding for increased grain Zn concentration is likely to be a more cost-effective approach in the longer term provided there is adequate plant-available Zn in the soil (Graham *et al*., 2001; Stein *et al*., 2007; Graham *et al*., 2007; Joy *et al*., 2017).

The ‘HarvestPlus’ programme is developing and deploying new wheat varieties with higher grain Zn concentrations in South Asia (Singh and Velu, 2017). The HarvestPlus target is to enhance the grain Zn concentration in locally-adapted wheat varieties by 8-12 mg kg^{-1}, from a baseline of ~25 mg kg^{-1}, without compromising grain yield or other grain quality attributes (Velu *et al*., 2012; Velu *et al*., 2014). Through collaboration with Banaras Hindu University (BHU), Uttar Pradesh (UP), India, and several private Indian seed companies including Sai Seeds, Nirmal Seeds, and Astha Beej, three varieties have been multiplied and released with increased grain Zn concentration in Eastern UP (North Eastern Plain Zone, NEPZ): Akshai (BHU-3), Abhay (Zinc Shakthi), and BHU-6 (Velu *et al*., 2015). A high zinc wheat variety ‘Zincol-2016’ has been recommended for release and multiplication in Pakistan by the Pakistan Agriculture Research Council (PARC; http://www.harvestplus.org/node/1647).

It is likely that optimal grain Zn concentrations will ultimately be achieved using a combination of crop improvement and agronomy (Trethowan, 2005; Joy *et al*., 2015; Joy *et al*., 2017; Mallikarjuna *et al*., 2015; Manickavelu *et al*., 2017). However, to date, little work has reported baseline relative contributions of genotype (G), environment (E) and G*E interactions on wheat grain Zn concentration under field conditions. Therefore, the aim of this study was to quantify baseline variation in grain Zn concentrations of field-grown wheat, using a diverse panel of Indian-adapted wheat genotypes grown on a wide range of soil types but without addition of Zn fertilisers. Simultaneously, the grain concentration of a wider range of elements (NB, the mineral composition of biological tissues is typically referred to as the ‘ionome’ (Salt *et al*., 2008) was determined.

3.4 Material and methods

3.4.1 Wheat genotypes, field sites and management

A panel of 36 elite wheat genotypes comprising *Triticum aestivum* L. (n=34) and *Triticum durum* L. (n=2) was selected for study under field conditions. These genotypes represent a diverse genetic background with adaptations to a range of climatic and soil environments. All genotypes and experimental conditions are described in Khokhar *et al*., 2017, including data for yield and yield components. In brief, the panel was grown at six field sites in major wheat growing areas of India, during *rabi* (winter) seasons 2013-14 and 2014-15. The six sites were, (1) IIWBR, Karnal, Haryana (HR); (2) IIWBR, Hisar (HR); (3) Narendra Deva University of Agriculture and Technology (NDUA&T), Kumarganj, Faizabad, Uttar Pradesh (UP), reclaimed site; (4) NDUA&T, Kumarganj, Faizabad (UP), sodic site; (5) Uttar Banga Krishi Viswavidyalaya (UBKV), Regional Research Sub-Station (RRSS), Mathurapur, Malda (WB) and (6) UBKV, Pundibari, Cooch Behar, West Bengal (WB). Seeds were manually placed in four rows per plot at 25 cm spacing between rows. The plot length was 2.5 m. The plots were arranged in a simple lattice design (6x6) with two replicates according to standard IIWBR practices.

3.4.2 Determining plant-available soil Zn

Top- and sub-soils were sampled with a hand-auger during both growing seasons at all six sites. Five samples were taken at each experimental site at each depth from the vertices of a ‘W-pattern’. A single composite sample of 1 kg was retained for each soil depth. To determine plant-available soil Zn concentrations, sun-dried and powdered soil samples were sieved through a 2 mm Ø sieve and

a 1.5 g subsample was placed in a 20 mL centrifuge tubes to which 10 mL of 0.01 M $Ca(NO_3)_2$ was added and mixed thoroughly for 1 h on a rotary shaker. Tubes were then centrifuged at 3300 rpm for 20 minutes. The supernatant was filtered through 0.22 µm polyether sulfone (PES) micro filter to a final volume of ~8 mL and acidified to a final concentration of 2% HNO_3. Multi-elemental analyses was conducted on (technical) triplicate samples using inductively coupled plasma-mass spectrometry (ICP-MS), as described for the grain samples below. A total of 30 and 36 soil samples were analysed in 2013-14 and 2014-15, respectively; at Kumarganj-reclaimed and Kumarganj-sodic sites, soil samples were taken only from one depth, 0-30 cm, in 2013-14.

3.4.3 Grain sampling and digestion

Grains of each plot from 5 sites (all sites except Pundibari) in 2013-14, and from plots all 6 sites in 2014-15 were harvested at physiological maturity and sun-dried. A representative sub-sample of grain from each plot was carefully hand-cleaned by discarding broken grains and foreign material. In 2013-14, ~10 grains of each genotype were weighed and digested using a microwave system comprising a Multiwave 3000 platform with a 48-vessel MF50 rotor (Anton Paar Gmbh, Graz, Austria); digestion vessels were perfluoroalkoxy (PFA) linear material and polyethylethylketone (PEEK) pressure jackets (Anton Paar GmbH). Grain was digested in 2 mL 70% Trace Analysis Grade (TAG) HNO_3, 1 mL Milli-Q water (18.2 MΩ cm; Fisher Scientific UK Ltd, Loughborough, UK), and 1 mL H_2O_2. Prior to digestion, the samples were soaked in this solution for 16 h at room temperature. In 2014-15, grain samples were crushed inside a paper bag, and subsamples (~0.200 g DW) were then used without the soaking step. The microwave setting were: power = 1400 W, temperature = 140°C,

pressure = 2 MPa, time = 45 minutes. Two operational blanks were included in each digestion run. Duplicate samples of certified reference material (CRM) of wheat flour (Wheat SRM 1567b, NIST, Gaithersburg, MD, USA) were included approximately every fourth digestion run. A laboratory reference material (LRM), Paragon was used for each digestion run. Following digestion, each tube was made up to a final volume of 15 mL by adding 11 mL Milli-Q water, then transferred to a 25 mL universal tube (Sarstedt Ltd., Nümbrecht, Germany) and stored at room temperature. Samples were further diluted 1:5 with Milli-Q water into 13 ml tubes (Sarstedt Ltd.).

3.4.4 Zinc and multi-element analysis

The grain and plant-available soil concentrations of Zn and 30 other elements were determined by ICP-MS (Thermo Fisher Scientific iCAPQ, Thermo Fisher Scientific, Bremen, Germany). The other elements were Ag, Al, As, B, Ba, Be, Ca, Cd, Cr, Co, Cs, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Rb, S, Se, Sr, Ti, Tl, U, and V. Three operational ICP-MS modes were used: (i) a helium collision-cell (He-cell) with kinetic energy discrimination to remove polyatomic interferences, (ii) standard mode (STD) in which the collision cell was evacuated, and (iii) a hydrogen collision-reaction cell (H_2-cell). Samples were introduced from an auto sampler incorporating an ASXpress™ rapid uptake module (Cetac ASX-520, Teledyne Technologies Inc., Omaha, NE, USA) through a PEEK nebulizer (Burgener Mira Mist, Mississauga, Burgener Research Inc., Canada). Internal standards were introduced to the sample stream on a separate line via the ASXpress unit and included Sc (20 µg L^{-1}), Rh (10 µg L^{-1}), Ge (10 µg L^{-1}) and Ir (5 µg L^{-1}) in 2% TAG HNO3 (Fisher Scientific UK Ltd). External multi-element calibration standards (Claritas-PPT grade CLMS-

2; SPEX Certiprep Inc., Metuchen, NJ, USA) included Ag, Al, As, B, Ba, Be, Cd, Ca, Co, Cr, Cs, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Rb, S, Se, Sr, Ti, Tl (semi-quant), U, V and Zn, in the range 0 – 100 µg L^{-1} (0, 20, 40, 100 µg L^{-1}). A bespoke external multi-element calibration solution (PlasmaCAL, SCP Science, Courtaboeuf, France) was used to create Ca, K, Mg and Na standards in the range 0-30 mg L^{-1}. Boron, P and S calibration utilized in-house standard solutions (KH_2PO_4, K_2SO_4 and H_3BO_3). In-sample switching was used to measure B and P in STD mode, Se in H_2-cell mode and all other elements in He-cell mode. Sample processing was undertaken using Qtegra™ software (Thermo Fisher Scientific) with external cross-calibration between pulse-counting and analogue detector modes when required. In total, 288 grain samples were analysed in 7 runs in 2013-14, and 432 grain samples in 12 runs in 2014-15, excluding blank, CRM and LRM samples. The Zn-specific recovery from CRMs was 96% in 2013-14 and 94% in 2014-15 compared with certified CRM values.

3.4.5 Data analysis of grain Zn concentration and the grain ionome

For each data-point, an element-specific operational blank concentration (mean of each ICP-MS run) was subtracted. Data were then multiplied by initial sample volume, divided by the initial dry mass of material, and converted to mg element kg^{-1} dry grain material. Element-specific limits of detection (LODs) were reported as 3 times the standard deviation (SD) of ten operational blank concentrations, assuming a notional starting dry weight of 0.4 g in 2013-14 and 0.2 g in 2014-15 (S3.1 Table). Out of 31 mineral elements, 15 (Ag, Al, B, Be, Cd, Co, Cr, Li, Na, Ni, Pb, Tl, Ti, U, V) were removed from further analysis because their mean grain concentration across all plots was less than the LOD (S3.2 Table). For the remaining elements, when an individual sample had a grain

element concentration less than the LOD, actual values were replaced with 50% LOD. Grain element concentrations >5 standard deviation (SDs) greater than the global arithmetic mean for each element were also removed from the analysis as a precaution against using contaminated samples (15 and 31 data points were removed in 2013-14 and 2014-15, respectively). All data are provided in S3.3 Table.

3.4.6 Statistical analyses

Variance components associated with grain concentration of Zn and 15 other grain mineral elements (As, Ba, Ca, Cs, Cu, Fe, K, Mg, Mn, Mo, P, Rb, S, Se, and Sr) were calculated. Analyses of Variance (ANOVA) and Least Significant Difference (LSD) tests were used to test for differences in mean grain elemental concentration between sites and genotypes. Difference between sites and genotypes for grain mineral composition traits were considered significant at $P<0.01$. Pearson correlation coefficients were calculated for the 16 grain mineral elements, along with grain yield, for each site in each year. All analyses were conducted using GenStat 17th Edition (VSN International Ltd, Hemel Hempstead, UK).

3.5 Results

This study reports the contribution of genotype and site factors to variation in grain Zn concentration, and the grain ionome, of 36 wheat genotypes in India. Primary data are provided in S3.4 Table.

3.5.1 Variation in wheat grain Zn concentration and the grain ionome

The mean grain Zn concentration across all plots and years (n=719) was 29.3 mg kg^{-1} and varied from 3.4 to 60.9 mg kg^{-1}, across all plots (**Table 3.1**). Among the macronutrients, the mean grain concentration of Ca, K, Mg, P and S were 369, 4190, 1160, 3610 and 1490 mg kg^{-1}, respectively and varied 20-fold for Ca, 14-fold for K, 15-fold for Mg, 189-fold for P and 17-fold for S. Among the micronutrients, the mean grain concentration of Cu, Fe, Mn and Mo across all plots were 4.3, 37.8, 37.5 and 0.74 mg kg^{-1}, respectively (n=719). Grain concentration varied 12-fold for Cu, 13-fold for Fe, 11-fold for Mn and 41-fold for Mo. Among trace elements, the mean grain As and Se concentrations were 0.02 and 0.16 mg kg^{-1}, respectively, and varied from 0.003 to 0.089 for As and from 0.02 to 0.8 mg kg^{-1} for Se (Table 1). Cadmium (Cd) and lead (Pb) are trace element of interest in the context of Zn biofortification (Qaswar *et al*., 2017) because they are potentially toxic to humans (Simmons *et al*., 2003; Sebastian *et al*., 2014; Xing *et al*., 2016; Hirzel *et al*., 2017). In this study, the mean grain Cd and Pb concentration across all plots were less than the LODs of 0.0341 and 0.0660 mg kg^{-1} for Cd and Pb, respectively, and were therefore not included in further data analyses.

Table 3.1 Grain concentrations of Zn and other mineral elements of Indian wheat. Data are in mg kg^{-1}, summarised across all plots (n=719)

Element	Mean	Median	SD	Range	LOD
Zn	29.3	28.4	6.99	3.44-60.9	0.744
As	0.0186	0.0107	0.0183	0.003-0.089	0.00564
Ba	4.29	4.09	2.12	0.27-13.2	0.0493
Ca	369	362	86.1	36.9-726	17.6
Cs	0.0161	0.0100	0.0170	0.0004-0.093	0.00077
Cu	4.34	4.28	0.939	0.65-7.53	1.3
Fe	37.8	37.4	9.74	6.43-85.9	12.9
K	4190	4180	609	476-6520	11.9
Mg	1160	1130	216	140-2090	2.9
Mn	37.5	37.1	10.1	5.82-66.5	3.51
Mo	0.740	0.762	0.471	0.056-2.44	0.111
P	3610	3640	524	311-6030	7.2
Rb	8.55	7.91	6.34	0.156-26.7	0.00426
S	1490	1520	292	140-2270	280
Se	0.159	0.0998	0.138	0.015-0.824	0.0297
Sr	5.07	5.27	3.3	0.20-17.9	0.161

3.5.2 Variance components associated with grain Zn concentration and the grain ionome

Genotype (G) and site terms (E) were associated with 10 and 6% of the variation in grain Zn concentration, respectively (**Table 3.2**). The G x E interaction term was associated with 20% of the variation in grain Zn concentration. The residual term (R) was associated with 64% of the variation in grain Zn concentration, and represents variation due to year, plot-to-plot variation between replicates, and technical/measurement errors.

Site (E) was typically associated with a greater proportion of the variation in the grain concentration of other minerals compared to Zn (**Table 3.2**). Among the macronutrients, 28, 18, 36, 8 and 12% of the variation in grain Ca, K, Mg, P and S concentration were associated with E; 18, 18, 11, 12 and 8% of the variation were associated with G, respectively. Among the micronutrients, E was associated with 14, 19, 55 and 79% of the variation in grain Cu, Fe, Mn and Mo

concentration, respectively; 14, 9, 11 and 4% of the variation was associated with G, respectively. Among non-essential trace elements, 70 and 67% of the variation in grain As and Se concentration, respectively, were associated with E, with just 2 and 1% of the variation associated with G, respectively.

Table 3.2 The contribution of G, E, G*E and residual factors to variation percentage (%) in grain Zn concentration and the grain ionome of a panel of 36 wheat genotypes grown at five sites in 2013-14 and at six sites in 2014-15.

Element	**Variation %**				**P value**		
	G	**E**	**G*E**	**Residual**	**G**	**E**	**G*E**
Zn	10	6	20	64	<0.001	<0.001	0.816
Others							
As	2	70	6	21	0.015	<0.001	0.908
Ba	27	39	11	22	<0.001	<0.001	<0.001
Ca	18	28	10	44	<0.001	<0.001	0.999
Cs	2	89	4	5	<0.001	<0.001	<0.001
Cu	14	14	11	61	<0.001	<0.001	1
Fe	9	19	9	63	<0.001	<0.001	1
K	18	18	15	49	<0.001	<0.001	0.841
Mg	11	36	12	41	<0.001	<0.001	0.93
Mn	11	55	9	25	<0.001	<0.001	0.591
Mo	4	79	4	13	<0.001	<0.001	0.798
P	12	8	21	59	<0.001	<0.001	0.446
Rb	2	87	3	8	<0.001	<0.001	0.213
S	8	12	9	71	0.019	<0.001	1
Se	1	67	5	27	0.960	<0.001	1
Sr	7	71	6	16	<0.001	<0.001	0.299
					<0.001	<0.001	0.816
d.f.	**35**	**5**	**175**	**503**			

3.5.3 Differences in grain Zn concentration and the grain ionome between genotypes

Grain Zn concentration differed between genotypes in both 2013-14 and 2014-15 ($P<0.001$). The mean grain Zn concentration of 36 genotypes, averaged across sites, varied from 21.4 to 35.6 mg kg^{-1} in 2013-14 (**Figure 3.1**a) and from 26.5 to 34.3 mg kg^{-1} in 2014-15 (**Figure 3.1**b). The Kharchia 65 genotype had

the greatest grain Zn concentration in both years. The HW 2044 and GW 322 genotypes had the smallest grain Zn concentration in 2013-14 and in 2014-15, respectively.

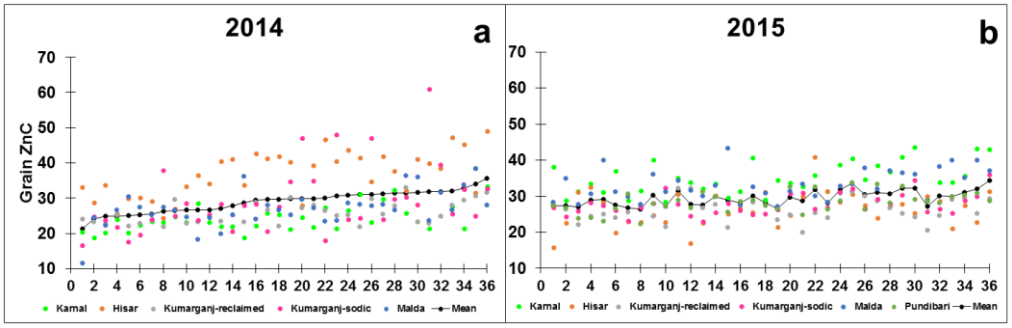


Figure 3.1 Grain Zn concentration in a panel of 36 genotypes, averaged across five sites in 2013-14 and six sites in 2014-15. Data represent the means of two replicate plots per genotype at Karnal, Hisar and Malda, and one replicate per genotype at Kumarganj-reclaimed and Kumarganj-sodic sites in 2013-14 (a), and the means of two replicate plots of each genotype at all six sites in 2014-15 (b). Genotypes 1-36 are labelled in the same order in both years on the x-axis: 1) HW 2044; 2) HD 2932; (3) RW 3684; (4) WH 1021; (5) HD 2967; (6) DBW 46; (7) KRL 1-4; (8) GW 322; (9) NW 4092; (10) GW 322; (11) NW 4092; (12) PDW 314; (13) RAJ 4229; (14) MACS 6222; (15) DPW 621-50; (16) WH 1105; (17) HI 1563; (18) KRL 210; (19) DBW 71; (20) NW 1067; (21) NW 4018; (22) DBW 14; (23) KRL 213; (24) HI 8498; (25) BH 1146; (26) DBW 51; (27) KRL 19; (28) UP 262; (29) DBW 17; (30) K 0307; (31) HD 2009; (32) HD 2733; (33) RAJ 4238; (34) DBW 39; (35) KRL 3-4; (36) Kharchia 65.

Among the macronutrients and micronutrients, the grain concentrations of Ca, Mg, S, Fe, Cu and Mn differed between genotypes in both 2013-14 and 2014-15 ($P<0.001$). Among the non-essential trace elements, the grain As and Se concentration did not differ significantly between genotypes in either year.

The mean grain Ca concentration of 36 genotypes, averaged across sites, varied from 285.2 to 437.1 mg kg^{-1} in 2013-14 and from 317.4 to 452.8 mg kg^{-1} in 2014-15. The KRL 3-4 and NW 1067 genotypes had the greatest grain Ca concentration in 2013-14 and in 2014-15, respectively. The CBW 38 and NW 4018 genotypes had the smallest grain Ca concentration in 2013-14 and in 2014-15, respectively. The mean grain Mg concentration of 36 genotypes, averaged across sites, varied from 911 to 1333 mg kg^{-1} in 2013-14 and from 1051 to 1375 mg kg^{-1} in 2014-15. The KRL 3-4 genotype had the greatest grain Mg concentration in both years. The HW 2044 and KRL 213 genotypes had the smallest grain Mg concentration in 2013-14 and in 2014-15, respectively. The mean grain S concentration of 36 genotypes, averaged across sites, varied from 1080 to 1565 mg kg^{-1} in 2013-14 and from 1475 to 1870 mg kg^{-1} in 2014-15. The KRL 3-4 and BH 1146 genotypes had the greatest grain S concentration in 2013-14 and in 2014-15, respectively. The HW 2044 and GW 322 genotypes had the smallest grain S concentration in 2013-14 and in 2014-15, respectively.

Among the micronutrients, the mean grain Cu concentration of 36 genotypes, averaged across sites, varied from 3.1 to 4.9 mg kg^{-1} in 2013-14 and from 3.8 to 5.3 mg kg^{-1} in 2014-15. The KRL 19 and HI 1563 genotypes had the greatest grain Cu concentration in 2013-14 and in 2014-15, respectively. The WH 1021 and DBW 46 genotypes had the smallest grain Cu concentration in 2013-14 and in 2014-15, respectively. The mean grain Fe concentration of 36 genotypes, averaged across sites, varied from 26.7 to 42.9 mg kg^{-1} in 2013-14 and from 34.6 to 47.6 mg kg^{-1} in 2014-15. The Kharchia 65 and KRL 3-4 genotypes had the greatest grain Fe concentration in 2013-14 and in 2014-15, respectively. The HW 2044 and PDW 314 genotypes had the smallest grain Fe concentration in

2013-14 and in 2014-15, respectively. The mean grain Mn concentration of 36 genotypes, averaged across sites, varied from 25.0 to 43.1 mg kg^{-1} in 2013-14 and from 29.0 to 47.8 mg kg^{-1} in 2014-15. The BH 1146 and KRL 210 genotypes had the greatest grain Mn concentration in 2013-14 and in 2014-15, respectively. The PDW 314 genotype had the smallest grain Mn concentration in both years.

The mean grain Zn concentration of 36 genotypes showed a positive relationship between 2013-14 and 2014-15 ($r=0.65$, $P<0.001$; **Figure 3.2**). Within sites, the mean grain Zn concentration of 36 genotypes showed positive relationships between 2013-14 and 2014-15 at Karnal ($r=0.64$; $P<0.001$), Hisar ($r=0.36$; $P<0.05$) and Malda ($r=0.63$; $P<0.001$).

The mean grain Ca, Mg, S, Cu, Fe and Mn concentrations of 36 genotypes showed positive relationships between 2013-14 and 2014-15 (r between 0.61 and 0.77; $P<0.001$; **Figure** 3.2). The mean grain As concentration of 36 genotypes showed a positive relationship between 2013-14 and 2014-15 ($r=0.37$, $P<0.05$). However, the mean grain Se concentration of 36 genotypes did not correlate between 2013-14 and 2014-15 (**Figure 3.2**).

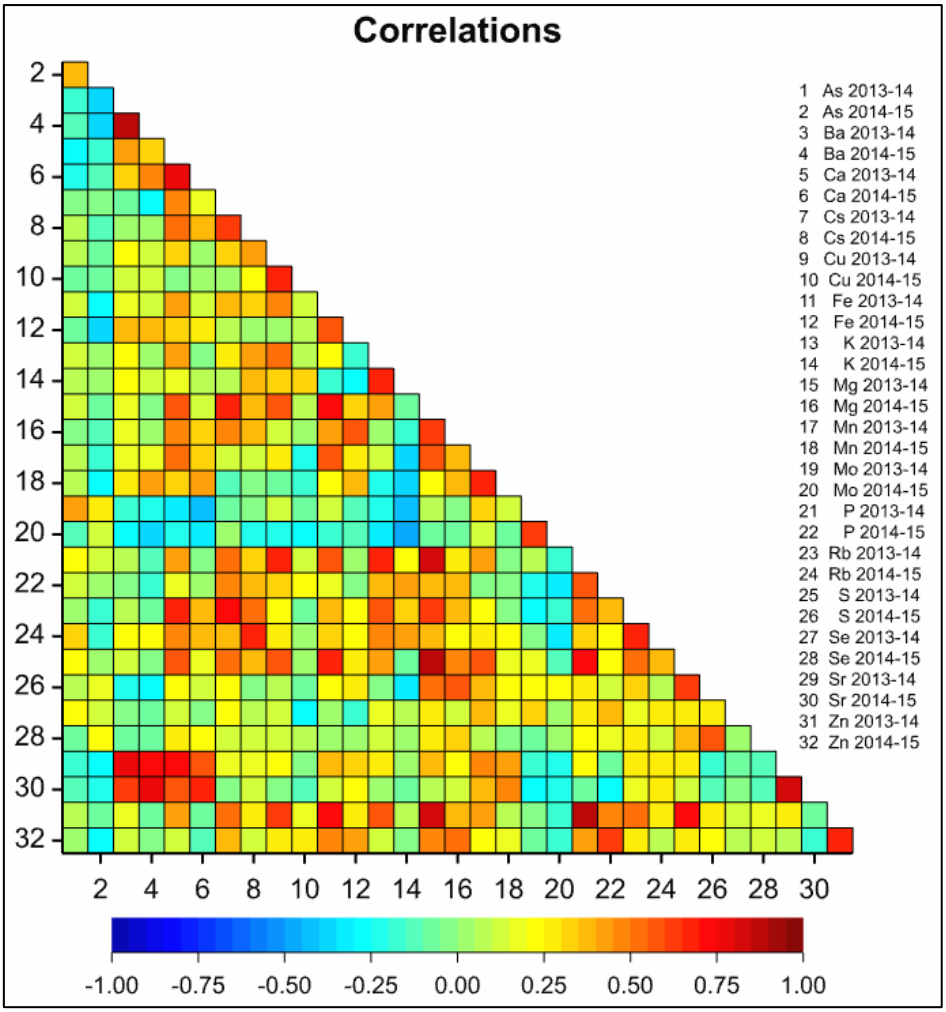


Figure 3.2 The correlation coefficients in grain ionome of a panel of 36 genotypes between 2013-14 and 2014-15. Data represent the means of two replicate plots per genotype at Karnal, Hisar and Malda, and one replicate per genotype at Kumarganj-reclaimed and Kumarganj-sodic sites in 2013-14, and the means of two replicate plots of each genotype at all six sites in 2014-15. Colour represents strength of correlation from strongly negative (dark blue) to strongly positive (dark red).

3.5.4 Differences in grain Zn concentration and the grain ionome between sites

Grain Zn concentration differed between sites (P<0.001) (**Figure 3.3**). The mean grain Zn concentration varied from 26.1 (Kumarganj-reclaimed) to 31.7 (Hisar) mg kg^{-1}, averaged across 36 genotypes and years (LSD=1.74) (**Figure 3.3**).

Among the macronutrients, grain Ca, Mg, S concentrations differed between sites. The mean grain Ca concentration varied from 309 (Malda) to 425.1 (Hisar) mg kg^{-1}, averaged across 36 genotypes and years (LSD=17.77). The mean grain Mg concentration varied from 1003 (Pundibari) to 1373 (Kumarganj-reclaimed) mg kg^{-1} (LSD=43.30). The mean grain S concentration varied from 1384 (Pundibari) to 1689 (Kumarganj-sodic) mg kg^{-1} (LSD=76.82).

Among the micronutrients, the mean grain Cu concentration varied from 3.7 (Kumarganj-reclaimed) to 5.0 (Kumarganj-sodic) mg kg^{-1}, averaged across 36 genotypes and years (LSD=0.23). The mean grain Fe concentration varied from 28.1 (Pundibari) to 41.9 (Kumarganj-sodic) mg kg^{-1} (LSD=2.41). The mean grain Mn concentration varied from 28.9 (Kumarganj-reclaimed) to 48.7 (Hisar) mg kg^{-1} (LSD=1.59). Among the non-essential trace elements, the mean grain As concentration varied from 0.003 (Pundibari) to 0.040 (Hisar) mg kg^{-1}, averaged across 36 genotypes and years (LSD=0.003). The mean grain Se concentration varied from 0.07 (Malda) to 0.36 (Hisar) mg kg^{-1} (LSD=0.02) (**Figure 3.3**).

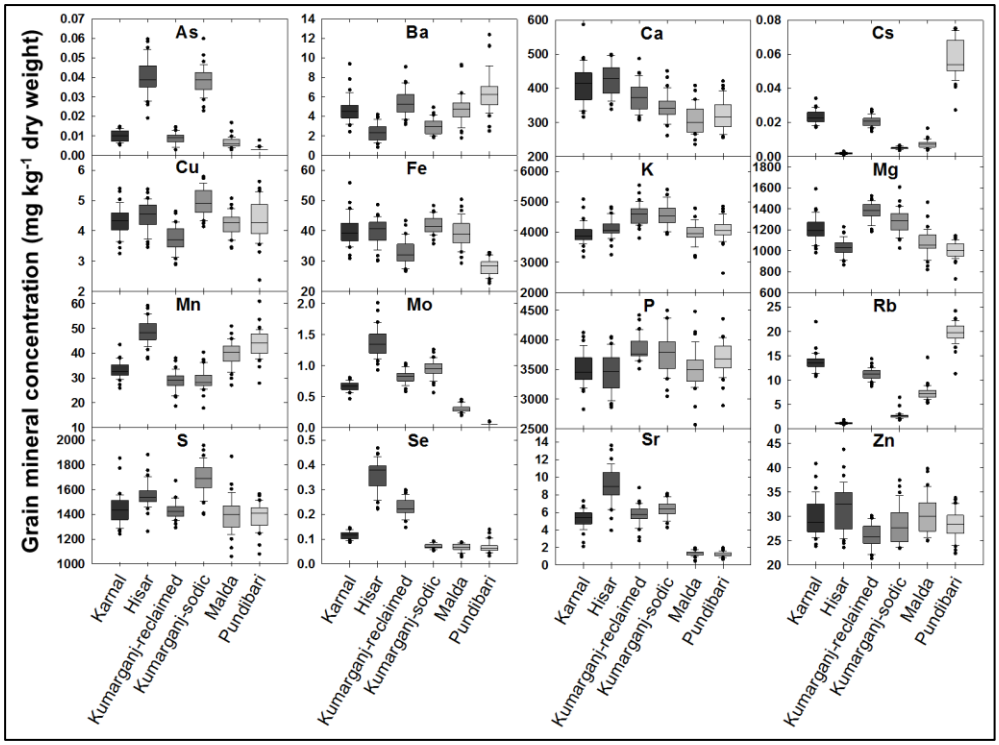


Figure 3.3 Grain element concentrations of 36 genotypes of wheat at six sites over two years. Data represent the means of two replicate plots per genotype at Karnal, Hisar, Malda and one replicate plot per genotype at Kumarganj-reclaimed and Kumarganj-sodic sites in 2013-14 and two replicate plots per genotype at all six sites in 2014-15. Boxes represent the two mid-quartiles with the median drawn; whiskers are the 95% confidence limits; circles are the outliers.

3.5.5 Relationship of grain Zn concentration with grain ionome and grain yield

There was no negative correlation between grain Zn concentration and grain yield (GYD), rather a weakly positive correlation (r=0.08; P=0.03) (**Figure 3.4**). The grain Zn concentration showed positive significant relationships with grain Ca, Cu, Fe, K, Mg, Mn, Mo, P, S and Sr (P<0.001) (**Figure 3.4**). However, grain Zn concentration did not show any relationships with grain As, Ba, Cs, Rb and Se concentrations. The grain Zn concentration showed stronger relationships with grain Cu, Fe, Mn, P and S (r = 0.61, 0.46, 0.43, 0.53, 0.46, respectively)

than with grain Ca, K, Mg, Mo and Sr (r= 0.36, 0.21, 0.33, 0.18, 0.15, respectively) concentrations (**Figure 3.4**).

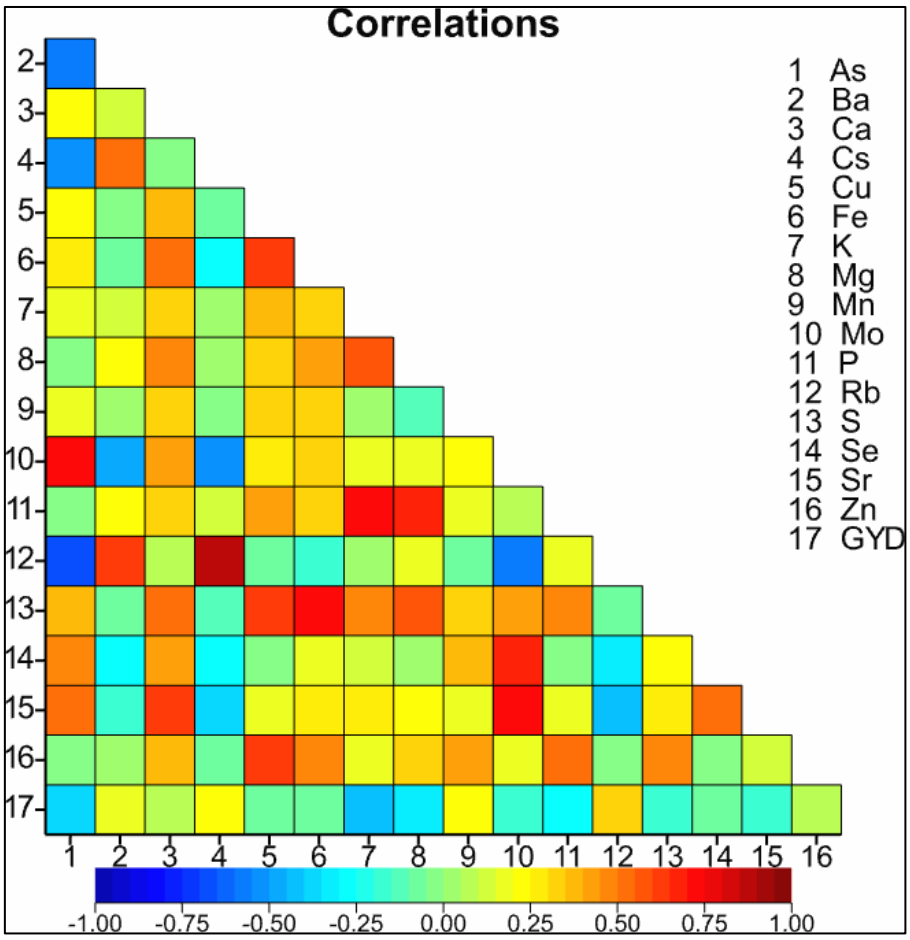


Figure 3.4 The relationship of grain Zn concentration (mg kg^{-1}) with GYD (t ha^{-1}) and other grain mineral elements in a panel of 36 wheat genotypes grown at five sites in 2013-14 and six sites in 2014-15. Data are means of two replicate per plot at Karnal, Hisar and Malda and one replicate at Kumarganj-reclaimed and Kumarganj-sodic sites in 2013-14 and two replicate per plot at six sites in 2004-15 (n=719). Colour represents strength of correlation from strongly negative (dark blue) to strongly positive (dark red).

3.5.6 Variation in grain Zn concentration due to variation in plant-available soil Zn

In the present study, plant-available soil Zn concentrations were reported in top and sub-surface soils at six sites in 2013-14 and 2014-15 based on the use of a non-conventional extract of $Ca(NO_3)_2$ (Anjos *et al*., 2012; Ray *et al*., 2013) (**Table 3.3**). Plant available soil Zn concentration varied from 0.04-1.10 mg kg^{-1} in 0-15 cm and from 0.03-2.14 mg kg^{-1} in 15-30 cm soil depths in 2013-14 while in 2014-15, it varied from 0.03-0.22 mg kg^{-1} in 0-15 cm and from 0.003-0.06 mg kg^{-1} in 15-30 cm soil depths, at six sites. All sites showed very low concentrations of immediately plant available Zn in the soil in both years except at Pundibari in 2013-14.

At Karnal, soil available Zn concentration was greater in 2014-15 than in 2013-14 at both soil depths and also showed greater grain Zn concentration in 2014-15 than in 2013-14. Contrastingly, at Malda, the soil available Zn concentration was greater in 2013-14 than 2014-15 in both the soil depths, but, grain Zn concentration was greater in 2014-15 than in 2013-14 (**Table 3.3**).

Table 3.3 Soil soluble Zn ($Ca(NO_3)_2$-extractable) and grain Zn concentration at six sites in 2013-14 and 2014-15. Soil Zn data are means of three replicate soil samples of each depth at each site. Grain Zn data are mean of two replicate at Karnal, Hisar, Malda and one replicate at Kumarganj-reclaimed and Kumarganj-sodic sites in 2013-14 and two replicates at all six sites in 2014-15**.**

Sites	$[Zn]_{soil}$ (mg kg^{-1}) at two soil depths (cm)				$[Zinc]_{grain}$	
	2013-14		2014-15			
	0-15	15-30	0-15	15-30	2013-14	2014-15
Karnal	0.04	0.03	0.10	0.06	24.6	34.9
Hisar	0.33	0.03	0.22	0.04	36.8	26.4
Kumarganj-reclaimed	**0.03***	**0.03***	0.03	0.03	25.8	26.3
Kumarganj-sodic	**0.03***	**0.03***	0.17	0.03	29.1	27.8
Malda	0.28	0.46	0.03	0.03	27.1	33.3
Pundibari	1.10	2.14	0.21	0.05	-	28.3

* Zn concentration at 0-30 cm of soil depth

3.6 Discussion

Wheat is an important dietary source of Zn for the Indian population and there is scope to increase grain Zn concentrations in wheat through breeding to help alleviate dietary Zn deficiency. In the present study, the grain Zn concentration of 36 wheat genotypes varied from 26-32 mg kg^{-1}. Our results are consistent with Zhao *et al*., 2009, who reported grain Zn concentration from 14 to 35 mg kg^{-1} in 150 field grown bread wheat lines. A similar range of grain Zn concentration were reported among 66 advanced wheat genotypes (20-39 mg kg^{-1}) selected from Central Asia Breeding Programs by Morgounov *et al*., 2007, and grown in Kazakhstan, Kyrgyzstan and Tajikistan. Among 40 bread wheat lines from CIMMYT breeding programmes grown at nine locations in South Asia and Mexico, grain Zn concentration from 29-40 mg kg^{-1} (Velu *et al*., 2012). A summary of grain Zn concentrations was recently published at global scale in

field grown wheat and reported grain Zn concentration from 20-31 mg kg^{-1}, showed a difference of 10 to 20 mg kg^{-1} from the biofortification target of 40 mg kg^{-1} for human diet (Chen *et al*., 2017).

Genotype (G) accounted for a relatively small proportion of the total variation in grain Zn concentration, indicating this is a very complex trait that is affected by many different sources of variation. Joshi *et al*., 2010; Velu *et al*., 2012 and Velu *et al*., 2016, also reported a significant effect of different environments on variation in grain Zn concentration. However, some genotypes still had a consistent ranking across sites and years for grain Zn concentration. For example, Kharchia 65 and BH 1146 genotypes showed comparatively greater grain Zn concentration across six sites. Genotype, Kharchia 65 is a salt tolerant genotype (Munns *et al*., 2006) and BH 1146 is an aluminium tolerant genotype (De Sousa, 1998). Therefore, Kharchia 65 and BH 1146 might be potential new sources for development of Zn-biofortified wheat varieties, including under saline/sodic and acidic soil areas. In addition to Kharchia 65 and BH 1146, several genotypes achieved more than 31 mg kg^{-1} of grain Zn concentration at different locations, which is equivalent to 50% of the HarvestPlus target of 12 mg kg^{-1} (i.e. above a notional baseline grain Zn concentration of 25 mg kg^{-1}). Given that these lines already have implicitly good grain yield and other quality attributes for South Asia, such lines could also be useful for crossing with high-Zn lines derived from the HarvestPlus, to support site-specific approaches as adopted previously for yield and yield component traits (Khokhar *et al*., 2017).

There was no evidence of a yield dilution effect on grain Zn concentration in this study. This observation supports the argument that locally adapted, high

yielding, genotypes have potential value in the development of Zn-biofortified varieties. Our result is therefore consistent with findings of Welch and Graham, 2004 and Joshi *et al*., 2010, who reported no trade- off between grain Zn and grain yield concentration in wheat. In contrast, other studies reported negative correlation of grain Zn with grain yield concentration in wheat (Monasterio and Graham, 2000; Qury *et al*., 2006). Oury *et al*., 2006, reported lower grain Zn concentrations in high yielding genotypes which may have been due to yield dilution. It is important to continue to monitor grain Zn concentration in the wider context of yield and yield component traits in breeding programmes, especially given that grain yields in the region are relatively low.

Most of the soils in the present study were probably Zn deficient, based on the use of a Ca $(NO_3)_2$ soil extraction to assess Zn-availability. Karami *et al*., 2009; Joshi *et al*., 2010 and Velu *et al*., 2016, who reported lower grain Zn concentrations in wheat genotypes when grown under Zn deficient soil conditions. Variation in plant-available Zn in soils is likely to represent a large proportion of environmental sources of variation in grain Zn concentration (Cakmak, 2008; White and Greenwood, 2013; Rengel, 2015). Soil Zn concentrations can be increased through the use of fertilisers (Cakmak, 2008; Joy *et al*., 2015; Joy *et al*., 2017). Zinc can be applied with granular fertilisers to soil or as foliar spray. Application of Zn fertiliser in granular form has produced increases in both grain yield and grain Zn concentration. However, application of Zn fertiliser as a foliar spray can reduce the amount Zn fertiliser needed in granular form and cereals are more responsive in terms of increase in grain Zn concentration, albeit at higher application cost. It is possible to reduce the cost of application by combining foliar application of Zn with pesticide

applications (Wang *et al*., 2016; Ram *et al*., 2016; Gregory *et al*., 2017). Based on a wide survey of farmers, application of basal Zn fertilisers increased grain yield in wheat in Indo-Gangetic area of Sindh and Punjab Provinces of Pakistan (Joy *et al*., 2017). Attempts to increase the grain Zn by genetic biofortification can clearly be complemented with the use of Zn fertilisers.

Increases in grain Zn concentration may also help to increase the grain Ca, Cu, Fe, K, Mg, Mn, Mo, P, and S concentrations given the observed positive correlation of grain Zn with these elements. Our results are consistent with those of Pandey *et al*., 2016, who reported a positive relationship of grain Zn concentrations and Ca, Cu, Fe, K, Mg, P and S concentrations in 150 bread wheat lines collected from India and Turkey. Many researchers also reported relationships between grain Zn and Fe (Velu *et al*., 2012; Guzman *et al*., 2014; Velu *et al*., 2017), P (Shi *et al*., 2008; Stangoulis *et al*., 2007) and S (McDonald *et al*., 2009). However, P is an important component of phytic acid (PA) which affects the bioavailability of Zn (Stangoulis *et al*., 2007). Therefore, the role of PA should be considered concomitantly in breeding programs intended to increase the grain Zn concentration in wheat genotypes.

Taken together, the results from this study show considerable potential for genetic improvement for Indian wheat genotypes. Some elite varieties (e.g. Kharchia 65) could be useful sources of variation that can be used at a wide range of sites and contribute to alleviating dietary Zn deficiency. This study also reveals the wealth of information that can be gleaned from studying the wider grain ionome across sites with a wide range of conditions, so that both breeding

and spatial approaches (e.g. site-specific crop selection, fertiliser-use, etc.) to improving diet quality can deployed most effectively.

The high-Zn wheat varieties were developed by HarvestPlus using the high Zn containing accessions of *Triticum durum* based synthetic hexaploid wheat, *Triticum spelta* and *Triticum dicoccon* based synthetic hexaploid wheat (Singh and Velu, 2017). The *T. durum* based synthetic hexaploid wheat was developed by crossing of *T. durum* wheat cultivar with *Aegilops tauschii*, a D genome donor of wheat, and further selections have developed a high-Zn variety, the Zinc Shakti (CROC1_/AE.SQUARROSA (210)//INQALAB91*2/KUKUNA/3/PBW343*2/KUKUNA) for North-Eastern Plain Zones of India and showed 14 mg kg^{-1} greater grain Zn concentration than the notional baseline grain Zn concentration of 25 mg kg^{-1}. The *T. dicoccon* based synthetic hexaploid wheat was developed by crossing of a high Zn containing accession of wild *T. dicoccon* with *Aegilops tauschii* and further selections have developed the WB02 and HPBW-01 (T.DICOCCON, CI9309/AE.SQUARROSA (409)//MUTUS/3/2*MUTUS) wheat varieties for North-Western Plain Zones of India and showed 7 mg kg^{-1} greater grain Zn concentration than the notional baseline grain Zn concentration of 25 mg kg^{-1}. Similarly, Zincol-2016 has been released for the Pakistan and developed by crossing of a well-adapted NARC2011 wheat variety with a high Zn containing accession of *T. spelta* and showed 9 mg kg^{-1} greater grain Zn concentration than the notional baseline grain Zn concentration of 25 mg kg^{-1} (Singh and Velu, 2017). However, wheat genotypes studied in present study have been developed by crossing of different well adapted wheat genotypes rather than using synthetic

wheats. Therefore, there is scope to explore the wild relatives of wheat for greater variation in grain Zn concentration.

3.7 Acknowledgments

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3.9 Supplementary tables

S3.1 Table. Element specific limit of detection (LOD) for concentration of 31 elements measured in grain of 36 Indian wheat genotypes by ICP-MS.

Sr. No.	Elements	LOD (mg kg^{-1})	Sr. No.	Elements	LOD (mg kg^{-1})
1	Ag	0.0127	**17**	Mn	3.51
2	Al	13.9	**18**	Mo	0.111
3	As	0.00564	**19**	Na	99.1
4	B	2.69	**20**	Ni	1.03
5	Ba	0.0493	**21**	P	7.20
6	Be	0.000784	**22**	Pb	0.0660
7	Ca	17.6	**23**	Rb	0.00426
8	Cd	0.0341	**24**	S	280
9	Co	0.0555	**25**	Se	0.0297
10	Cr	2.149	**26**	Sr	0.161
11	Cs	0.000770	**27**	Ti	105
12	Cu	1.30	**28**	Tl	0.00105
13	Fe	12.9	**29**	U	0.00105
14	K	11.9	**30**	V	0.0113
15	Li	0.000989	**31**	Zn	0.744
16	Mg	2.90			

S3.2 Table. The grain mineral elements whose grain concentrations were below the limit of detection (LOD) values (highlighted in red). Elements highlighted in red excluded from data analyses.

Elements	n	Mean (mg kg^{-1})	Median (mg kg^{-1})	Minimum (mg kg^{-1})	Maximum (mg kg^{-1})	SD	LOD (mg kg^{-1})
Ag	715	0.00764	0.00634	0.00634	0.0400	0.00392	0.0127
Al	717	7.94	7.00	7.00	39.4	3.74	13.99
As	719	0.0186	0.0107	0.00282	0.0893	0.0183	0.00564
B	717	1.46	1.35	1.35	8.62	0.687	2.69
Ba	719	4.29	4.10	0.273	13.2	2.12	0.0493
Be	717	0.000396	0.000392	0.000392	0.000935	0.0000429	0.000784
Ca	719	369	361.9	36.9	726	86.1	17.6
Cd	717	0.0287	0.0171	0.0171	0.131	0.0184	0.0341
Co	718	0.0312	0.0277	0.0277	0.129	0.0144	0.0555
Cr	718	1.08	1.07	1.07	2.930	0.111	2.14935
Cs	719	0.0161	0.0100	0.000385	0.0933	0.0170	0.000770
Cu	718	4.34	4.28	0.651	7.93	0.939	1.30
Fe	719	37.8	37.4	6.43	85.9	9.74	12.9
K	719	4190	4175	476	6519	609	11.9
Li	715	0.0137	0.00494	0.00494	0.0630	0.0112	0.00989
Mg	719	1162	1132	140	2086	216	2.90
Mn	719	37.5	37.1	5.82	66.5	10.1	3.51
Mo	719	0.740	0.762	0.056	2.44	0.471	0.111
Na	713	56.6	49.5	49.5	273	28.7	99.1
Ni	717	0.534	0.517	0.517	2.13	0.144	1.03
P	719	3611	3640	311	6026	524	7.20
Pb	717	0.0374	0.0330	0.0330	0.278	0.0235	0.0660
Rb	719	8.54	7.91	0.156	26.7	6.34	0.00426
S	719	1486	1515	140	2271	292	280
Se	719	0.159	0.0998	0.0148	0.824	0.138	0.0297
Sr	719	5.06	5.27	0.201	18.0	3.30	0.161
Ti	710	58.3	52.6	52.6	287	29.4	105
Tl	719	0.000523	0.000523	0.000523	0.000523	0.0000	0.00105
U	713	0.00438	0.00262	0.00262	0.0476	0.00584	0.00524
V	717	0.00906	0.00565	0.00565	0.0501	0.00644	0.0113
Zn	719	29.3	28.4	3.44	60.9	7.00	0.744

S3.3 Table. Grain mineral concentrations (mg kg^{-1}) of 31 elements of 36 wheat genotypes grown at 5 sites in 2013/14 and at 6 sites in 2014/15 in India. Elements highlighted in red excluded from analysis (values below than LOD) and values higher than mean+(5*SD) (highlighted in yellow) are removed from data before analysis.

S3.4 Table. Data of grain mineral concentration traits (mg kg^{-1}) of 36 wheat genotypes grown at five sites in 2013-14 and at six sites in 2014-15 in India. Data below limit of detection (LOD) have been replaced by half LOD values and values above than mean+(5*SD) have been removed.

CHAPTER 4. ASSOCIATING JUVENILE ROOT TRAITS WITH GRAIN YIELD, YIELD COMPONENTS AND GRAIN MINERAL CONCENTRATION IN INDIAN WHEAT UNDER CONTRASTING FIELD ENVIRONMENTS

4.1 Abstract

Background: Correlations between juvenile root traits and grain yield and component traits under optimal field conditions have previously been reported in wheat. The aim of this study was to test the hypothesis that juvenile root traits correlate with yield, yield components and grain mineral quality traits under a range of hostile soil environments in India.

Methods: A panel of thirty-six Indian wheat genotypes were grown for ten days in 'pouch and wick' high-throughput phenotyping (HTP) system (20 replicates). Correlations between juvenile root architecture traits, including primary and lateral root length,, and grain yield, yield components and grain mineral composition traits were determined, using field data from previously published experiments at six sites in India.

Results: Some juvenile root traits correlated with grain yield (GYD), yield components, and grain mineral concentration traits. A narrow root angle, potentially representing a 'steep' phenotype, correlated with grain yield and harvest index (HI) averaged across sites and years. Length related root traits were not correlated with GYD or HI at most sites, however, total length of lateral roots and lateral root number correlated with GYD at a sodic site of pH 9.5. The total length of lateral roots (TLLR) correlated with grain zinc (Zn) concentration

at one site. A wider root angle, representing a shallow root system, correlated with grain iron (Fe) concentration at most sites. The total length of all roots (TLAR) and total length of primary roots (TLPR) correlated with grain S concentration at most sites.

Conclusion: Narrow root angle could be a useful proxy trait for screening juvenile germplasm for improved grain yield. Lateral root and shallow root traits could potentially be used to improve grain mineral concentrations. The use of juvenile root traits should be explored further in wheat breeding.

4.2 Introduction

Root architecture describes the spatial configuration of plant roots in soil, which is important for anchorage, nutrient/water uptake, and for coping with various biotic and abiotic stresses (Lynch, 2007; Gewin, 2010; De Smet, 2012). A 'steep, cheap and deep' root system has been proposed to make plants more efficient in water and nutrient uptake from deeper layers of soil, even under less fertile and drought conditions (Lynch, 2013). The Green Revolution increased the grain production tremendously based on selection of shoot traits, including semi-dwarf varieties (Khush, 2001). Root traits have not been used directly in wheat breeding. Interestingly, modern wheat varieties have root biomass less than two-third of the mean of wheat landraces (Waines and Ehdai, 2007).

Wheat root system consist of three to eight primary roots (also called seminal roots).The secondary root system comprising adventitious/nodal roots, arise from basal nodes of the coleoptile and stem; adventitious root length, thickness and numbers increase with numbers of leaves and tillers (Hoad *et al*., 2001; Bradley *et al*., 2008). The relative root distribution of winter wheat cultivars was measured in 17 field experiments, sampling by soil coring between anthesis and harvest up to 1 meter depth, total root length was calculated and it ranged from 3 to 18 km m^{-2}, and different soil environmental conditions, such as soil pH, soil texture, water level and other environmental stresses effect the root spatial configuration in soil (White *et al*., 2015).

Studying wheat root traits in field condition is challenging, therefore researchers have started to deploy high throughput phenotyping (HTP) systems to screen seedling root traits. For example, a germination paper based 'cigar roll' system

was used to grow 199 double haploid wheat near isogenic lines (NILs) for 11 days to screen the seedling root traits. They reported no correlation of primary root length and lateral root length with matured plant height measured in field (Bai *et al*., 2013). Similarly, narrow root angle between the primary pair of seminal roots of 14 days old seedlings grown in root boxes did not correlated with grain yield measured in field of 52 wheat genotypes (McDonald, 2010).

A 'pouch & wick' germination paper based approach was used to grow 94 double haploid wheat lines in nutrient solution for nine days to study the root architectural traits by Atkinson *et al*., 2015. They reported no correlation between seedling root traits and grain yield and plant height, measured in field experiments with high nitrogen and low nitrogen treatments. Xie *et al*., 2017 grew 226 recombinant inbred lines (RIL) in 'pouch & wick' growth system to study the root traits of 13 days old seedlings and to test the association of seedling root traits with grain yield and yield components of inbred wheat lines measured under field conditions. They reported that maximum width and depth of roots correlated with grain yield harvested in field, and maximum width root traits also associated with grain m^{-2} and spikes m^{-2} measured in field trials. The total root length and primary root number of 13 days old seedlings correlated positively with numbers of grain per spike and biomass per unit area under field conditions. There were negative relationships of total root length and primary root number with 1000 grain weight of 226 RILs measured in field conditions. In contrast, total root length and primary root number showed negative correlation with 1000 grain weight measured in glasshouse pot experiment. However, they did not show any relationships between root emergence angles of primary roots with grain yield in the field. Clearly, the association of juvenile

root architecture traits with grain yield and yield component traits in the field warrants further exploration.

In this study, we have used a germination paper based HTP 'pouch & wick' system to characterise the root architectural traits of 36 widely adapted Indian genotypes. The aim of this study was to test the hypothesis that juvenile root traits correlate with yield, yield components and grain mineral composition traits measured under a range of soil environmental conditions in India, including under hostile soil conditions. Data of grain yield and component traits, and mineral composition traits of 36 genotypes grown at six different environmental sites (pH 4.5 to 9.5) in India in 2013-14 and 2014-15 have been used from Khokhar *et al*., 2017, and Khokhar *et al*., submitted.

4.3 Materials and methods

4.3.1 Wheat genotypes, field experiments and grain mineral analysis

A panel of 36 elite wheat genotypes comprising *Triticum aestivum* L. (n=34) and *Triticum durum* L. (n=2) were selected for study under field conditions. These genotypes represent a diverse genetic background with adaptations to a range of climatic and soil environments. All genotypes and experimental conditions are described in Khokhar *et al*., 2017, including data for yield and yield components. In brief, the panel was grown at six field sites in major wheat growing areas of India, during *rabi* (winter) seasons 2013-14 and 2014-15. The six sites were, (1) Indian Institute of Wheat and Barley Research (IIWBR), Karnal, Haryana (HR); (2) IIWBR, Hisar (HR); (3) Narendra Deva University of Agriculture and Technology (NDUA&T), Kumarganj, Faizabad, Uttar

Pradesh (UP), reclaimed site; (4) NDUA&T, Kumarganj, Faizabad (UP), sodic site; (5) Uttar Banga Krishi Viswavidyalaya (UBKV), Regional Research Sub-Station (RRSS), Mathurapur, Malda (WB) and (6) UBKV, Pundibari, Cooch Behar, West Bengal (WB). Seeds were manually placed in four rows per plot at 25 cm spacing between rows. The plot length was 2.5 m. The plots were arranged in a simple lattice design (6x6) with two replicates according to standard IIWBR practices. Grain mineral composition traits were measured from samples collected from five sites, except Pundibari, in 2013-14 and from all six sites in 2014-15, as reported in Khokhar *et al*., submitted.

4.3.2 High throughput root phenotyping platform and procedure

4.3.2.1 The HTP platform

A two dimensional (2D) hydroponic-based 'pouch and wick' HTP platform was used to study the root architectural trait of Indian genotypes under controlled conditions. The HTP system is described by Atkinson *et al*., 2015; Thomas *et al*., 2016a and Xie *et al*., 2017. In brief, the system comprised a set of aluminium frames (104 x 62 x 102 cm; KJN Ltd., Leicester, UK). Each frame had two long black polypropylene sheets (101 x 31 x 0.3 cm) and two short black polypropylene sheets (63 x 31 x 0.3 cm) covering the frame from all sides to maintain darkness within the frame (**Figure 4.1**B). In this 'pouch and wick' HTP system, each pouch comprised blue germination paper (24 x 30 cm, SD 7640; Anchor paper Company, St. Paul, MN, USA), covered with black polythene film of the same size, and attached to an acrylic rod (316 x 15 x 5 mm; Acrylic Online Hull, UK) using two fold back clips. The growth pouches with acrylic rod were suspended above drip trays using a toothed acrylic holder fixed to the aluminium frame.

Each aluminium frame comprised 9 drip trays arranged in 3 columns and 3 rows. The trays contained 10 or 11 pouches, with 96 pouches per frame. Each drip tray contained 2 L of 50% strength Hoagland's solution (No. 2 Basal salt Mixture, Sigma Aldrich, Dorset, UK) prepared with deionised water. Every three days during an experiment, 500 mL deionised water was added to the drip trays to ensure germinated paper remained saturated.

Grain of 36 genotypes were sieved using a set of calibrated sieves (Scientific Laboratory Supplies Ltd, Hessle, UK) and grain of size within a range 3.35–4 mm were used. Grains were sterilized by 5% (v/v) sodium hypochloride for 15 minutes and then rinsed three times with sterilized water. Grains were placed on pre-soaked germination paper, crease side down and incubated at 4°C for 24 hours (**Figure 4.1**A). Subsequently, grains were sown into the pouches by placing a single seed ventrally (side has the deep crease), with embryo pointed downwards, ~2 cm from the top edge on the germinated paper; the black polythene sheet held the grain in place. Two grains were grown per pouch, one on each side. Thus, a total of 192 plants were grown per frame. Two frames were used in each experiment run, to give a potential size of 384 plants per run. Two runs were carried out to get the 20 replicates of each genotype. Atkinson *et al*., 2015, recommended at least 15 replications for significant differences in root traits in wheat and Adu *et al*., 2014 and Thomas *et al*., 2016a,b, recommended 6-43 and 11-36 replicates, respectively, to have sufficient power to detect 50 and 30% differences in seedling root traits of *Brassica rapa* L. and *Brassica napus* L. genotypes. The frames were placed in controlled environment room (12 h photoperiod: 20°C day, 15°C night, with a light intensity of 400 µmol m^{-2} s^{-1} Photosynthetically Active Radiation (PAR).

4.3.2.2 Root imaging and analysis

Ten days after sowing (DAS), pouches were transferred to a copy stand, the black polythene sheets were removed from each pouch carefully and root images were taken using a Digital Single Lens Reflex (DSLR) camera (Canon EOS 1100D, Canon Inc., Tokyo, Japan) fitted on copy stand (model SGCS-920; Speed Graphic, Hampshire, UK) at specific height, using canon software (**Figure 4.1**C, D).

The root images were renamed with their corresponding genotypic names in experiment. All images were cropped using *ImageJ* software (https://imagej.nih.gov/ij/). Cropped root images were processed and analysed to quantify the different root traits (**Table 4.1**; **Figure 4.2**) using RootNav software (Pound *et al*., 2013).The root traits measured are described in Table 4.1.

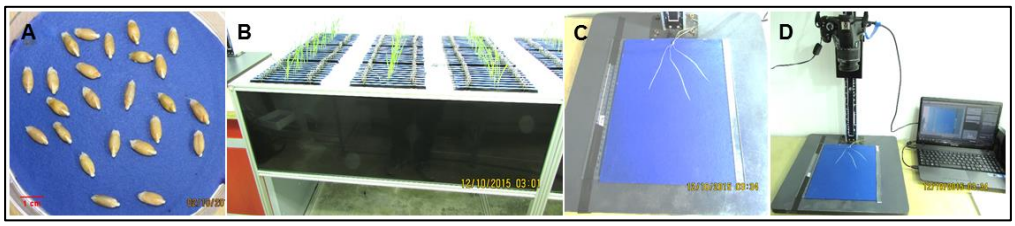


Figure 4.1 (A) Seeds were soaked on germination paper (B) Wheat seedlings growing in hydroponic tank (C) Seedling root image after 10 days of sowing (D) Copy stand with mounted camera above germination paper with root for imaging.

Table 4.1 Wheat seedling root traits measured in HTP system

Abbreviations	Descriptions of root traits (unit)
LRRT	**Length related root traits**
TLAR	Total length of all roots (cm)
TLPR	Total length of all primary roots (cm)
TLLR	Total length of all lateral roots (cm)
MLAR	Average length of all roots (cm)
MLPR	Average length of primary roots (cm)
MLLR	Average length of all lateral roots (cm)
RCH	Root convex hull, the smallest area of the convex covered by root system (cm2)
MWR	Maximum width of the root system (cm)
MDR	Maximum depth of the root system (cm)
CMRX	Centre of mass of the root system, X-axis (cm)
CMRY	Centre of mass of the root system, Y-axis (cm)
CHCRX	Centre of mass of convex hull, X-axis (cm)
CHCRY	Centre of mass of convex hull, Y-axis (cm)
ARRT	**Angle related root traits**
PEA 301	Emergence angle between the outermost pair of primary roots measured at 30 pixel (px), degree
PEA 302	Emergence angle between the second inner pair of primary roots measured at 30 pixel (px), degree
PEA 951	Emergence angle between the outermost pair of primary roots measured at 95 pixel (px), degree
PEA 952	Emergence angle between the second inner pair of primary roots measured at 95 pixel (px), degree
PEA 251	Emergence angle between the outermost pair of primary roots measured at 25% length of root, degree
PEA 252	Emergence angle between the second inner pair of primary roots measured at 25% length of root, degree
PEA 501	Emergence angle between the outermost pair of primary roots measured at 50% length of root, degree
PEA 502	Emergence angle between the second inner pair of primary roots measured at 50% length of root, degree
PEA 751	Emergence angle between the outermost pair of primary roots measured at 75% length of root, degree
PEA 752	Emergence angle between the second inner pair of primary roots measured at 75% length of root, degree
PEA 1001	Emergence angle between the outermost pair of primary roots measured at root tips, degree
PEA 1002	Emergence angle between the second inner pair of primary roots measured at root tips, degree
ORT	**Other root traits**
LRN	Lateral root number
PRN	Primary root number
WDR	Ratio of maximum width and depth of the root system (MWR/MDR)

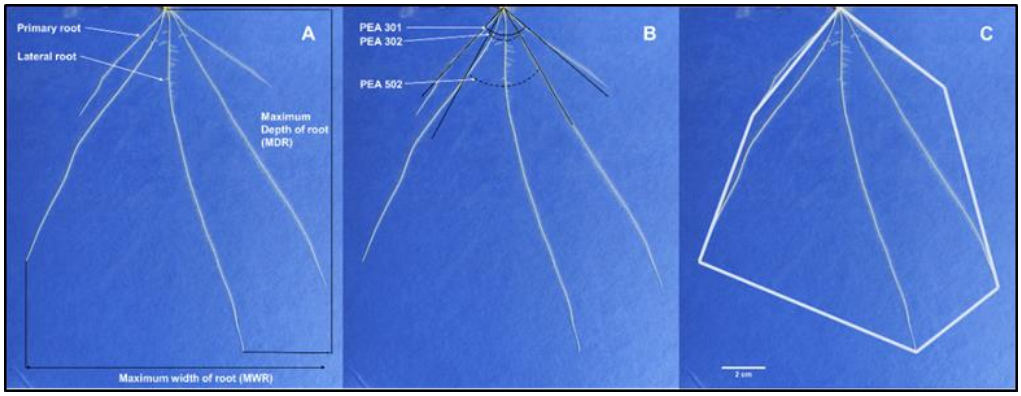


Figure 4.2 (A) Wheat seedling root traits (B) Root angles; PEA 301 and PEA 302 represent the paired emergence angle at 30 pixel of root length between out and inner pair of primary roots, respectively (C) Hexagonal area covered by white line showing the convex hull area, smallest area that cover the entire root system.

4.3.3 Statistical analysis

Pearson correlation coefficients were calculated to study correlations between mean juvenile root traits in HTP and field traits of 36 wheat genotypes, and among the juvenile root traits themselves. Variance components were calculated to determine the contribution of genotype to variation in the juvenile root traits. The power of the experiment to detect differences in juvenile root trait means between genotypes, as a function of the number of replicates, was determined and visualised as contour plots (c.f. Thomas *et al*., 2016a). All data analyses were conducted using GenStat 17th Edition (VSN International Ltd, Hemel Hempstead, UK).

4.4 Results

4.4.1 Relationships of length related roots traits with grain yield and component traits

The length-related root traits (CHCRY, CHCRX, CMRX, CMRY, MDR, TLAR, TLPR, RCH) did not show relationships with mean grain yield (GYD, t ha^{-1}), biological yield (BYD, g), harvest index (HI %), 1000 grain weight (TGW, g) and plant height (PHT, cm), of 36 genotypes averaged across sites and years (S 4.1 Table). However, maximum width of root (MWR) and total length of lateral roots (TLLR) showed positive relationships with PHT of 36 genotypes, averaged across sites and years (r=0.42 and 0.52, respectively) (**Table 4.2**).

The total length of lateral roots (TLLR) correlated with GYD (r=0.43) and BYD (r=0.47) of 36 genotypes, averaged across years, only at Kumarganj-sodic site. The TLLR showed positive relationships with PHT of 36 genotypes, averaged across years, at all sites ($P<0.05$) except at Kumarganj-sodic and Pundibari (acidic soil) sites.

The mean GYD, TGW and HI of 36 genotypes averaged across years, did not show relationships with any seedling root length traits at Karnal, Hisar (saline), Kumarganj-reclaimed (saline), Malda and Pundibari (acidic) sites, except Kumarganj-sodic site.

4.4.2 Relationships of juvenile root angle traits with grain yield and component traits

A narrow juvenile root angle potentially represents a steeper root system. A wider juvenile root angle potentially represents a shallower root system. A narrow root angle between primary roots showed positive relationships with GYD and component traits of 36 genotypes, averaged across sites and years. For example, narrow root angle traits (PEA 251 and PEA 301) showed positive relationship with GYD, averaged across sites and years ($r=0.46$ and 0.44; $P<0.05$, respectively). Similarly, BYD of 36 genotypes, averaged across sites and years, showed positive relationships with narrow root angle traits, PEA 251 and PEA 301, ($r=0.49$, 0.48; $P<0.05$, respectively) (**Table 4.2**).

Table 4.2 Correlation coefficients (r) between seedling root traits measured in HTP and grain yield and component traits of 36 genotypes grown at six sites over two years (2013-14 and 2004-15). Abbreviations in Table 1.

BYD	1															
GYD	2	0.50*														
HI	3	-0.22	0.72***	-												
PHT	4	0.35	-0.47*	-0.82***	-											
TGW	5	0.05	0.05	0.03	0.18	-										
MDR	6	0.19	0.30	0.16	0.17	-0.02	-									
MWR	7	-0.19	-0.32	-0.27	0.42*	-0.17	0.61**	-								
TLAR	8	-0.05	0.12	0.17	0.14	-0.14	0.90***	0.72***	-							
TLLR	9	0.16	-0.10	-0.19	0.52*	0.06	0.48*	0.39	0.59**	-						
TLPR	10	-0.05	0.12	0.17	0.13	-0.14	0.90***	0.71***	1.00***	0.58**	-					
PEA 251	11	-0.49*	-0.46*	-0.18	0.09	-0.10	-0.07	0.59**	0.14	0.02	0.14	-				
PEA 252	12	-0.30	-0.47*	-0.37	0.17	-0.11	-0.07	0.44*	-0.09	-0.26	-0.09	0.56**	-			
PEA 301	13	-0.48*	-0.44*	-0.16	0.18	0.07	0.00	0.55**	0.20	0.17	0.20	0.91***	0.50*	-		
PEA 302	14	-0.24	0.10	0.20	-0.06	0.13	0.34	0.39	0.31	0.23	0.31	0.37	0.42*	0.49**	-	
RCH	15	-0.06	-0.07	-0.07	0.30	-0.13	0.83***	0.93***	0.88***	0.48*	0.88***	0.40	0.26	0.38	0.44*	-
		BYD	**GYD**	**HI**	**PHT**	**TGW**	**MDR**	**MWR**	**TLAR**	**TLLR**	**TLPR**	**PEA 251**	**PEA 252**	**PEA 301**	**PEA 302**	**RCH**

***, ** and * represent significant levels of P<0.001; P<0.01; P<0.05, respectively. BYD: biological yield; GYD: grain yield (t ha^{-1}); HI: harvest index (%).

A narrow juvenile root angle traits showed positive relationships with GYD of 36 genotypes averaged across years, at Karnal (S 4.2 Table), Kumarganj-reclaimed (S 4.4 Table), Malda (S 4.6 Table) and Pundibari (S 4.7 Table) sites ($P<0.01$). For example, narrow root angle, PEA 752, showed significant positive relationships with GYD of 36 genotypes, averaged across years, at Karnal ($r=0.42$) (**Figure 4.3**A), Kumarganj-reclaimed ($r= 0.44$) (**Figure 4.3**B), Malda ($r=0.44$) (**Figure 4.3**C) and Pundibari (acidic soil) ($r=0.51$) sites (**Figure 4.3**D). Similarly, narrow root angle trait showed significant positive relationship with HI of 36 genotypes, averaged across years, at all the sites except at Kumarganj-sodic and Pundibari sites.

Contrastingly, wider root angle traits showed positive relationships with mean PHT of 36 genotypes, averaged across years, at all the sites except at Pundibari. ($P<0.05$). The mean TGW of 36 genotypes, averaged across years at Hisar (saline soil) showed significant positive relationships with wider root angle, PEA 302 ($r=0.46$, $P<0.05$).

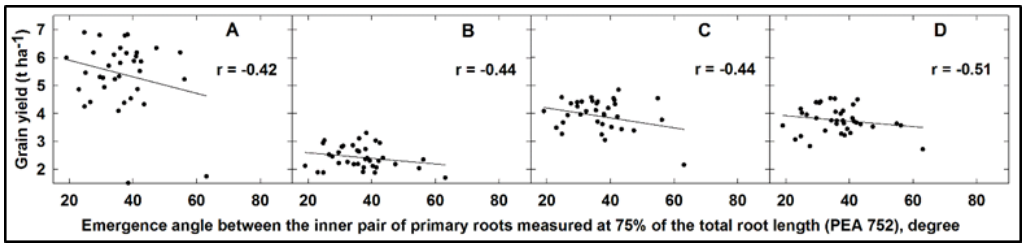


Figure 4.3 Relationship between grain yields of 36 genotypes measured in field and seedling root angle trait, PEA 752, measured in HTP system. Grain yield data are mean of 36 genotypes with two replicates over two years, 2013-14 and 2014-15 at Karnal (A), Kumarganj-reclaimed (B), Malda (C) and Pundibari (D). Root angle data (PEA 752) is the mean of 36 genotypes with 20 replications in HTP system.

4.4.3 Correlations between length-related juvenile root traits, grain Zn concentration and the grain ionome

Grain Zn concentration has previously been reported for these 36 genotypes (Khokhar *et al*., submitted) because this micronutrient is an important breeding target for grain quality and human nutrition. There was little evidence of associated between lengths- related juvenile root traits and grain Zn concentration. Grain Zn concentration averaged across years, correlated with the TLLR only at the Pundibari (acidic) site ($r=0.45$; $P<0.05$).

Among the macronutrients, grain magnesium (Mg) concentration, averaged across years, correlated with LRN ($r=0.43$) and TLLR ($r=0.58$) at Karnal, TLLR ($r=0.47$) at Hisar, MWR ($r=0.48$) at Kumarganj-reclaimed site, LRN ($r=0.53$) at Malda and with LRN ($r=0.47$) and TLLR ($r=0.44$) at Pundibari site. The grain sulphur (S) concentration of 36 genotypes, averaged across years, correlated with most of the length related roots traits (TLAR, TLPR, TLLR, MLLR, MWR, CHCRY) and other root traits (LRN, PRN and RCH) at most of the sites, except at Kumarganj-sodic site (r between 0.42 and 0.65; P between <0.05 and <0.001). For example, mean grain sulphur S concentration of 36 genotypes, averaged across years, correlated with total length of all roots (TLAR) and total length of primary roots (TLPR) at Karnal ($r = 0.47$; $r=0.46$, respectively), Hisar ($r=0.51$; $r=0.50$, respectively), Kumarganj-reclaimed ($r=0.63$; $r=0.63$, respectively), Malda ($r=0.44$; $r=0.43$, respectively) and Pundibari ($r=0.55$; $r=0.55$, respectively) sites (S4.2, S4.3, S4.4, S4.6, S4.7 Tables).

Among the other micronutrients, grain copper (Cu) concentration of 36 genotypes, averaged across years, correlated positively with MWR ($r=0.43$) at

Hisar and negatively with primary root number (PRN; r=-0.45) at Pundibari site. The mean grain Fe concentration of 36 genotypes, averaged across sites and years, correlated with MWR (r=0.63), root convex hull area (RCH; r=0.48) and TLLR (r=0.42). However, grain Fe concentration of 36 genotypes, averaged across years, correlated with MWR at Karnal (r=0.58), Hisar (r=0.48) and at Malda (r=0.55) sites. The grain manganese (Mn) concentration of 36 genotypes, averaged across years, correlated with LRN at Karnal (r=0.43) and Malda (r=0.55) and with TLLR at Kumarganj-reclaimed (r=0.46) site. Among the non-essential elements, the grain arsenic (As) concentration of 36 genotypes, averaged across years, correlated with TLAR and TLPR (r=0.42) only at Karnal site. The grain selenium (Se) concentration of 36 genotypes, correlated with PRN at Karnal (r=0.44), maximum width of roots (r=0.42) and root convex hull area (RCH) at Kumarganj-reclaimed (r=0.43) site and with LRN at Malda (r=0.49) site.

4.4.4 Correlations between angle-related juvenile root traits, grain Zn concentration and the grain ionome

Grain Zn concentration of 36 genotypes, averaged across years, did not correlate with root angle traits at any site.

Among the macronutrients, grain calcium (Ca) concertation of 36 genotypes, averaged across years, correlated with wider root angle traits at Hisar (PEA 302; r=0.53), at Kumarganj-reclaimed (PEA 252; r=0.42) and at Pundibari (PEA 251; r=0.54). The grain potassium (K) concentration of 36 genotypes, averaged across years, correlated with wider root angle traits at Karnal site (r between 0.43 and 0.58). The grain Mg concentration of 36 genotypes, averaged across

years, correlated wider root angle trait (PEA 301) only at Karnal (r=0.51) site. The grain S concentration of 36 genotypes, averaged across years, correlated with narrow root angle traits at Pundibari (acidic soil) site.

Among the micronutrients, the grain Cu concentration of 36 genotypes, averaged across years, correlated with wider root angle traits which potentially represent the shallow root system, at Malda site. The grain Fe concentration of 36 genotypes, averaged across years, correlated with wider root angle traits at Karnal (**Figure 4.4**A), at Kumarganj-reclaimed (**Figure 4.4**B) and at Malda (**Figure 4.4**C) sites. The grain molybdenum (Mo) concentration of 36 genotypes, averaged across years, correlated with narrow root angle traits which potentially represent the steep root angle system, at Hisar and Kumarganj-sodic sites. Among the non-essential elements, grain arsenic (As) concentration of 36 genotypes correlated with narrow root angle traits at Kumarganj-reclaimed and with wider root angle traits at Pundibari sites. The grain Se concentration of 36 genotypes, averaged across years, correlate with narrow root angle traits at Hisar and Pundibari sites.

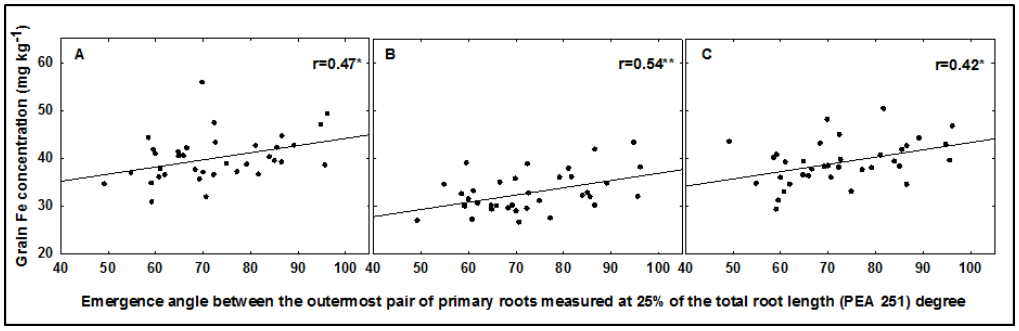


Figure 4.4 Correlation of mean grain Fe concentration of 36 genotypes grown at Karnal (A), Kumarganj-reclaimed (B) and Malda (C) sites with root angle trait, PEA 251 measured in HTP system. Grain Fe concentration is the data of two replicate per plot of 36 genotypes over two years (2013-14 and 2014-15) at Karnal and Malda sites and one replicate per plot in 2013-14 and two replicate per plot in 2014-15 at Kumarganj-reclaimed site. *P <0.05; **P <0.01.

4.4.5 Correlations within seedling root traits in HTP system

Positive significant relationships were observed within length-related root traits (CHCRY, CHCRX, CMRX, CMRY, MDR, MWR, TLAR, TLPR, TLLR, RCH) and within root angle traits (PEA 251, 252, 301, 302, 501, 502, 751, 752, 951, 952, 1001, 1002) (r=0.42-0.99; P between <0.05 and <0.001). For example, total length of all roots (TLAR) showed positive relationship (P<0.001) with total length of primary roots (TLPR) and with maximum depth of root (MDR). Width depth ratio (WDR) and root convex hull (RCH) represent the shape of root system. WDR more strongly associated with maximum width of the root (MWR) (r=0.79, P<0.001) than depth of root (MDR) (r=0.02, P=0.9). Similarly, emergence angle between the second inner pair of primary roots measured at 30 pixel (PEA 302) correlated significantly and positively with primary root angle trait, PEA 252 (P<0.001).

However, some root length traits, for example, CHCRX, CMRX and MWR also showed positive significant relationships with root angle traits, PEA 502, PEA 302 and PEA 751 (r=0.42, r=0.44, r=0.68, respectively). Moreover, wider root system associated with the wider/shallower root system (S 4.1 Table).

4.4.6 Variance components associated with root traits and, number of replications required to detect the differences in root traits between genotypes

A panel of 36 genotypes showed significant variation for most of the root traits except traits related to lateral roots. Genotype term associated with 10 to 30% of variations in root traits under HTP system (**Table 4.3**). The residual term was associated with 20 to 83% of variation in root traits which could be due to variation in seed size and tray-to-tray variation in tanks.

Table 4.3 The contribution of genotype, tank, replications and residual factors to variation percentage (%) in root traits of 36 genotypes grown in HTP system. Data are means of ~20 replications.

	Variation %			
Root traits	**Genotype**	**Tank**	**Replication**	**Residual**
TLAR	17.16	0.58	5.27	76.99
TLPR	16.96	0.59	5.31	77.14
TLLR	40.36	4.09	23.19	32.37
MLAR	13.67	3.14	6.03	77.16
MLPR	19.30	2.21	5.14	73.35
MLLR	33.89	2.33	13.69	50.08
RCH	20.63	1.44	6.09	71.84
MWR	17.94	0.59	4.46	77.01
MDR	19.90	2.45	6.85	70.81
CMRX	14.82	0.34	2.48	82.36
CMRY	19.80	3.78	5.95	70.46
CHCRX	12.52	0.50	4.06	82.91
CHCRY	19.14	3.02	5.51	72.32
PEA_301	19.22	2.72	4.65	73.41
PEA_302	30.14	1.16	3.08	65.63
PEA_251	23.68	3.99	2.67	69.66
PEA_252	22.94	2.20	5.47	69.39
PEA 501	24.11	2.98	2.00	70.91
PEA 502	22.91	1.32	2.37	73.40
PEA 751	22.22	2.76	2.62	72.41
PEA 752	23.59	1.85	3.97	70.59
PEA 951	25.37	2.90	2.60	69.14
PEA 952	24.03	2.82	5.53	67.62
PEA 1001	20.22	2.96	3.42	73.40
PEA 1002	23.81	1.92	4.82	69.45
LRN	47.09	6.72	26.67	19.52
PRN	13.41	0.75	3.11	82.73
WDR ratio	15.95	0.76	2.33	80.96

The number of replications required to detect the differences between genotypes for mean root traits under HTP system was measured by constructing the power plot. For example, at 90% power, to detect the 20% of difference between

genotypes for root traits like, MDW, TLPR and RCH, would require 10, 4 and 6 number of replications, respectively (**Figure 4.5**).

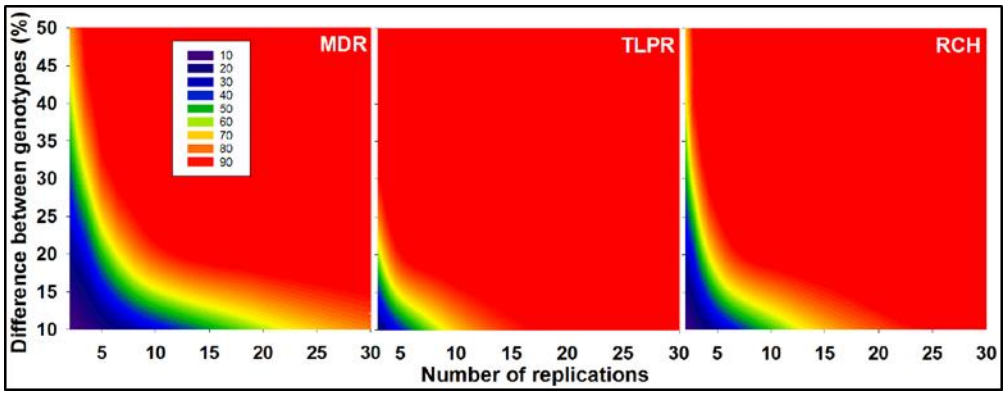


Figure 4.5 The power of experiment (z-axis, legend (10-90) in percentage) to detect percentage of differences in root trait means between genotypes (y-axis) as a function of the number of replicates (x-axis) in HTP system.

4.5 Discussion

A low-cost two dimensional high throughput phenotyping (2-D HTP) 'pouch and wick' germination paper based platform was used to study the root architecture of 36 Indian adapted wheat genotypes. Paper-based 'pouch & wick' systems have been used to study the relationships between juvenile root traits and grain yield and component traits under optimal field conditions in wheat (Bai *et al*., 2013; Atkinson *et al*., 2015; Xie *et al*., 2017). However, the present study identified that juvenile root traits correlate with yield, yield components and grain mineral composition traits under a wide range of hostile soil environments in India.

4.5.1 Significant relationships between juvenile root traits, grain yield and yield components

A panel of 36 widely adapted Indian genotypes have shown differences in grain yield and yield component traits when grown at six sites (pH 4.5-9.5) in India in 2013-14 and 2014-15. Mean grain yield was 1.0 and 5.5 t ha^{-1} at hostile and non-hostile soils, respectively. Grain yield of 36 genotypes showed reduction up to 59% under saline soils (Hisar) than normal soil (Karnal) (Khokhar *et al.*, 2017). This reduction in grain yield and yield components could be due to soil salinity/alkalinity/acidity conditions, weather conditions, and root traits, which might affected the water and nutrient uptake from different hostile soils. It is evident that grain size will affect the root and shoot length in wheat (Kakhki *et al*., 2008; Maydup *et al*., 2012) and grain diameter affect the root length traits in *Brassica napus* L. (Thomas *et al*., 2016b), thus, we sieved the grain and selected the seeds of particular range to avoid any confounding effects of grain size in this study.

Length related juvenile root traits did not correlate with GYD, BYD, HI and TGW at most of the field sites. This could be due to limited variation in length related root traits between the genotypes and due to short growing period used; the roots of most genotypes roots reached ~60% of the length of the germination paper. Our results are consistent with Atkinson *et al*., 2015, who reported no relationships between length-related root traits measured in HTP system and grain yield and component traits of field grown double haploid population of winter wheat. Contrastingly, Xie *et al*., 2017 reported relationships between juvenile root length traits and GYD of wheat genotypes under normal soil field condition. The total length of lateral roots and number of lateral roots associated

with mature plant height (PHT) of 36 genotypes at most of the field sites except Kumarganj-sodic and Pundibari (acidic) sites. Our observations are consistent to some extent with Bai *et al*., 2013 and Atkinson *et al*., 2015, who reported significant positive relationships between length related juvenile root traits and mature PHT.

Narrow root angle traits potentially represent a steeper root system and correlated with GYD in this study. For example, a wheat variety, DBW 71, had narrow root angle (PEA 252; 40.08°) and showed much greater GYD (3.8 t ha^{-1}, averaged across sites and years than Kharchia 65 (1.8 t ha^{-1}) which had wider root angle (PEA 252; 67.35°). Our observations are consistent with McDonald, 2010 and Manschadi *et al*., 2008, who reported that wheat genotypes with narrow juvenile root angles when grown in soil boxes and gel-filled chamber growth systems showed greater GYD, than those genotypes wider root angle varieties. In addition, narrow root angle trait showed significant positive relationship with GYD at hostile soils, for example, at Kumarganj-reclaimed (saline/reclaimed) and Pundibari (acidic) sites, indicating that narrow root angle may help to increase the grain yield through better absorption of water and nutrients from deeper layers under harsh soils. Richard *et al*., 2015, also reported that narrow root angle could result into the development of compact and deeper root system, which is highly desirable trait in wheat particularly when grown in water deficient soil conditions.

Plants with greater numbers of roots at deeper levels in the soil makes plants more efficient in exploration of sub-surface water and other nutrients under drought and rainfed conditions which may benefit in the improvement of wheat

grain production (Kirkegaard *et al*., 2007; Manschadi *et al*., 2010; Richard *et al*., 2015). However, wider root angles, potentially representing a shallow root system, were associated with TGW only at Hisar (saline soil) site. Contrastingly, seminal root angle traits measured on filter paper showed negative association with 1000 grain weight of field grown 183 durum wheat lines under irrigated and rainfed conditions (Cane *et al*., 2014).

4.5.2 Significant relationships between juvenile root traits and grain Zn concentration and the grain ionome

Zinc is an essential element for plants and people (Cakmak *et al*., 2000; Broadley *et al*., 2007). Dietary Zn deficiency is widespread and affecting 20 percent of the world's population, especially in developing countries. Dietary Zn deficiency is linked to diarrhoea, respiratory infections and stunting in children (Hess and King, 2009; King *et al*., 2016). Wheat is an important dietary source of Zn and supply ~50% Zn of daily needs in India (Kumssa *et al*., 2015). The grain Zn concentration and the grain ionome of 36 wheat genotypes differed when grown under different hostile soil environments in India (Khokhar *et al*., submitted). Root traits have shown importance in the absorption of soil nutrients in many crops (Zhao *et al*., 2008; Liu *et al*., 2013; White and Greenwood, 2013; Thomas *et al*., 2016a). In the present study, the grain Zn concentration of 36 genotypes, averaged across years, correlated with TLLR at Pundibari (acidic) site. Increased length of lateral roots potentially increase the surface area which may help the roots to explore more Zn in the soil. Rose *et al*., 2013 also reported that longer lateral roots and longer root hairs increases the acquisition of soil Zn by roots of rice genotypes.

The wider root angle traits showed association with grain Ca concentration of 36 wheat genotypes under hostile soils, whilst length related root traits associated grain Mg and S concentration under hostile and non-hostile soil environments. Lower soil Ca concentration rarely affect the plant growth (White and Broadley, 2003), but higher S in soil have shown increase in root number in soybean (Zhao *et al*., 2008). The wider root angle traits and lateral root length associated with grain Fe concentration of 36 wheat genotypes under hostile and non-hostile soil sites. Thomas *et al*., 2016a, have reported positive association between lateral root density in HTP system and leaf Fe concentration measured in field in oilseed rape genotypes. Therefore, there could be a possibility that wider root system and greater length of lateral roots might increase the efficiency of plants in exploration and acquisition of Fe from the heterogeneous soils. Lateral root traits associated with grain Mn concentration under normal/saline field sites which are in agreement with Lui *et al*., 2013, who reported positive association between lateral roots and grain Mn concentration in rice genotypes under field condition. There is possibility that developing more dense root system with increase in lateral root length and number can enable the roots to explore more Mn and Zn in the mineral rich pockets in the soil (White and Broadley, 2009; White and Greenwood, 2013). Association between juvenile root traits and the grain mineral composition traits of wheat genotypes measured under wide range of hostile soils have not been yet studied. Therefore, more work is needed to determine the effects of different nutrients, with adequate and limited levels in solution, on different root traits.

The residual term explained most of the variations in juvenile root traits of 36 wheat genotypes, which indicates requirement of large numbers of replicates to

see the differences between root traits. Present study showed that 4-10 replications required to detect the 25% difference between wheat genotypes for MDR, TLPR and RCH root traits. However, Adu *et al*., 2014 and Thomas *et al*., 2016a reported that 6-43 and 11-36 replications to be required to detect the 30 % and 50% differences between the *Brassica rapa* L. and *Brassica napus* L. genotypes for different root traits, respectively.

The time taken to get the root data of each plant from HTP system was 1-3 minutes in present study. Comparatively, root phenotyping in field conditions, from root extraction, washing to data analysis, took ~20 minutes per plant in *Brassica napus* L species and, it costs less than £1 per plant using HTP system in *Brassica napus* L (Thomas *et al*., 2016a). This HTP system present a huge potential to breeding institutes, for example, Indian Institute of Wheat & Barley research, Karnal, India, which has collection of more than 10,000 wheat germplasm lines, to characterise their big germplasm collection for different root traits before incorporating them into breeding programmes to develop the advance breeding material.

4.5.3 Conclusion

This study shows that juvenile root traits are associated with grain yield, yield components and grain mineral composition traits under a wide range of soil environments. Narrow root angle traits associated with grain yield and biological yield under hostile soils. A wider root system and lateral root length/number was associated with grain Zn concentration and the other mineral composition traits. These result suggest that root traits for example, narrow root angle and total

length of lateral roots should be introgressed in to wheat genotypes to increase the grain yield and grain Zn concentration, respectively. The association between juvenile root traits and grain yield, component traits and grain mineral composition traits under a wide range of soil environments have not been yet studied. Therefore the use of juvenile root traits should be explored further in wheat breeding to improve the grain yield and grain quality traits under different hostile soils.

4.6 References

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4.7 Supplementary tables

S4.1 Table Correlation coefficients between seedling root traits and grain yield, yield components and grain mineral composition traits. Root data are mean of ~ 20 replications grown in HTP system, yield & yield components data are mean of two replicates each plot, averaged across years and sites and mineral composition traits data are means of two replicates per plot per genotype at Karnal, Hisar and Malda, one replicate per plot at Kumarganj-reclaimed and Kumarganj-sodic sites in 2013-14 and two replicates per plot per genotype at six sites in 2014-15.

r values													
As	1	-											
BYD	2	-0.1554	-										
Ba	3	-0.2304	-0.397	-									
CHCRX	4	-0.2058	0.1098	0.2263	-								
CHCRY	5	0.1259	0.1843	-0.0045	0.5797	-							
CMRX	6	-0.1113	0.0815	0.1927	0.9302	0.6767	-						
CMRY	7	0.1946	0.1906	0.0098	0.5529	0.9823	0.6498	-					
Ca	8	-0.1356	-0.1832	0.3427	0.129	-0.0083	0.0324	-0.0172	-				
Cs	9	-0.0369	-0.1053	0.0691	-0.0609	-0.3375	-0.2373	-0.3086	0.475	-			
Cu	10	0.0202	-0.3614	0.2182	0.291	0.0518	0.2963	0.0637	0.1873	0.3851	-		
Fe	11	-0.2809	-0.152	0.1921	0.2331	0.0765	0.2897	-0.009	0.0471	0.2458	0.5164	-	
GYD	12	0.2716	0.4988	-0.1074	-0.0502	0.2735	-0.012	0.3405	-0.0985	-0.3503	-0.2934	-0.5687	-
HI_%	13	0.4274	-0.2233	0.1369	-0.2216	0.1411	-0.1418	0.2113	-0.0678	-0.3351	-0.0587	-0.5289	0.7153
K	14	0.05	-0.386	0.3312	-0.3673	-0.3173	-0.4198	-0.2738	0.4639	0.352	0.1389	0.016	-0.1978
LRN	15	0.1118	0.3366	-0.1562	0.2849	0.6209	0.3099	0.6033	0.1937	0.0843	0.1533	0.2522	-0.0007
MDR	16	0.1587	0.1855	0.0191	0.5596	0.9877	0.6577	0.9727	0.0202	-0.3569	0.0542	0.0743	0.301
MLAR	17	0.0711	0.0609	0.1283	0.6507	0.8679	0.7406	0.8638	-0.0457	-0.3782	0.012	0.0126	0.2469
MLLR	18	0.0452	-0.1046	-0.0069	-0.0498	0.1582	0.0959	0.109	0.0789	-0.0949	0.1743	0.2439	-0.0162
MLPR	19	0.0557	0.1174	0.0584	0.674	0.9635	0.7892	0.933	-0.0045	-0.3318	0.1335	0.2369	0.1217
MWR	20	-0.0647	-0.1869	0.1039	0.5224	0.5798	0.6137	0.4715	0.1619	-0.1666	0.2952	0.6311	-0.3222
Mg	21	0.1068	-0.1606	-0.1584	0.1104	0.1926	0.091	0.2122	0.1755	0.5251	0.5679	0.5215	-0.4032
Mn	22	-0.0041	0.2405	0.1212	0.2116	0.2912	0.2404	0.3534	0.3555	0.2323	0.2533	0.1344	0.037
Mo	23	0.2273	0.346	-0.3299	0.1729	0.3106	0.1571	0.3547	-0.3651	0.0157	0.0495	-0.1313	0.2475
P	24	0.1568	-0.082	-0.0432	0.0086	-0.0113	-0.0674	0.0438	0.1602	0.4919	0.4349	0.2404	-0.3026
PEA_1001	25	-0.1742	-0.2984	0.3675	0.2959	0.0353	0.2539	-0.0821	0.3226	0.0298	0.1145	0.5259	-0.4444
PEA_1002	26	-0.5358	0.1066	0.1561	0.4283	0.1336	0.3825	0.023	0.175	0.0309	0.063	0.5314	-0.463
PEA_251	27	-0.0986	-0.4857	0.3816	0.0709	-0.1177	0.0649	-0.219	0.4061	0.121	0.1142	0.4251	-0.464
PEA_252	28	-0.4295	-0.2985	0.4036	0.3916	-0.0583	0.2656	-0.1527	0.296	0.2804	0.185	0.4338	-0.4697
PEA_301	29	-0.0067	-0.4838	0.3879	0.1533	-0.0357	0.132	-0.106	0.3783	0.2606	0.1707	0.456	-0.444
PEA_302	30	-0.0686	-0.2396	0.4993	0.5023	0.3597	0.4403	0.3258	0.5355	0.159	0.2395	0.2433	0.1017
PEA_501	31	-0.1351	-0.4181	0.3983	0.1371	-0.0964	0.1059	-0.2114	0.4197	0.1268	0.0774	0.4678	-0.498
PEA_502	32	-0.4627	-0.1387	0.2738	0.4199	0.0826	0.331	-0.0358	0.1851	0.1207	0.0727	0.5546	-0.5305
PEA_751	33	-0.1779	-0.3368	0.3957	0.2556	-0.0102	0.2104	-0.1247	0.3965	0.0943	0.1035	0.5177	-0.4873
PEA_752	34	-0.4664	0.0196	0.1261	0.4317	0.1234	0.3782	0.0056	0.1455	0.0473	0.0426	0.5514	-0.5321
PEA_951	35	-0.0706	-0.4701	0.3764	0.1194	-0.0689	0.1393	-0.156	0.3391	0.1296	0.165	0.4723	-0.4112
PEA_952	36	-0.2039	-0.3638	0.5394	0.405	0.0981	0.3251	0.0501	0.53	0.3749	0.3337	0.3682	-0.1466
PHT	37	-0.1807	0.3484	-0.3892	0.3379	0.2006	0.3305	0.1178	-0.03	0.1847	0.0381	0.5094	-0.4665
PRN	38	0.3867	-0.3785	0.0667	-0.5183	-0.0634	-0.4038	-0.0501	-0.1996	-0.1384	0.2784	0.0925	0.0091
RCH	39	0.0129	-0.0609	0.1284	0.5569	0.8049	0.6661	0.7189	0.1009	-0.2732	0.2085	0.4837	-0.0677
Rb	40	0.0038	0.2129	0.0751	-0.1081	-0.2291	-0.23	-0.1955	0.5047	0.6869	0.0889	0.1318	-0.0857
S	41	0.2741	-0.0249	-0.259	0.1257	0.5227	0.1929	0.5207	0.1033	0.1165	0.4201	0.2632	-0.0487
Se	42	0.2546	0.0633	-0.1623	-0.1284	0.2099	-0.1129	0.2384	0.148	0.0263	0.0594	-0.1497	-0.0582
Sr	43	-0.0691	-0.2815	0.6529	0.1257	-0.1456	0.0023	-0.1194	0.7339	0.4685	0.2198	-0.0133	0.0593
TGW	44	0.1267	0.0479	-0.2163	-0.0286	-0.0038	-0.0449	0.0001	-0.1984	0.0142	-0.2717	-0.0577	0.0471
TLAR	45	0.2219	-0.0453	0.0905	0.4291	0.8814	0.5853	0.8564	-0.0624	-0.3689	0.2579	0.2656	0.1153
TLLR	46	0.0784	0.163	-0.1595	0.1656	0.4987	0.2733	0.4488	0.0947	-0.012	0.2324	0.4208	-0.0975
TLPR	47	0.2234	-0.048	0.0934	0.4287	0.8811	0.5845	0.8569	-0.0627	-0.3706	0.2564	0.2607	0.1192
WDR	48	-0.1911	-0.3895	0.1389	0.2674	-0.0031	0.2926	-0.1167	0.2805	0.1347	0.3309	0.6969	-0.6351
Zn	49	-0.1883	-0.2141	-0.0262	0.1153	-0.0703	0.1	-0.0543	-0.0079	0.4184	0.6056	0.5185	-0.6272
		1	2	3	4	5	6	7	8	9	10	11	12
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD

HI_%	13	-											
K	14	0.0612	-										
LRN	15	-0.2395	-0.2078	-									
MDR	16	0.1596	-0.2705	0.6048	-								
MLAR	17	0.1744	-0.1411	0.2404	0.8774	-							
MLLR	18	0.1174	-0.0691	0.3172	0.1609	-0.0138	-						
MLPR	19	0.0167	-0.2881	0.5792	0.9502	0.8893	0.208	-					
MWR	20	-0.2692	-0.0331	0.3349	0.6079	0.6051	0.2119	0.7055	-				
Mg	21	-0.3057	0.1742	0.5802	0.1748	-0.0213	0.3137	0.2295	0.2723	-			
Mn	22	-0.1965	0.0461	0.5477	0.2632	0.0708	0.1632	0.3151	-0.0107	0.4518	-		
Mo	23	0.019	-0.5045	0.258	0.2885	0.1455	-0.0936	0.1988	-0.0933	0.2178	0.0622	-	
P	24	-0.243	0.4141	0.3499	-0.0246	-0.1433	0.1283	0.024	0.0149	0.7563	0.4849	0.1899	-
PEA_1001	25	-0.3244	0.1173	0.0101	0.0939	0.1417	0.1618	0.1708	0.7	-0.0134	-0.2652	-0.371	-0.1843
PEA_1002	26	-0.642	-0.0734	0.2245	0.1379	0.1698	-0.1652	0.2392	0.5593	0.0466	-0.0205	-0.3179	-0.1502
PEA_251	27	-0.1767	0.3572	-0.1266	-0.0721	0.0167	0.2553	0.0139	0.591	0.0099	-0.2883	-0.4466	-0.0019
PEA_252	28	-0.367	0.1799	-0.232	-0.0736	0.1302	-0.2465	0.0389	0.4442	-0.0275	-0.1953	-0.3262	-0.0847
PEA_301	29	-0.1554	0.2699	0.0298	-0.0038	0.0405	0.3008	0.0932	0.547	0.2385	-0.0934	-0.3256	0.1671
PEA_302	30	0.2042	0.021	0.2251	0.3403	0.3248	0.1777	0.3789	0.3873	0.1579	0.2166	-0.0997	-0.0392
PEA_501	31	-0.2818	0.3152	-0.0913	-0.0458	0.0396	0.1951	0.0423	0.6177	-0.0241	-0.2938	-0.4738	-0.0957
PEA_502	32	-0.5274	0.0955	0.0294	0.0789	0.2152	-0.1726	0.2066	0.6203	0.0387	-0.2083	-0.3797	-0.1133
PEA_751	33	-0.3404	0.218	-0.0018	0.0446	0.1066	0.1479	0.1283	0.676	0.0035	-0.2613	-0.4131	-0.1287
PEA_752	34	-0.6491	0.0035	0.1591	0.1243	0.2119	-0.1735	0.2489	0.6207	0.0626	-0.1176	-0.355	-0.1104
PEA_951	35	-0.124	0.2743	-0.1045	-0.0332	0.0564	0.2974	0.0586	0.5899	0.0702	-0.2611	-0.3703	-0.0049
PEA_952	36	0.012	0.2032	-0.1059	0.0791	0.2162	-0.0132	0.1604	0.4029	0.0862	0.0404	-0.1968	-0.0349
PHT	37	-0.8198	-0.3953	0.4964	0.1714	0.0249	0.1308	0.2933	0.4233	0.4313	0.3341	0.2271	0.254
PRN	38	0.3717	0.3432	0.0148	-0.0023	-0.1317	0.3633	-0.1117	0.0649	0.2236	-0.2155	0.076	0.1846
RCH	39	-0.0716	-0.1109	0.4651	0.8295	0.7815	0.2744	0.8736	0.9311	0.235	0.0544	0.0246	-0.0335
Rb	40	-0.3137	0.5886	0.1396	-0.2109	-0.1925	-0.1108	-0.2045	-0.0857	0.2916	0.404	-0.3121	0.4288
S	41	-0.0069	-0.0463	0.659	0.5325	0.2472	0.4776	0.523	0.4038	0.7151	0.4844	0.2304	0.5482
Se	42	-0.1128	0.0634	0.4722	0.255	-0.0171	0.3415	0.1602	0.0347	0.3767	0.4937	0.2227	0.445
Sr	43	0.1951	0.5368	-0.1574	-0.1306	-0.0344	-0.1298	-0.1516	-0.0625	-0.0498	0.1848	-0.4247	0.1138
TGW	44	0.0262	-0.4924	0.0998	-0.0221	-0.15	0.0268	-0.1065	-0.1664	0.0613	-0.2012	0.3825	-0.1658
TLAR	45	0.1676	-0.1198	0.5805	0.898	0.7773	0.356	0.9004	0.7154	0.3131	0.2175	0.192	0.1171
TLLR	46	-0.1938	-0.2296	0.86	0.4754	0.1248	0.6963	0.5225	0.3933	0.6137	0.5215	0.117	0.3376
TLPR	47	0.1735	-0.1147	0.5734	0.8984	0.7818	0.351	0.8996	0.7148	0.3081	0.2115	0.1909	0.1137
WDR	48	-0.4692	0.1815	-0.025	0.0206	0.1123	0.0622	0.1644	0.7879	0.2331	-0.1673	-0.2785	0.0569
Zn	49	-0.4788	0.2646	0.2347	-0.116	-0.1324	0.1704	0.0492	0.1479	0.7387	0.3514	0.0317	0.7902
		13	14	15	16	17	18	19	20	21	22	23	24
		HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P

PEA_1001	25	-											
PEA_1002	26	0.601	-										
PEA_251	27	0.8653	0.377	-									
PEA_252	28	0.6161	0.7104	0.5568	-								
PEA_301	29	0.7636	0.3285	0.9068	0.5014	-							
PEA_302	30	0.3564	0.1661	0.3684	0.419	0.4942	-						
PEA_501	31	0.9464	0.49	0.9444	0.6153	0.8169	0.3383	-					
PEA_502	32	0.7381	0.9035	0.5937	0.8847	0.5395	0.3095	0.6819	-				
PEA_751	33	0.9875	0.5884	0.8964	0.6327	0.782	0.3593	0.9781	0.7415	-			
PEA_752	34	0.6575	0.9741	0.4647	0.7636	0.4013	0.1656	0.5771	0.9553	0.6567	-		
PEA_951	35	0.8223	0.365	0.9616	0.563	0.9242	0.4371	0.8662	0.5847	0.8356	0.442	-	
PEA_952	36	0.4684	0.2849	0.5516	0.7172	0.595	0.8487	0.5024	0.51	0.4892	0.3212	0.6155	-
PHT	37	0.2374	0.5067	0.085	0.1726	0.1829	-0.0552	0.142	0.3608	0.2096	0.5032	0.0889	-0.0365
PRN	38	0.042	-0.3679	0.1824	-0.3195	0.1363	-0.1522	0.0881	-0.2901	0.0338	-0.3519	0.1801	-0.1764
RCH	39	0.5326	0.4079	0.3982	0.2649	0.3841	0.4367	0.4318	0.451	0.4992	0.4523	0.4121	0.3323
Rb	40	0.079	0.1839	0.1585	0.2424	0.2301	0.0965	0.1605	0.2111	0.1349	0.1987	0.1562	0.2638
S	41	0.002	-0.0764	-0.0118	-0.262	0.1669	0.0591	-0.0541	-0.1461	-0.0305	-0.0925	0.0041	-0.133
Se	42	-0.0656	-0.1695	-0.0423	-0.3942	0.0622	-0.2196	-0.0906	-0.3207	-0.0899	-0.2314	-0.0937	-0.37
Sr	43	0.1737	0.0746	0.3201	0.4734	0.337	0.6061	0.2934	0.2112	0.2427	0.0699	0.3186	0.7027
TGW	44	-0.1202	-0.0886	-0.1008	-0.1085	0.0681	0.1307	-0.2003	-0.1104	-0.1627	-0.116	0.0475	0.0242
TLAR	45	0.2112	0.104	0.1358	-0.089	0.1994	0.3085	0.1059	0.0983	0.1659	0.1152	0.1805	0.0891
TLLR	46	0.0834	0.1208	0.0231	-0.2631	0.1715	0.2301	0.022	-0.0274	0.061	0.0754	0.0551	-0.0852
TLPR	47	0.2113	0.1017	0.137	-0.0871	0.1991	0.3087	0.1065	0.0985	0.1662	0.1139	0.1816	0.0915
WDR	48	0.7977	0.6249	0.8031	0.6815	0.7183	0.2989	0.7979	0.7452	0.8091	0.7021	0.7941	0.5369
Zn	49	-0.091	0.0936	0.036	0.0733	0.1319	-0.1235	-0.0398	0.1007	-0.0509	0.1322	0.0547	0.0028
		25	26	27	28	29	30	31	32	33	34	35	36
		PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952

PHT	37	-												
PRN	38	-0.3634	-											
RCH	39	0.3039	0.0965	-										
Rb	40	0.1565	-0.1737	-0.157	-									
S	41	0.3692	0.2941	0.4639	0.0615	-								
Se	42	0.2935	0.3166	0.0755	0.1205	0.683	-							
Sr	43	-0.3813	-0.1783	-0.0771	0.5261	-0.2309	-0.2201	-						
TGW	44	0.176	-0.0852	-0.1279	-0.259	-0.1254	-0.0629	-0.1505	-					
TLAR	45	0.1358	0.318	0.8759	-0.2361	0.6379	0.31	-0.1988	-0.1367	-				
TLLR	46	0.5235	0.1761	0.4801	0.0124	0.7376	0.4808	-0.2588	0.0581	0.5874	-			
TLPR	47	0.1275	0.3201	0.8759	-0.2361	0.6329	0.3061	-0.1953	-0.1386	0.9999	0.5785	-		
WDR	48	0.411	0.0293	0.5248	0.1109	0.0841	-0.1291	0.1099	-0.1144	0.1976	0.0866	0.197	-	
Zn	49	0.3663	0.1079	0.0302	0.2241	0.4005	0.1916	-0.0655	-0.1858	0.0976	0.3291	0.0933	0.2555	-
		37	38	39	40	41	42	43	44	45	46	47	48	49
		PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.1 Table continued.

P values																	
As	1	-															
BYD	2	0.4789	-														
Ba	3	0.2902	0.0607	-													
CHCRX	4	0.3461	0.6179	0.2991	-												
CHCRY	5	0.5669	0.3999	0.9836	0.0037	-											
CMRX	6	0.6132	0.7115	0.3783	<0.001	<0.001	-										
CMRY	7	0.3737	0.3836	0.9647	0.0062	<0.001	<0.001	-									
Ca	8	0.5372	0.4027	0.1094	0.5575	0.97	0.8831	0.9381	-								
Cs	9	0.8671	0.6324	0.7541	0.7824	0.1153	0.2756	0.1519	0.022	-							
Cu	10	0.9272	0.0902	0.3171	0.1779	0.8144	0.1699	0.7726	0.3921	0.0696	-						
Fe	11	0.1941	0.4888	0.3798	0.2845	0.7288	0.18	0.9675	0.8311	0.2583	0.0116	-					
GYD	12	0.2101	0.0154	0.6258	0.8199	0.2066	0.9566	0.1119	0.6548	0.1013	0.1742	0.0046	-				
HI_%	13	0.0419	0.3058	0.5334	0.3096	0.5207	0.5187	0.3331	0.7586	0.118	0.7901	0.0095	<0.001	-			
K	14	0.8206	0.0689	0.1227	0.0847	0.1402	0.0461	0.2062	0.0258	0.0995	0.5272	0.9422	0.3656	0.7813	-		
LRN	15	0.6115	0.1163	0.4767	0.1877	0.0016	0.1501	0.0023	0.3758	0.7021	0.4851	0.2457	0.9974	0.2711	0.3413	-	
MDR	16	0.4696	0.3967	0.9312	0.0055	<0.001	<0.001	<0.001	0.9272	0.0946	0.8058	0.7362	0.1629	0.4669	0.2119	0.0022	-
MLAR	17	0.7472	0.7826	0.5597	<0.001	<0.001	<0.001	<0.001	0.836	0.0752	0.9566	0.9547	0.2561	0.4261	0.5207	0.2692	<0.001
MLLR	18	0.8376	0.6346	0.9752	0.8215	0.4709	0.6634	0.6206	0.7206	0.6668	0.4265	0.262	0.9415	0.5936	0.7541	0.1403	0.4634
MLPR	19	0.8005	0.5936	0.7914	<0.001	<0.001	<0.001	<0.001	0.9836	0.1219	0.5436	0.2765	0.5803	0.9399	0.1824	0.0038	<0.001
MWR	20	0.7694	0.3932	0.6369	0.0105	0.0037	0.0018	0.0231	0.4604	0.4473	0.1715	0.0012	0.1338	0.2142	0.8807	0.1183	0.0021
Mg	21	0.6276	0.4643	0.4702	0.616	0.3787	0.6797	0.3309	0.4232	0.0101	0.0047	0.0107	0.0564	0.1561	0.4267	0.0037	0.4251
Mn	22	0.9853	0.269	0.5816	0.3325	0.1777	0.2692	0.0981	0.0959	0.2862	0.2436	0.5409	0.8669	0.3688	0.8344	0.0068	0.2251
Mo	23	0.297	0.1058	0.1243	0.4301	0.1491	0.4742	0.0968	0.0867	0.9432	0.8226	0.5504	0.255	0.9313	0.0141	0.2346	0.1819
P	24	0.4749	0.7101	0.845	0.9688	0.9591	0.7601	0.8427	0.4653	0.0171	0.0381	0.2691	0.1605	0.2639	0.0495	0.1017	0.9112
PEA_1001	25	0.4266	0.1666	0.0845	0.1704	0.8731	0.2424	0.7096	0.1332	0.8927	0.6028	0.01	0.0336	0.131	0.5939	0.9635	0.67
PEA_1002	26	0.0084	0.6283	0.4769	0.0415	0.5432	0.0716	0.9171	0.4246	0.8888	0.7753	0.0091	0.0261	<0.001	0.7392	0.303	0.5303
PEA_251	27	0.6545	0.0188	0.0724	0.7477	0.5928	0.7686	0.3154	0.0545	0.5823	0.6039	0.0431	0.0257	0.4199	0.0943	0.565	0.7437
PEA_252	28	0.0408	0.1665	0.0562	0.0646	0.7918	0.2206	0.4868	0.1703	0.1949	0.398	0.0386	0.0237	0.085	0.4114	0.2867	0.7387
PEA_301	29	0.9758	0.0193	0.0674	0.4849	0.8714	0.5482	0.6302	0.0751	0.2297	0.436	0.0287	0.0338	0.4789	0.2129	0.8928	0.9863
PEA_302	30	0.7556	0.2708	0.0153	0.0146	0.0919	0.0355	0.1293	0.0085	0.4686	0.2711	0.2633	0.6442	0.35	0.9243	0.3018	0.1121
PEA_501	31	0.5389	0.0471	0.0598	0.5327	0.6618	0.6306	0.3329	0.0462	0.5642	0.7257	0.0244	0.0156	0.1926	0.143	0.6786	0.8356
PEA_502	32	0.0262	0.5279	0.2062	0.0461	0.708	0.1229	0.8713	0.3978	0.5833	0.7418	0.006	0.0092	0.0097	0.6646	0.8941	0.7204
PEA_751	33	0.4167	0.1161	0.0616	0.2392	0.9632	0.3352	0.5707	0.061	0.6688	0.6384	0.0114	0.0184	0.112	0.3177	0.9934	0.8399
PEA_752	34	0.0249	0.9294	0.5663	0.0397	0.5749	0.0752	0.9799	0.5077	0.8303	0.8471	0.0064	0.009	<0.001	0.9874	0.4684	0.572
PEA_951	35	0.7488	0.0236	0.0767	0.5874	0.7547	0.5261	0.4773	0.1134	0.5556	0.4518	0.0229	0.0512	0.5729	0.2053	0.6353	0.8806
PEA_952	36	0.3508	0.0879	0.0079	0.0552	0.6561	0.1302	0.8205	0.0093	0.0779	0.1197	0.0839	0.5044	0.9566	0.3523	0.6304	0.7197
PHT	37	0.4094	0.1033	0.0664	0.1149	0.3588	0.1235	0.5925	0.8918	0.3988	0.8631	0.013	0.0249	<0.001	0.0619	0.016	0.4343
PRN	38	0.0684	0.0749	0.7623	0.0113	0.7737	0.056	0.8205	0.3612	0.529	0.1983	0.6747	0.9671	0.0807	0.1089	0.9465	0.9916
RCH	39	0.9534	0.7826	0.5594	0.0058	<0.001	<0.001	<0.001	0.647	0.2073	0.3397	0.0194	0.7589	0.7454	0.6146	0.0253	<0.001
Rb	40	0.9862	0.3295	0.7335	0.6236	0.2929	0.2911	0.3712	0.014	<0.001	0.6866	0.5487	0.6975	0.1449	0.0031	0.5252	0.3341
S	41	0.2056	0.9104	0.2328	0.5675	0.0105	0.3778	0.0108	0.6392	0.5965	0.046	0.225	0.8252	0.9752	0.834	<0.001	0.0089
Se	42	0.241	0.774	0.4594	0.5593	0.3363	0.6081	0.2732	0.5003	0.9052	0.7878	0.4955	0.7918	0.6084	0.7737	0.0229	0.2403
Sr	43	0.7541	0.1932	<0.001	0.5676	0.5074	0.9916	0.5874	<0.001	0.0241	0.3137	0.952	0.788	0.3724	0.0083	0.4731	0.5524
TGW	44	0.5645	0.8281	0.3215	0.8968	0.9862	0.8389	0.9998	0.3642	0.9488	0.2098	0.7935	0.8312	0.9056	0.017	0.6504	0.9203
TLAR	45	0.3088	0.8375	0.6812	0.041	<0.001	0.0033	<0.001	0.7772	0.0832	0.2349	0.2207	0.6003	0.4445	0.5861	0.0037	<0.001
TLLR	46	0.7221	0.4574	0.4674	0.45	0.0154	0.207	0.0317	0.6673	0.9568	0.286	0.0456	0.6581	0.3757	0.2919	<0.001	0.0219
TLPR	47	0.3055	0.8279	0.6717	0.0413	<0.001	0.0034	<0.001	0.7763	0.0817	0.2376	0.2295	0.5881	0.4286	0.6023	0.0042	<0.001
WDR	48	0.3824	0.0662	0.5273	0.2173	0.9888	0.1755	0.596	0.1948	0.54	0.123	<0.001	0.0011	0.0239	0.4073	0.9098	0.9258
Zn	49	0.3895	0.3265	0.9055	0.6002	0.7499	0.6499	0.8055	0.9714	0.047	0.0022	0.0113	0.0014	0.0208	0.2224	0.281	0.5982
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR

MLAR	17	-															
MLLR	18	0.9503	-														
MLPR	19	<0.001	0.341	-													
MWR	20	0.0022	0.3318	<0.001	-												
Mg	21	0.923	0.1449	0.2922	0.2087	-											
Mn	22	0.7484	0.4569	0.1431	0.9615	0.0304	-										
Mo	23	0.5078	0.6711	0.3631	0.672	0.3181	0.7781	-									
P	24	0.5143	0.5598	0.9135	0.9461	<0.001	0.019	0.3856	-								
PEA_1001	25	0.5188	0.4608	0.4359	<0.001	0.9516	0.2214	0.0814	0.3999	-							
PEA_1002	26	0.4385	0.4512	0.2716	0.0055	0.8326	0.9259	0.1394	0.494	0.0024	-						
PEA_251	27	0.9396	0.2398	0.9498	0.003	0.9644	0.1821	0.0327	0.9931	<0.001	0.0762	-					
PEA_252	28	0.5536	0.2569	0.8601	0.0337	0.901	0.3717	0.1288	0.7009	0.0017	<0.001	0.0058	-				
PEA_301	29	0.8544	0.1631	0.6724	0.0069	0.2731	0.6715	0.1295	0.4461	<0.001	0.1259	<0.001	0.0148	-			
PEA_302	30	0.1304	0.4174	0.0746	0.0679	0.4717	0.3209	0.6508	0.8589	0.0951	0.4488	0.0837	0.0466	0.0165	-		
PEA_501	31	0.8578	0.3723	0.8479	0.0017	0.913	0.1737	0.0224	0.6641	<0.001	0.0176	<0.001	0.0018	<0.001	0.1143	-	
PEA_502	32	0.324	0.4311	0.3441	0.0016	0.861	0.3403	0.0739	0.6067	<0.001	<0.001	0.0028	<0.001	0.0079	0.1507	<0.001	-
PEA_751	33	0.6284	0.5008	0.5595	<0.001	0.9874	0.2285	0.0501	0.5584	<0.001	0.0031	<0.001	0.0012	<0.001	0.0922	<0.001	<0.001
PEA_752	34	0.3318	0.4285	0.2521	0.0016	0.7767	0.593	0.0965	0.6161	<0.001	<0.001	0.0255	<0.001	0.0577	0.4501	0.0039	<0.001
PEA_951	35	0.7981	0.1682	0.7905	0.003	0.7504	0.2289	0.082	0.9822	<0.001	0.0868	<0.001	0.0052	<0.001	0.037	<0.001	0.0034
PEA_952	36	0.3217	0.9523	0.4648	0.0566	0.6956	0.8547	0.3681	0.8743	0.0242	0.1877	0.0064	<0.001	0.0027	<0.001	0.0146	0.0129
PHT	37	0.9103	0.5519	0.1744	0.0442	0.0399	0.1192	0.2974	0.2422	0.2755	0.0136	0.6997	0.4311	0.4036	0.8024	0.5181	0.0908
PRN	38	0.5491	0.0884	0.6118	0.7686	0.305	0.3235	0.7304	0.3991	0.8491	0.0841	0.4048	0.1373	0.5351	0.4883	0.6894	0.1794
RCH	39	<0.001	0.2052	<0.001	<0.001	0.2805	0.8054	0.9111	0.8793	0.0089	0.0533	0.0598	0.2219	0.0704	0.0372	0.0396	0.0308
Rb	40	0.3789	0.6147	0.3494	0.6975	0.177	0.0559	0.1471	0.0412	0.7201	0.4009	0.47	0.2651	0.2909	0.6613	0.4645	0.3336
S	41	0.2554	0.0212	0.0104	0.056	<0.001	0.0191	0.2902	0.0068	0.9927	0.729	0.9573	0.2271	0.4466	0.7889	0.8065	0.5061
Se	42	0.9381	0.1107	0.4652	0.8751	0.0764	0.0167	0.3071	0.0333	0.7661	0.4393	0.848	0.0627	0.778	0.314	0.6809	0.1357
Sr	43	0.8761	0.5549	0.4899	0.7768	0.8215	0.3987	0.0434	0.6052	0.428	0.7351	0.1364	0.0225	0.1158	0.0022	0.1743	0.3334
TGW	44	0.4945	0.9033	0.6287	0.4479	0.7812	0.3572	0.0717	0.4497	0.5848	0.6878	0.6474	0.6222	0.7576	0.5521	0.3596	0.616
TLAR	45	<0.001	0.0954	<0.001	<0.001	0.1458	0.3188	0.3802	0.5947	0.3334	0.6368	0.5366	0.6864	0.3617	0.1521	0.6307	0.6553
TLLR	46	0.5706	<0.001	0.0105	0.0633	0.0018	0.0107	0.595	0.1151	0.7052	0.583	0.9168	0.2251	0.434	0.2909	0.9206	0.9012
TLPR	47	<0.001	0.1005	<0.001	<0.001	0.1527	0.3326	0.383	0.6054	0.3331	0.6442	0.5331	0.6929	0.3625	0.1518	0.6286	0.6547
WDR	48	0.6099	0.7781	0.4535	<0.001	0.2844	0.4455	0.1982	0.7964	<0.001	0.0014	<0.001	<0.001	<0.001	0.1659	<0.001	<0.001
Zn	49	0.5469	0.4369	0.8236	0.5005	<0.001	0.1001	0.886	<0.001	0.6796	0.6711	0.8705	0.7395	0.5484	0.5744	0.8568	0.6477
		17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
		MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502

PEA_751	33	-																
PEA_752	34	<0.001	-															
PEA_951	35	<0.001	0.0347	-														
PEA_952	36	0.0178	0.1351	0.0018	-													
PHT	37	0.3372	0.0144	0.6867	0.8686	-												
PRN	38	0.8785	0.0996	0.411	0.4209	0.0883	-											
RCH	39	0.0153	0.0302	0.0507	0.1214	0.1586	0.6612	-										
Rb	40	0.5393	0.3635	0.4767	0.2239	0.4758	0.428	0.4742	-									
S	41	0.8901	0.6748	0.9853	0.5451	0.083	0.1732	0.0258	0.7804	-								
Se	42	0.6835	0.2881	0.6707	0.0822	0.174	0.1411	0.732	0.5839	<0.001	-							
Sr	43	0.2646	0.7512	0.1384	<0.001	0.0726	0.4155	0.7265	0.0099	0.2892	0.3128	-						
TGW	44	0.4583	0.5981	0.8296	0.9126	0.4219	0.6991	0.5608	0.2327	0.5687	0.7756	0.4931	-					
TLAR	45	0.4494	0.6006	0.41	0.6859	0.5367	0.1393	<0.001	0.278	0.0011	0.15	0.3633	0.534	-				
TLLR	46	0.7822	0.7324	0.8029	0.699	0.0104	0.4215	0.0204	0.9553	<0.001	0.0202	0.2331	0.7923	0.0032	-			
TLPR	47	0.4486	0.605	0.407	0.6779	0.562	0.1365	<0.001	0.2781	0.0012	0.1554	0.3719	0.5282	<0.001	0.0038	-		
WDR	48	<0.001	<0.001	<0.001	0.0083	0.0514	0.8945	0.0101	0.6145	0.703	0.5572	0.6177	0.6033	0.3662	0.6944	0.3676	-	
Zn	49	0.8177	0.5478	0.8044	0.99	0.0856	0.6241	0.8911	0.304	0.0582	0.3811	0.7664	0.3961	0.6578	0.1252	0.672	0.2393	-
		33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.2 Table Correlation coefficients between seedling root traits and grain yield, yield components and grain mineral composition traits of 36 Indian wheat genotypes at Karnal site. Seedling root traits data are mean of ~20 replications, yield & yield components and mineral elements data are mean of two replications per plot per genotype over two years at Karnal site.

r values																																																		
Traits																																																		
As	1	-																																																
BYD	2	-0.4737	-																																															
Ba	3	0.1666	-0.4081	-																																														
CHCRX	4	-0.0243	0.2659	0.3171	-																																													
CHCRY	5	0.1856	0.2783	0.0411	0.5797	-																																												
CMRX	6	0.1135	0.1939	0.3431	0.9302	0.6767	-																																											
CMRY	7	0.2116	0.2758	0.0555	0.5529	0.9823	0.6498	-																																										
Ca	8	-0.0598	0.2424	0.0058	0.2841	-0.022	0.1786	-0.0112	-																																									
Cs	9	-0.2358	0.084	-0.3058	0.0025	-0.4125	-0.1877	-0.3762	0.5472	-																																								
Cu	10	0.2631	-0.2051	0.1527	0.4192	0.0994	0.4261	0.0995	0.0898	0.1266	-																																							
Fe	11	0.245	-0.2759	0.1816	0.2647	-0.0788	0.3205	-0.1532	-0.0648	0.0004	0.6594	-																																						
GYD	12	-0.0791	0.6229	-0.1511	0.0945	0.2728	0.0747	0.324	0.222	-0.0655	-0.3398	-0.589	-																																					
HI_%	13	0.2211	0.1202	0.0767	-0.0823	0.168	-0.0437	0.237	0.1001	-0.1622	-0.2824	-0.5592	0.8459	-																																				
K	14	0.2493	-0.4365	0.313	-0.1221	-0.3505	-0.1669	-0.3373	0.2271	0.1825	0.29	0.4117	-0.3253	-0.1498	-																																			
LRN	15	0.1809	0.323	-0.184	0.2849	0.6209	0.3099	0.6033	0.1861	-0.0085	0.1938	0.1145	0.0172	-0.1698	-0.2215	-																																		
MDR	16	0.2018	0.2912	0.0465	0.5596	0.9877	0.6577	0.9727	-0.0165	-0.4327	0.1086	-0.0513	0.3008	0.1919	-0.3108	0.6048	-																																	
MLAR	17	0.0991	0.2356	0.1948	0.6507	0.8679	0.7406	0.8638	-0.0337	-0.4164	0.1201	-0.0328	0.2711	0.1767	-0.1362	0.2404	0.8774	-																																
MLLR	18	0.0989	-0.0813	0.1417	-0.0498	0.1582	0.0959	0.109	0.1663	-0.146	0.3411	0.3624	-0.1192	-0.0405	0.1404	0.3172	0.1609	-0.0138	-																															
MLPR	19	0.2141	0.21	0.1463	0.674	0.9635	0.7892	0.933	-0.0058	-0.4373	0.2243	0.126	0.127	0.0295	-0.2503	0.5792	0.9502	0.8893	0.208	-																														
MWR	20	0.2768	-0.1088	0.1721	0.5224	0.5798	0.6137	0.4715	0.0021	-0.3295	0.3276	0.5803	-0.2618	-0.2767	0.1211	0.3349	0.6079	0.6051	0.2119	0.7055	-																													
Mg	21	0.2162	-0.1462	0.0391	0.1632	-0.0442	0.1495	-0.0644	0.2993	0.2673	0.5846	0.6339	-0.4777	-0.4764	0.4513	0.4255	-0.0483	-0.1528	0.484	0.0837	0.3097	-																												
Mn	22	0.222	0.0782	0.1605	0.3745	0.2498	0.5084	0.2676	0.3083	-0.075	0.4314	0.454	-0.1761	-0.2512	-0.0249	0.4293	0.2308	0.1513	0.4101	0.4102	0.3046	0.5013	-																											
Mo	23	-0.066	0.3369	-0.4172	0.147	0.248	0.0478	0.2597	0.0811	0.1866	0.1568	-0.1187	0.2953	0.1714	-0.1581	0.2437	0.2424	0.107	0.0488	0.1494	-0.0818	0.1844	-0.1702	-																										
P	24	0.2106	-0.1768	0.0553	0.1726	-0.1363	0.1231	-0.1411	0.2617	0.295	0.566	0.5971	-0.453	-0.4473	0.5517	0.2382	-0.1452	-0.1672	0.4109	0.0079	0.1848	0.891	0.4698	0.1766	-																									
PEA_1001	25	0.078	-0.2222	0.3766	0.2959	0.0353	0.2539	-0.0821	0.1655	-0.157	0.2065	0.5716	-0.3269	-0.3037	0.4296	0.0101	0.0939	0.1417	0.1618	0.1708	0.7	0.3309	0.0438	-0.192	0.2469	-																								
PEA_1002	26	-0.0994	0.1064	0.1195	0.4283	0.1336	0.3825	0.023	-0.0271	-0.0723	0.0471	0.4484	-0.3652	-0.5782	0.0263	0.2245	0.1379	0.1698	-0.1652	0.2392	0.5593	0.1065	0.0998	-0.3863	0.0168	0.601	-																							
PEA_251	27	0.1313	-0.3764	0.3847	0.0709	-0.1177	0.0649	-0.219	0.2165	-0.0519	0.1245	0.4661	-0.3081	-0.1734	0.5833	-0.1266	-0.0721	0.0167	0.2553	0.0139	0.591	0.3547	0.0191	-0.3294	0.3245	0.8653	0.377	-																						
PEA_252	28	-0.0749	-0.2094	0.3456	0.3916	-0.0583	0.2656	-0.1527	0.0376	0.1185	0.0572	0.3257	-0.3197	-0.3396	0.243	-0.232	-0.0736	0.1302	-0.2465	0.0389	0.4442	-0.0413	-0.1576	-0.3944	-0.0141	0.6161	0.7104	0.5568	-																					
PEA_301	29	0.1765	-0.3279	0.4301	0.1533	-0.0357	0.132	-0.106	0.218	0.0373	0.1493	0.4447	-0.299	-0.1784	0.4928	0.0298	-0.0038	0.0405	0.3008	0.0932	0.547	0.5114	0.1473	-0.2488	0.4531	0.7636	0.3285	0.9068	0.5014	-																				
PEA_302	30	0.0428	0.0853	0.453	0.5023	0.3597	0.4403	0.3258	0.3653	0.0176	0.0706	0.0624	0.276	0.282	-0.0046	0.2251	0.3403	0.3248	0.1777	0.3789	0.3873	0.1438	0.1934	-0.0702	-0.0281	0.3564	0.1661	0.3684	0.419	0.4942	-																			
PEA_501	31	0.086	-0.2958	0.38	0.1371	-0.0964	0.1059	-0.2114	0.2388	-0.0506	0.1372	0.5176	-0.34	-0.2714	0.5325	-0.0913	-0.0458	0.0396	0.1951	0.0423	0.6177	0.3076	0.0036	-0.2887	0.2579	0.9464	0.49	0.9444	0.6153	0.8169	0.3383	-																		
PEA_502	32	-0.0666	-0.0912	0.2519	0.4199	0.0826	0.331	-0.0358	-0.0337	-0.0364	0.0613	0.4688	-0.4094	-0.5115	0.2501	0.0294	0.0789	0.2152	-0.1726	0.2066	0.6203	0.1368	-0.0539	-0.3629	0.0984	0.7381	0.9035	0.5937	0.8847	0.5395	0.3095	0.6819	-																	
PEA_751	33	0.0766	-0.2459	0.3864	0.2556	-0.0102	0.2104	-0.1247	0.2248	-0.0818	0.1793	0.5584	-0.343	-0.3104	0.4865	-0.0018	0.0446	0.1066	0.1479	0.1283	0.676	0.3276	0.0378	-0.2428	0.251	0.9875	0.5884	0.8964	0.6327	0.782	0.3593	0.9781	0.7415	-																
PEA_752	34	-0.068	0.0454	0.1144	0.4317	0.1234	0.3782	0.0056	-0.0195	-0.0399	0.0675	0.4984	-0.4153	-0.604	0.1421	0.1591	0.1243	0.2119	-0.1735	0.2489	0.6207	0.1605	0.0587	-0.3573	0.1046	0.6575	0.9741	0.4647	0.7636	0.4013	0.1656	0.5771	0.9553	0.6567	-															
PEA_951	35	0.1598	-0.4248	0.424	0.1194	-0.0689	0.1393	-0.156	0.1627	-0.0512	0.1639	0.4861	-0.3043	-0.1344	0.5797	-0.1045	-0.0332	0.0564	0.2974	0.0586	0.5899	0.3971	0.0597	-0.3334	0.3523	0.8223	0.365	0.9616	0.563	0.9242	0.4371	0.8662	0.5847	0.8356	0.442	-														
PEA_952	36	-0.0573	-0.1479	0.4513	0.405	0.0981	0.3251	0.0501	0.2459	0.1326	0.1323	0.16	0.0142	0.0707	0.1641	-0.1059	0.0791	0.2162	-0.0132	0.1604	0.4029	0.0656	0.0475	-0.2903	-0.03	0.4684	0.2849	0.5516	0.7172	0.595	0.8487	0.5024	0.51	0.4892	0.3212	0.6155	-													
PHT	37	-0.0578	0.1902	-0.2613	0.3472	0.2683	0.3656	0.1802	0.0855	0.1092	0.2419	0.4887	-0.4373	-0.6884	-0.2021	0.5611	0.2416	0.0588	0.2419	0.3615	0.4928	0.5384	0.5035	0.1531	0.4807	0.2664	0.4926	0.126	0.151	0.2342	0.0031	0.169	0.3458	0.2342	0.4853	0.1348	-0.0206	-												
PRN	38	0.4358	-0.4198	0.0711	-0.5183	-0.0634	-0.4038	-0.0501	-0.3714	-0.3112	0.2126	0.1727	-0.1299	0.1493	0.3706	0.0148	-0.0023	-0.1317	0.3633	-0.1117	0.0649	0.1942	-0.2029	0.1132	0.1014	0.042	-0.3679	0.1824	-0.3195	0.1363	-0.1522	0.0881	-0.2901	0.0338	-0.3519	0.1801	-0.1764	-0.2651	-											
RCH	39	0.2351	0.0427	0.1758	0.5569	0.8049	0.6661	0.7189	-0.045	-0.4399	0.2715	0.3832	-0.0393	-0.0827	-0.0273	0.4651	0.8295	0.7815	0.2744	0.8736	0.9311	0.1811	0.2653	0.037	0.0492	0.5326	0.4079	0.3982	0.2649	0.3841	0.4367	0.4318	0.451	0.4992	0.4523	0.4121	0.3323	0.3842	0.0965	-										
Rb	40	-0.1829	0.1408	-0.0991	0.0343	-0.3197	-0.1001	-0.3002	0.5398	0.6504	0.1357	0.2907	-0.1032	-0.2657	0.5851	-0.0048	-0.2936	-0.1844	0.0839	-0.2539	-0.0457	0.355	0.1636	-0.1439	0.4558	0.1802	0.1757	0.2535	0.269	0.267	0.0789	0.2728	0.2447	0.2503	0.2389	0.2541	0.1922	0.1014	-0.2176	-0.16	-									
S	41	0.413	-0.0141	-0.0346	0.2866	0.2896	0.294	0.251	0.3146	-0.0007	0.4946	0.4885	-0.2427	-0.2742	0.2112	0.4988	0.3094	0.1305	0.5356	0.3803	0.4559	0.7496	0.4996	0.3889	0.739	0.3333	0.0302	0.2668	-0.1408	0.3857	0.0704	0.2772	0.0259	0.3011	0.0794	0.234	-0.1327	0.5839	0.1889	0.4072	0.1166	-								
Se	42	0.22	-0.213	0.1657	-0.0326	-0.0532	-0.0608	-0.0488	0.1445	0.0832	0.4592	0.4786	-0.292	-0.237	0.3696	0.2221	0.0315	-0.1201	0.3413	0.015	0.2594	0.4036	0.3128	0.0391	0.4462	0.3394	-0.0379	0.3551	-0.0638	0.3598	-0.0496	0.3691	-0.0422	0.3605	-0.0425	0.2667	-0.0325	0.2298	0.4438	0.1885	0.2593	0.5288	-							
Sr	43	0.0286	0.0908	0.4651	0.3229	-0.1136	0.2494	-0.038	0.6784	0.3432	0.0551	-0.1134	0.3449	0.3563	0.2658	-0.1662	-0.1038	0.045	0.0936	-0.0711	-0.197	0.1033	0.2821	-0.1778	0.1909	0.0332	-0.1726	0.1361	0.1174	0.259	0.4876	0.092	-0.0915	0.0665	-0.17	0.1882	0.4055	-0.2676	-0.3465	-0.1904	0.4647	0.0437	0.0074	-						
TGW	44	0.0294	0.1757	-0.2125	0.027	0.3041	0.0346	0.326	-0.0617	-0.0059	-0.3024	-0.3063	0.42	0.4397	-0.4098	0.2389	0.2904	0.0772	0.0792	0.1694	-0.1099	-0.0292	-0.1252	0.4988	-0.0699	-0.2769	-0.3848	-0.3069	-0.3845	-0.1513	0.1995	-0.3728	-0.3858	-0.3336	-0.3916	-0.1925	-0.0973	0.0767	-0.0112	0.0521	-0.2788	0.0804	-0.2639	0.02	-					
TLAR	45	0.4183	0.0255	0.1707	0.4291	0.8814	0.5853	0.8564	-0.1399	-0.5466	0.3134	0.2062	0.0744	0.0983	-0.0556	0.5805	0.898	0.7773	0.356	0.9004	0.7154	0.1979	0.3251	0.1649	0.0855	0.2112	0.104	0.1358	-0.089	0.1994	0.3085	0.1059	0.0983	0.1659	0.1152	0.1805	0.0891	0.2445	0.318	0.8759	-0.3191	0.4674	0.2133	-0.1943	0.1399	-				
TLLR	46	0.2221	0.1517	-0.0883	0.1656	0.4987	0.2733	0.4488	0.1071	-0.1437	0.3104	0.3496	-0.1495	-0.2406	-0.1603	0.86	0.4754	0.1248	0.6963	0.5225	0.3933	0.5777	0.59	0.1694	0.4027	0.0834	0.1208	0.0231	-0.2631	0.1715	0.2301	0.022	-0.0274	0.061	0.0754	0.0551	-0.0852	0.6265	0.1761	0.4801	-0.0396	0.6546	0.312	-0.1724	0.2068	0.5874	-			
TLPR	47	0.4176	0.0247	0.1728	0.4287	0.8811	0.5845	0.8569	-0.1411	-0.5477	0.3117	0.2025	0.0784	0.1035	-0.0517	0.5734	0.8984	0.7818	0.351	0.8996	0.7148	0.1923	0.3186	0.164	0.0808	0.2113	0.1017	0.137	-0.0871	0.1991	0.3087	0.1065	0.0985	0.1662	0.1139	0.1816	0.0915	0.2358	0.3201	0.8759	-0.3183	0.4618	0.2111	-0.1921	0.1379	0.9999	0.5785	-		
WDR	48	0.1947	-0.3573	0.1916	0.2674	-0.0031	0.2926	-0.1167	0.0899	-0.0038	0.2771	0.6942	-0.5248	-0.4671	0.394	-0.025	0.0206	0.1123	0.0622	0.1644	0.7879	0.4011	0.1892	-0.3026	0.3063	0.7977	0.6249	0.8031	0.6815	0.7183	0.2989	0.7979	0.7452	0.8091	0.7021	0.7941	0.5369	0.4404	0.0293	0.5248	0.2095	0.2884	0.2701	-0.0926	-0.3314	0.1976	0.0866	0.197	-	
Zn	49	0.0549	-0.3495	0.0633	0.1498	-0.1948	0.1394	-0.2183	0.0463	0.2181	0.6275	0.6439	-0.7543	-0.693	0.3715	0.1344	-0.2316	-0.2063	0.3277	-0.0194	0.1906	0.7864	0.4475	0.005	0.8365	0.1846	0.1316	0.2196	0.0266	0.2842	-0.2112	0.1854	0.1643	0.1893	0.201	0.2332	-0.1024	0.5038	0.031	0.0213	0.2354	0.5419	0.327	-0.08	-0.2604	0.0095	0.3319	0.0042	0.3458	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.2 Table continued.

P values																																																		
As	1	-																																																
BYD	2	0.0224	-																																															
Ba	3	0.4473	0.0532	-																																														
CHCRX	4	0.9125	0.2201	0.1404	-																																													
CHCRY	5	0.3966	0.1985	0.8523	0.0037	-																																												
CMRX	6	0.6063	0.3753	0.1089	<0.001	<0.001	-																																											
CMRY	7	0.3324	0.2027	0.8015	0.0062	<0.001	<0.001	-																																										
Ca	8	0.7864	0.2651	0.9789	0.1889	0.9206	0.4148	0.9595	-																																									
Cs	9	0.2786	0.7032	0.1559	0.991	0.0505	0.3912	0.0769	0.0069	-																																								
Cu	10	0.2252	0.3478	0.4868	0.0465	0.6517	0.0426	0.6515	0.6837	0.5647	-																																							
Fe	11	0.2599	0.2025	0.4069	0.2223	0.7208	0.136	0.4851	0.7691	0.9987	<0.001	-																																						
GYD	12	0.7199	0.0015	0.4915	0.6681	0.2078	0.7348	0.1315	0.3086	0.7666	0.1126	0.0031	-																																					
HI_%	13	0.3106	0.5848	0.7279	0.709	0.4436	0.843	0.2762	0.6495	0.4596	0.1917	0.0055	<0.001	-																																				
K	14	0.2514	0.0373	0.1459	0.579	0.101	0.4465	0.1155	0.2974	0.4046	0.1796	0.051	0.1298	0.4952	-																																			
LRN	15	0.4089	0.1328	0.4006	0.1877	0.0016	0.1501	0.0023	0.3953	0.9693	0.3757	0.603	0.9378	0.4386	0.3099	-																																		
MDR	16	0.3559	0.1776	0.8332	0.0055	<0.001	<0.001	<0.001	0.9405	0.0392	0.6218	0.8161	0.1631	0.3804	0.1489	0.0022	-																																	
MLAR	17	0.6529	0.2791	0.373	<0.001	<0.001	<0.001	<0.001	0.8786	0.0481	0.5852	0.8818	0.2109	0.42	0.5355	0.2692	<0.001	-																																
MLLR	18	0.6533	0.7124	0.5189	0.8215	0.4709	0.6634	0.6206	0.4482	0.5061	0.1112	0.0892	0.5882	0.8544	0.5228	0.1403	0.4634	0.9503	-																															
MLPR	19	0.3266	0.3361	0.5054	<0.001	<0.001	<0.001	<0.001	0.979	0.0369	0.3034	0.5668	0.5637	0.8937	0.2494	0.0038	<0.001	<0.001	0.341	-																														
MWR	20	0.201	0.6212	0.4323	0.0105	0.0037	0.0018	0.0231	0.9926	0.1247	0.127	0.0037	0.2276	0.2012	0.5821	0.1183	0.0021	0.0022	0.3318	<0.001	-																													
Mg	21	0.3217	0.5055	0.8594	0.4568	0.8414	0.4958	0.7702	0.1653	0.2175	0.0034	0.0012	0.0212	0.0215	0.0306	0.0429	0.8268	0.4864	0.0193	0.7042	0.1505	-																												
Mn	22	0.3086	0.7229	0.4645	0.0783	0.2503	0.0132	0.217	0.1524	0.7339	0.0399	0.0295	0.4214	0.2475	0.9102	0.0409	0.2894	0.4908	0.0519	0.0519	0.1576	0.0148	-																											
Mo	23	0.7647	0.116	0.0477	0.5032	0.254	0.8287	0.2314	0.7129	0.394	0.475	0.5897	0.1714	0.4341	0.4712	0.2625	0.2651	0.627	0.8251	0.4964	0.7105	0.3995	0.4376	-																										
P	24	0.3348	0.4197	0.8022	0.4311	0.5351	0.5759	0.5207	0.2278	0.1718	0.0049	0.0026	0.03	0.0324	0.0063	0.2737	0.5085	0.4457	0.0515	0.9715	0.3985	<0.001	0.0237	0.4202	-																									
PEA_1001	25	0.7237	0.3081	0.0765	0.1704	0.8731	0.2424	0.7096	0.4504	0.4743	0.3444	0.0044	0.1279	0.1588	0.0408	0.9635	0.67	0.5188	0.4608	0.4359	<0.001	0.123	0.8428	0.3802	0.2561	-																								
PEA_1002	26	0.6519	0.629	0.5871	0.0415	0.5432	0.0716	0.9171	0.9024	0.743	0.831	0.0319	0.0866	0.0039	0.9052	0.303	0.5303	0.4385	0.4512	0.2716	0.0055	0.6285	0.6504	0.0686	0.9394	0.0024	-																							
PEA_251	27	0.5504	0.0767	0.0699	0.7477	0.5928	0.7686	0.3154	0.3212	0.8141	0.5715	0.025	0.1526	0.4288	0.0035	0.565	0.7437	0.9396	0.2398	0.9498	0.003	0.0968	0.9312	0.1249	0.1308	<0.001	0.0762	-																						
PEA_252	28	0.734	0.3375	0.1062	0.0646	0.7918	0.2206	0.4868	0.8649	0.5903	0.7955	0.1294	0.137	0.1129	0.2639	0.2867	0.7387	0.5536	0.2569	0.8601	0.0337	0.8517	0.4727	0.0625	0.9489	0.0017	<0.001	0.0058	-																					
PEA_301	29	0.4206	0.1267	0.0405	0.4849	0.8714	0.5482	0.6302	0.3177	0.8658	0.4965	0.0335	0.1657	0.4153	0.0169	0.8928	0.9863	0.8544	0.1631	0.6724	0.0069	0.0126	0.5024	0.2523	0.0299	<0.001	0.1259	<0.001	0.0148	-																				
PEA_302	30	0.8463	0.6988	0.03	0.0146	0.0919	0.0355	0.1293	0.0865	0.9363	0.7489	0.7772	0.2023	0.1924	0.9834	0.3018	0.1121	0.1304	0.4174	0.0746	0.0679	0.5128	0.3767	0.7502	0.8986	0.0951	0.4488	0.0837	0.0466	0.0165	-																			
PEA_501	31	0.6963	0.1705	0.0737	0.5327	0.6618	0.6306	0.3329	0.2726	0.8188	0.5324	0.0114	0.1125	0.2103	0.0089	0.6786	0.8356	0.8578	0.3723	0.8479	0.0017	0.1533	0.987	0.1815	0.2347	<0.001	0.0176	<0.001	0.0018	<0.001	0.1143	-																		
PEA_502	32	0.7625	0.6791	0.2463	0.0461	0.708	0.1229	0.8713	0.8787	0.869	0.781	0.024	0.0524	0.0126	0.2498	0.8941	0.7204	0.324	0.4311	0.3441	0.0016	0.5337	0.8071	0.0888	0.6552	<0.001	<0.001	0.0028	<0.001	0.0079	0.1507	<0.001	-																	
PEA_751	33	0.7284	0.258	0.0685	0.2392	0.9632	0.3352	0.5707	0.3023	0.7107	0.413	0.0056	0.1091	0.1494	0.0186	0.9934	0.8399	0.6284	0.5008	0.5595	<0.001	0.127	0.8641	0.2643	0.2479	<0.001	0.0031	<0.001	0.0012	<0.001	0.0922	<0.001	<0.001	-																
PEA_752	34	0.7578	0.837	0.6032	0.0397	0.5749	0.0752	0.9799	0.9295	0.8564	0.7596	0.0155	0.0488	0.0023	0.5179	0.4684	0.572	0.3318	0.4285	0.2521	0.0016	0.4646	0.7902	0.0941	0.6348	<0.001	<0.001	0.0255	<0.001	0.0577	0.4501	0.0039	<0.001	<0.001	-															
PEA_951	35	0.4665	0.0433	0.0438	0.5874	0.7547	0.5261	0.4773	0.4584	0.8164	0.4549	0.0187	0.158	0.5409	0.0037	0.6353	0.8806	0.7981	0.1682	0.7905	0.003	0.0606	0.7867	0.1201	0.0992	<0.001	0.0868	<0.001	0.0052	<0.001	0.037	<0.001	0.0034	<0.001	0.0347	-														
PEA_952	36	0.7951	0.5007	0.0307	0.0552	0.6561	0.1302	0.8205	0.2581	0.5465	0.5474	0.4658	0.9486	0.7487	0.4545	0.6304	0.7197	0.3217	0.9523	0.4648	0.0566	0.7662	0.8296	0.179	0.8921	0.0242	0.1877	0.0064	<0.001	0.0027	<0.001	0.0146	0.0129	0.0178	0.1351	0.0018	-													
PHT	37	0.7933	0.3847	0.2285	0.1046	0.2158	0.0862	0.4107	0.6981	0.6198	0.2661	0.018	0.0369	<0.001	0.355	0.0053	0.2667	0.7898	0.2662	0.0901	0.0169	0.008	0.0143	0.4855	0.0202	0.2191	0.0169	0.5667	0.4915	0.2822	0.9888	0.4408	0.1061	0.2821	0.0189	0.5398	0.9257	-												
PRN	38	0.0376	0.0461	0.7472	0.0113	0.7737	0.056	0.8205	0.081	0.1483	0.3302	0.4307	0.5546	0.4966	0.0817	0.9465	0.9916	0.5491	0.0884	0.6118	0.7686	0.3745	0.3531	0.6071	0.6452	0.8491	0.0841	0.4048	0.1373	0.5351	0.4883	0.6894	0.1794	0.8785	0.0996	0.411	0.4209	0.2214	-											
RCH	39	0.2802	0.8465	0.4225	0.0058	<0.001	<0.001	<0.001	0.8385	0.0357	0.2102	0.0711	0.8585	0.7075	0.9016	0.0253	<0.001	<0.001	0.2052	<0.001	<0.001	0.4084	0.2211	0.8669	0.8235	0.0089	0.0533	0.0598	0.2219	0.0704	0.0372	0.0396	0.0308	0.0153	0.0302	0.0507	0.1214	0.0703	0.6612	-										
Rb	40	0.4037	0.5216	0.6529	0.8764	0.137	0.6496	0.1639	0.0078	<0.001	0.537	0.1785	0.6393	0.2204	0.0034	0.9826	0.1739	0.3997	0.7036	0.2423	0.8359	0.0964	0.4558	0.5123	0.0288	0.4106	0.4226	0.2432	0.2145	0.2182	0.7204	0.2078	0.2604	0.2493	0.2723	0.2419	0.3796	0.6454	0.3185	0.4657	-									
S	41	0.0502	0.9491	0.8754	0.1849	0.1801	0.1733	0.248	0.1438	0.9973	0.0164	0.018	0.2644	0.2055	0.3334	0.0154	0.1508	0.5528	0.0084	0.0734	0.0288	<0.001	0.0152	0.0666	<0.001	0.1202	0.8913	0.2185	0.5217	0.0691	0.7496	0.2003	0.9065	0.1626	0.7188	0.2826	0.5463	0.0034	0.3881	0.0538	0.5961	-								
Se	42	0.3131	0.3292	0.4499	0.8827	0.8093	0.7827	0.8251	0.5107	0.706	0.0275	0.0209	0.1763	0.2763	0.0826	0.3084	0.8867	0.5853	0.111	0.9457	0.232	0.0561	0.1462	0.8594	0.0328	0.1132	0.8637	0.0963	0.7724	0.0917	0.8223	0.083	0.8484	0.091	0.8472	0.2186	0.883	0.2915	0.0339	0.389	0.2322	0.0095	-							
Sr	43	0.897	0.6805	0.0253	0.1329	0.6058	0.2511	0.8634	<0.001	0.1089	0.8029	0.6064	0.107	0.0951	0.2202	0.4484	0.6373	0.8384	0.6708	0.7471	0.3676	0.6392	0.1922	0.4171	0.3828	0.8804	0.4309	0.5358	0.5937	0.2327	0.0183	0.6763	0.6781	0.7629	0.4381	0.3899	0.0549	0.217	0.1053	0.3842	0.0255	0.843	0.9734	-						
TGW	44	0.8942	0.4226	0.3304	0.9026	0.1583	0.8755	0.129	0.7796	0.9789	0.1608	0.1552	0.046	0.0358	0.0521	0.2722	0.1788	0.7263	0.7195	0.4398	0.6176	0.8948	0.5691	0.0154	0.7513	0.2008	0.0698	0.1544	0.07	0.4907	0.3615	0.0798	0.069	0.1197	0.0646	0.3788	0.6588	0.7281	0.9597	0.8134	0.1977	0.7154	0.2236	0.928	-					
TLAR	45	0.047	0.9082	0.4362	0.041	<0.001	0.0033	<0.001	0.5243	0.007	0.1453	0.3452	0.7359	0.6554	0.8011	0.0037	<0.001	<0.001	0.0954	<0.001	<0.001	0.3655	0.1301	0.4522	0.6982	0.3334	0.6368	0.5366	0.6864	0.3617	0.1521	0.6307	0.6553	0.4494	0.6006	0.41	0.6859	0.2608	0.1393	<0.001	0.1378	0.0245	0.3285	0.3744	0.5242	-				
TLLR	46	0.3084	0.4895	0.6888	0.45	0.0154	0.207	0.0317	0.6266	0.5131	0.1494	0.102	0.496	0.2688	0.465	<0.001	0.0219	0.5706	<0.001	0.0105	0.0633	0.0039	0.003	0.4397	0.0567	0.7052	0.583	0.9168	0.2251	0.434	0.2909	0.9206	0.9012	0.7822	0.7324	0.8029	0.699	0.0014	0.4215	0.0204	0.8577	<0.001	0.1473	0.4315	0.3437	0.0032	-			
TLPR	47	0.0474	0.9107	0.4306	0.0413	<0.001	0.0034	<0.001	0.5207	0.0068	0.1477	0.3542	0.7221	0.6384	0.8148	0.0042	<0.001	<0.001	0.1005	<0.001	<0.001	0.3793	0.1384	0.4546	0.714	0.3331	0.6442	0.5331	0.6929	0.3625	0.1518	0.6286	0.6547	0.4486	0.605	0.407	0.6779	0.2787	0.1365	<0.001	0.1388	0.0265	0.3335	0.38	0.5302	<0.001	0.0038	-		
WDR	48	0.3733	0.0941	0.3811	0.2173	0.9888	0.1755	0.596	0.6833	0.9862	0.2005	<0.001	0.0101	0.0246	0.0629	0.9098	0.9258	0.6099	0.7781	0.4535	<0.001	0.0579	0.3872	0.1605	0.1551	<0.001	0.0014	<0.001	<0.001	<0.001	0.1659	<0.001	<0.001	<0.001	<0.001	<0.001	0.0083	0.0354	0.8945	0.0101	0.3373	0.1821	0.2125	0.6744	0.1224	0.3662	0.6944	0.3676	-	
Zn	49	0.8036	0.1022	0.7741	0.495	0.373	0.5259	0.317	0.8339	0.3175	0.0014	<0.001	<0.001	<0.001	0.0809	0.5409	0.2877	0.345	0.1269	0.9299	0.3837	<0.001	0.0323	0.9819	<0.001	0.399	0.5495	0.3141	0.904	0.1887	0.3334	0.397	0.4537	0.387	0.3576	0.2842	0.6419	0.0142	0.8885	0.9231	0.2795	0.0076	0.1277	0.7166	0.2302	0.9656	0.1218	0.9849	0.106	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD_g	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI	K	LRN	MDR	MLAR	MLLR	MLPR	MWR_cm	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.3 Table Correlation coefficients between seedling root traits and grain yield, yield components and grain mineral composition traits of 36 Indian wheat genotypes at Hisar site. Seedling root traits data are mean of ~20 replications, yield, yield components and mineral elements data are mean of two replication per plot per genotype over two years at Hisar.

r values																																																		
As	1	-																																																
BYD	2	-0.3291	-																																															
Ba	3	-0.3135	0.3872	-																																														
CHCRX	4	-0.213	0.1347	0.072	-																																													
CHCRY	5	0.0745	0.1429	-0.1069	0.5797	-																																												
CMRX	6	-0.0898	0.0768	-0.0316	0.9302	0.6767	-																																											
CMRY	7	0.1585	0.1148	-0.0966	0.5529	0.9823	0.6498	-																																										
Ca	8	-0.0971	0.1059	0.6053	-0.1683	-0.0762	-0.2297	-0.0859	-																																									
Cs	9	0.0306	0.0965	-0.0544	-0.1086	-0.0344	-0.0929	-0.0778	0.2732	-																																								
Cu	10	-0.0049	-0.2513	0.3304	0.0478	-0.0165	0.1094	-0.0066	0.3825	0.4858	-																																							
Fe	11	-0.2406	-0.1021	0.1632	0.199	0.0848	0.2633	0.0479	0.2229	0.6009	0.7883	-																																						
GYD	12	0.2558	0.7105	0.1857	0.0262	0.2838	0.0406	0.3286	0.1309	-0.011	-0.28	-0.334	-																																					
HI_%	13	0.671	0.0248	-0.1103	-0.1383	0.2403	-0.0525	0.3308	0.0396	-0.141	-0.1535	-0.4025	0.7114	-																																				
K	14	0.082	-0.1903	0.5079	-0.4131	-0.3684	-0.4595	-0.3167	0.5297	0.1839	0.4586	0.1239	-0.1133	0.0062	-																																			
LRN	15	0.0628	0.0108	-0.1417	0.2849	0.6209	0.3099	0.6033	0.1134	-0.0714	0.0231	0.0858	0.0514	0.0348	-0.2207	-																																		
MDR	16	0.1236	0.1353	-0.1241	0.5596	0.9877	0.6577	0.9727	-0.0646	-0.0596	-0.0536	0.0308	0.3046	0.2792	-0.3592	0.6048	-																																	
MLAR	17	0.1034	0.1411	-0.0965	0.6507	0.8679	0.7406	0.8638	-0.266	-0.104	-0.1485	-0.0546	0.2781	0.2287	-0.3276	0.2404	0.8774	-																																
MLLR	18	0.1377	-0.2908	-0.2913	-0.0498	0.1582	0.0959	0.109	-0.0057	-0.0003	0.0773	0.0653	-0.0194	0.2907	-0.0463	0.3172	0.1609	-0.0138	-																															
MLPR	19	0.0345	0.0857	-0.1219	0.674	0.9635	0.7892	0.933	-0.144	-0.0575	0.0116	0.1566	0.1783	0.135	-0.3827	0.5792	0.9502	0.8893	0.208	-																														
MWR	20	-0.0927	0.0231	-0.0648	0.5224	0.5798	0.6137	0.4715	0.0389	0.1962	0.1039	0.3038	-0.1188	-0.2382	-0.1532	0.3349	0.6079	0.6051	0.2119	0.7055	-																													
Mg	21	-0.1173	-0.236	0.3331	0.0651	0.1805	0.0888	0.1743	0.3727	0.3076	0.7899	0.7345	-0.284	-0.1706	0.4443	0.3205	0.1299	-0.0655	0.2567	0.201	0.2472	-																												
Mn	22	0.063	-0.0847	0.2488	0.0934	0.2437	0.1026	0.3006	0.4491	-0.0524	0.4801	0.3409	0.1482	0.2293	0.2	0.324	0.2062	-0.0079	0.1171	0.2144	-0.0853	0.5359	-																											
Mo	23	0.1497	-0.2127	-0.1735	0.1274	0.2588	0.1721	0.318	0.0064	0.2131	0.39	0.3324	0.0297	0.2439	0.0482	0.167	0.2544	0.1139	0.0449	0.1672	-0.0688	0.3301	0.4114	-																										
P	24	-0.2731	0.1017	0.6836	0.0769	-0.0686	-0.0176	-0.0689	0.4939	0.2357	0.6373	0.5108	-0.0712	-0.2215	0.6071	0.0064	-0.1134	-0.1636	-0.057	-0.0356	0.1104	0.7527	0.4961	0.1702	-																									
PEA_1001	25	-0.1157	-0.0854	0.0563	0.2959	0.0353	0.2539	-0.0821	0.203	0.1257	-0.0656	0.0918	-0.2568	-0.3249	0.0615	0.0101	0.0939	0.1417	0.1618	0.1708	0.7	-0.0084	-0.3179	-0.2867	0.0427	-																								
PEA_1002	26	-0.445	0.2753	0.1678	0.4283	0.1336	0.3825	0.023	-0.0293	-0.0701	-0.1031	0.1167	-0.2618	-0.6703	-0.1785	0.2245	0.1379	0.1698	-0.1652	0.2392	0.5593	-0.0352	-0.3345	-0.4347	-0.0298	0.601	-																							
PEA_251	27	-0.038	-0.1402	0.1274	0.0709	-0.1177	0.0649	-0.219	0.3048	0.1787	-0.0262	0.04	-0.2256	-0.2367	0.295	-0.1266	-0.0721	0.0167	0.2553	0.0139	0.591	0.03	-0.2276	-0.2784	0.2065	0.8653	0.377	-																						
PEA_252	28	-0.3853	0.2656	0.4623	0.3916	-0.0583	0.2656	-0.1527	0.1842	0.1641	0.0957	0.2129	-0.1575	-0.5277	0.1868	-0.232	-0.0736	0.1302	-0.2465	0.0389	0.4442	0.1043	-0.2185	-0.3463	0.3296	0.6161	0.7104	0.5568	-																					
PEA_301	29	0.065	-0.2693	0.1456	0.1533	-0.0357	0.132	-0.106	0.3093	0.1377	0.0384	0.1298	-0.2569	-0.1691	0.2865	0.0298	-0.0038	0.0405	0.3008	0.0932	0.547	0.1854	-0.0521	-0.2044	0.2413	0.7636	0.3285	0.9068	0.5014	-																				
PEA_302	30	-0.1158	0.1726	0.4925	0.5023	0.3597	0.4403	0.3258	0.534	0.1382	0.1845	0.2584	0.2715	0.1564	0.1381	0.2251	0.3403	0.3248	0.1777	0.3789	0.3873	0.2956	0.2619	0.0127	0.3448	0.3564	0.1661	0.3684	0.419	0.4942	-																			
PEA_501	31	-0.0936	-0.0881	0.1007	0.1371	-0.0964	0.1059	-0.2114	0.2614	0.1129	-0.1107	-0.0036	-0.2301	-0.2895	0.1751	-0.0913	-0.0458	0.0396	0.1951	0.0423	0.6177	-0.0492	-0.2931	-0.347	0.1015	0.9464	0.49	0.9444	0.6153	0.8169	0.3383	-																		
PEA_502	32	-0.4006	0.2191	0.2687	0.4199	0.0826	0.331	-0.0358	0.0256	0.0592	-0.0914	0.1312	-0.2708	-0.6365	-0.0059	0.0294	0.0789	0.2152	-0.1726	0.2066	0.6203	0.0248	-0.3976	-0.4919	0.1333	0.7381	0.9035	0.5937	0.8847	0.5395	0.3095	0.6819	-																	
PEA_751	33	-0.1304	-0.06	0.0926	0.2556	-0.0102	0.2104	-0.1247	0.2366	0.1062	-0.1029	0.0432	-0.2433	-0.3357	0.1082	-0.0018	0.0446	0.1066	0.1479	0.1283	0.676	-0.0308	-0.3145	-0.3153	0.0745	0.9875	0.5884	0.8964	0.6327	0.782	0.3593	0.9781	0.7415	-																
PEA_752	34	-0.4063	0.2262	0.1322	0.4317	0.1234	0.3782	0.0056	-0.0826	-0.0446	-0.1479	0.0938	-0.3039	-0.685	-0.1692	0.1591	0.1243	0.2119	-0.1735	0.2489	0.6207	-0.0437	-0.403	-0.4946	-0.0064	0.6575	0.9741	0.4647	0.7636	0.4013	0.1656	0.5771	0.9553	0.6567	-															
PEA_951	35	0.0302	-0.1576	0.1423	0.1194	-0.0689	0.1393	-0.156	0.2894	0.2662	0.0716	0.1668	-0.218	-0.2066	0.321	-0.1045	-0.0332	0.0564	0.2974	0.0586	0.5899	0.1303	-0.2221	-0.2102	0.2316	0.8223	0.365	0.9616	0.563	0.9242	0.4371	0.8662	0.5847	0.8356	0.442	-														
PEA_952	36	-0.1817	0.1753	0.5409	0.405	0.0981	0.3251	0.0501	0.4897	0.3526	0.309	0.3754	0.0927	-0.1185	0.3551	-0.1059	0.0791	0.2162	-0.0132	0.1604	0.4029	0.2749	0.1207	-0.0561	0.4644	0.4684	0.2849	0.5516	0.7172	0.595	0.8487	0.5024	0.51	0.4892	0.3212	0.6155	-													
PHT	37	-0.3033	-0.0233	-0.3418	0.3731	0.2485	0.3561	0.1515	-0.2101	0.0038	0.0277	0.3605	-0.3605	-0.544	-0.4419	0.5249	0.2248	0.0553	0.1037	0.3356	0.4705	0.2034	0.1413	0.0445	-0.0021	0.2626	0.5545	0.0855	0.1757	0.132	-0.0379	0.156	0.3811	0.2318	0.5379	0.0547	-0.0518	-												
PRN	38	0.3842	-0.3148	-0.0115	-0.5183	-0.0634	-0.4038	-0.0501	0.1438	0.1528	0.2822	-0.0341	-0.0156	0.3532	0.5054	0.0148	-0.0023	-0.1317	0.3633	-0.1117	0.0649	0.3345	-0.0632	0.2165	0.1818	0.042	-0.3679	0.1824	-0.3195	0.1363	-0.1522	0.0881	-0.2901	0.0338	-0.3519	0.1801	-0.1764	-0.3504	-											
RCH	39	-0.0178	0.0771	-0.0698	0.5569	0.8049	0.6661	0.7189	-0.0006	0.1176	0.0346	0.2082	0.0619	-0.0181	-0.2354	0.4651	0.8295	0.7815	0.2744	0.8736	0.9311	0.2205	-0.0154	0.0306	0.0302	0.5326	0.4079	0.3982	0.2649	0.3841	0.4367	0.4318	0.451	0.4992	0.4523	0.4121	0.3323	0.3571	0.0965	-										
Rb	40	-0.1171	0.3348	0.1537	-0.2283	-0.1504	-0.3466	-0.1655	0.3907	0.4185	0.0093	0.1002	0.1233	-0.2269	0.4147	0.1268	-0.154	-0.2063	-0.113	-0.1904	0.0525	0.1424	0.042	-0.2456	0.262	0.088	0.2054	0.2041	0.3307	0.1879	0.1536	0.1667	0.27	0.1422	0.2237	0.2167	0.36	0.1248	-0.0813	-0.0398	-									
S	41	0.2501	-0.3876	-0.2467	-0.0825	0.356	0.06	0.3275	0.3035	0.5076	0.5977	0.5472	-0.1966	0.073	0.176	0.4884	0.3451	0.0466	0.4954	0.339	0.3623	0.6448	0.4625	0.4375	0.2152	0.0934	-0.1526	0.113	-0.2145	0.2002	0.0935	0.0477	-0.1826	0.0521	-0.181	0.1756	0.0367	0.2843	0.4277	0.3833	0.114	-								
Se	42	0.4356	-0.4742	-0.3909	-0.2657	0.0553	-0.2018	0.1302	-0.0022	-0.3036	-0.0361	-0.1923	-0.0996	0.2927	0.0949	0.3148	0.0876	-0.1154	0.2233	-0.0133	-0.2403	0.0272	0.3933	0.2529	-0.2482	-0.259	-0.2704	-0.1872	-0.5287	-0.0282	-0.27	-0.3	-0.4548	-0.2973	-0.3532	-0.1486	-0.4165	0.1205	0.1611	-0.1881	-0.0048	0.3492	-							
Sr	43	-0.1477	0.3731	0.8214	-0.0832	-0.1702	-0.1899	-0.1794	0.7895	0.2403	0.314	0.0947	0.2613	-0.0302	0.5979	-0.1	-0.1764	-0.1779	-0.1739	-0.2041	-0.001	0.2392	0.2421	-0.2555	0.6017	0.134	0.1004	0.3206	0.4662	0.2948	0.5452	0.2588	0.2403	0.198	0.0926	0.306	0.6679	-0.3368	0.0439	-0.0508	0.5127	-0.0496	-0.3207	-						
TGW	44	-0.0616	0.3835	0.2287	0.2591	0.3623	0.2169	0.3437	0.1102	0.292	-0.0882	0.2976	0.2487	-0.046	-0.1219	0.1421	0.341	0.3353	-0.1298	0.3056	0.2348	0.1622	-0.0392	0.0606	0.161	0.0823	0.1256	0.0392	0.3024	0.1258	0.4564	0.0346	0.2635	0.0789	0.1758	0.1682	0.4385	0.069	-0.2606	0.3355	0.3439	-0.0288	-0.3083	0.1821	-					
TLAR	45	0.2178	-0.0534	-0.1122	0.4291	0.8814	0.5853	0.8564	-0.0543	0.0083	0.1276	0.1183	0.1616	0.2722	-0.1413	0.5805	0.898	0.7773	0.356	0.9004	0.7154	0.3195	0.175	0.2226	0.0462	0.2112	0.104	0.1358	-0.089	0.1994	0.3085	0.1059	0.0983	0.1659	0.1152	0.1805	0.0891	0.1842	0.318	0.8759	-0.2039	0.5071	0.0901	-0.1506	0.1559	-				
TLLR	46	0.0509	-0.1606	-0.2282	0.1656	0.4987	0.2733	0.4488	0.0693	-0.0222	0.1553	0.2401	-0.0582	0.0677	-0.198	0.86	0.4754	0.1248	0.6963	0.5225	0.3933	0.466	0.3486	0.1021	0.0506	0.0834	0.1208	0.0231	-0.2631	0.1715	0.2301	0.022	-0.0274	0.061	0.0754	0.0551	-0.0852	0.5361	0.1761	0.4801	0.015	0.6415	0.2993	-0.1739	0.0175	0.5874	-			
TLPR	47	0.2205	-0.0517	-0.1105	0.4287	0.8811	0.5845	0.8569	-0.0556	0.0083	0.1247	0.1134	0.1653	0.276	-0.1381	0.5734	0.8984	0.7818	0.351	0.8996	0.7148	0.3145	0.17	0.222	0.0445	0.2113	0.1017	0.137	-0.0871	0.1991	0.3087	0.1065	0.0985	0.1662	0.1139	0.1816	0.0915	0.1759	0.3201	0.8759	-0.2037	0.5016	0.0874	-0.1485	0.1572	0.9999	0.5785	-		
WDR	48	-0.1933	-0.0485	0.0613	0.2674	-0.0031	0.2926	-0.1167	0.1723	0.3183	0.1949	0.3772	-0.3514	-0.5123	0.1451	-0.025	0.0206	0.1123	0.0622	0.1644	0.7879	0.2329	-0.2122	-0.2021	0.2608	0.7977	0.6249	0.8031	0.6815	0.7183	0.2989	0.7979	0.7452	0.8091	0.7021	0.7941	0.5369	0.4186	0.0293	0.5248	0.2697	0.1962	-0.3157	0.2001	0.1071	0.1976	0.0866	0.197	-	
Zn	49	-0.4218	-0.0442	0.5476	0.2023	-0.0178	0.1566	-0.0435	0.2303	0.2317	0.6916	0.6624	-0.3684	-0.4878	0.4477	0.0201	-0.0889	-0.0725	-0.045	0.0709	0.2092	0.7532	0.3083	0.0573	0.8614	0.0535	0.1666	0.1566	0.3619	0.201	0.2693	0.0514	0.2801	0.0548	0.1905	0.2167	0.4217	0.1716	0.0612	0.1138	0.1286	0.2008	-0.2901	0.3897	0.1176	0.0974	0.115	0.0948	0.3328	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.3 Table continued.

P values																																																		
As	1	-																																																
BYD	2	0.1252	-																																															
Ba	3	0.1452	0.068	-																																														
CHCRX	4	0.3292	0.5401	0.7442	-																																													
CHCRY	5	0.7353	0.5155	0.6274	0.0037	-																																												
CMRX	6	0.6837	0.7277	0.8862	<0.001	<0.001	-																																											
CMRY	7	0.4701	0.602	0.661	0.0062	<0.001	<0.001	-																																										
Ca	8	0.6592	0.6306	0.0022	0.4428	0.7295	0.2918	0.6966	-																																									
Cs	9	0.8898	0.6614	0.8052	0.6218	0.8762	0.6733	0.724	0.2072	-																																								
Cu	10	0.9824	0.2475	0.1237	0.8286	0.9405	0.6193	0.9762	0.0716	0.0188	-																																							
Fe	11	0.2687	0.6428	0.4569	0.3626	0.7005	0.2248	0.8282	0.3067	0.0024	<0.001	-																																						
GYD	12	0.2388	<0.001	0.3964	0.9054	0.1895	0.8542	0.1257	0.5515	0.9604	0.1957	0.1193	-																																					
HI_%	13	<0.001	0.9106	0.6165	0.5292	0.2693	0.8119	0.1231	0.8575	0.5211	0.4844	0.0569	<0.001	-																																				
K	14	0.7099	0.3844	0.0134	0.0501	0.0837	0.0274	0.1409	0.0093	0.401	0.0277	0.5733	0.6069	0.9775	-																																			
LRN	15	0.7761	0.9608	0.5189	0.1877	0.0016	0.1501	0.0023	0.6063	0.7461	0.9166	0.6972	0.8158	0.8748	0.3117	-																																		
MDR	16	0.5742	0.5383	0.5725	0.0055	<0.001	<0.001	<0.001	0.7696	0.787	0.8081	0.8889	0.1576	0.197	0.0924	0.0022	-																																	
MLAR	17	0.6386	0.5207	0.6612	<0.001	<0.001	<0.001	<0.001	0.2199	0.6366	0.499	0.8045	0.1989	0.2939	0.127	0.2692	<0.001	-																																
MLLR	18	0.5308	0.1783	0.1774	0.8215	0.4709	0.6634	0.6206	0.9793	0.9988	0.7259	0.7673	0.93	0.1784	0.8337	0.1403	0.4634	0.9503	-																															
MLPR	19	0.8757	0.6975	0.5796	<0.001	<0.001	<0.001	<0.001	0.5123	0.7943	0.958	0.4754	0.4157	0.539	0.0715	0.0038	<0.001	<0.001	0.341	-																														
MWR	20	0.6739	0.9168	0.7691	0.0105	0.0037	0.0018	0.0231	0.8602	0.3695	0.6372	0.1588	0.5893	0.2737	0.4852	0.1183	0.0021	0.0022	0.3318	<0.001	-																													
Mg	21	0.5939	0.2784	0.1204	0.7678	0.4099	0.687	0.4264	0.0799	0.1533	<0.001	<0.001	0.1891	0.4364	0.0337	0.1359	0.5546	0.7667	0.237	0.3579	0.2555	-																												
Mn	22	0.7752	0.7008	0.2523	0.6715	0.2624	0.6412	0.1633	0.0316	0.8124	0.0204	0.1114	0.4996	0.2926	0.3602	0.1315	0.3451	0.9716	0.5947	0.326	0.6988	0.0084	-																											
Mo	23	0.4955	0.3298	0.4285	0.5623	0.2331	0.4324	0.1393	0.9768	0.329	0.0658	0.1212	0.893	0.2621	0.827	0.4464	0.2415	0.6048	0.8387	0.4458	0.7552	0.124	0.0511	-																										
P	24	0.2073	0.6443	<0.001	0.7272	0.7556	0.9363	0.7547	0.0166	0.2789	0.0011	0.0127	0.7467	0.3097	0.0021	0.977	0.6064	0.4557	0.7962	0.8717	0.616	<0.001	0.0161	0.4375	-																									
PEA_1001	25	0.5992	0.6984	0.7985	0.1704	0.8731	0.2424	0.7096	0.3528	0.5676	0.7661	0.677	0.2369	0.1303	0.7804	0.9635	0.67	0.5188	0.4608	0.4359	<0.001	0.9696	0.1393	0.1848	0.8467	-																								
PEA_1002	26	0.0334	0.2036	0.4441	0.0415	0.5432	0.0716	0.9171	0.8944	0.7505	0.6397	0.5958	0.2276	<0.001	0.4152	0.303	0.5303	0.4385	0.4512	0.2716	0.0055	0.8731	0.1188	0.0382	0.8926	0.0024	-																							
PEA_251	27	0.8634	0.5234	0.5624	0.7477	0.5928	0.7686	0.3154	0.1573	0.4146	0.9056	0.8562	0.3007	0.2768	0.1718	0.565	0.7437	0.9396	0.2398	0.9498	0.003	0.8918	0.2963	0.1983	0.3446	<0.001	0.0762	-																						
PEA_252	28	0.0694	0.2206	0.0263	0.0646	0.7918	0.2206	0.4868	0.4001	0.4543	0.6639	0.3294	0.4728	0.0096	0.3935	0.2867	0.7387	0.5536	0.2569	0.8601	0.0337	0.6358	0.3165	0.1055	0.1246	0.0017	<0.001	0.0058	-																					
PEA_301	29	0.7684	0.214	0.5074	0.4849	0.8714	0.5482	0.6302	0.1509	0.5308	0.8619	0.5551	0.2366	0.4406	0.1851	0.8928	0.9863	0.8544	0.1631	0.6724	0.0069	0.3971	0.8135	0.3495	0.2674	<0.001	0.1259	<0.001	0.0148	-																				
PEA_302	30	0.5987	0.4309	0.017	0.0146	0.0919	0.0355	0.1293	0.0087	0.5296	0.3994	0.2338	0.2102	0.476	0.5298	0.3018	0.1121	0.1304	0.4174	0.0746	0.0679	0.1708	0.2274	0.9541	0.1071	0.0951	0.4488	0.0837	0.0466	0.0165	-																			
PEA_501	31	0.6708	0.6892	0.6474	0.5327	0.6618	0.6306	0.3329	0.2282	0.6081	0.6151	0.987	0.2909	0.1803	0.4242	0.6786	0.8356	0.8578	0.3723	0.8479	0.0017	0.8235	0.1747	0.1047	0.6448	<0.001	0.0176	<0.001	0.0018	<0.001	0.1143	-																		
PEA_502	32	0.0582	0.3151	0.2151	0.0461	0.708	0.1229	0.8713	0.9077	0.7884	0.6782	0.5507	0.2114	0.0011	0.9788	0.8941	0.7204	0.324	0.4311	0.3441	0.0016	0.9106	0.0603	0.0171	0.5443	<0.001	<0.001	0.0028	<0.001	0.0079	0.1507	<0.001	-																	
PEA_751	33	0.5533	0.7857	0.6744	0.2392	0.9632	0.3352	0.5707	0.2771	0.6295	0.6404	0.8449	0.2633	0.1173	0.6231	0.9934	0.8399	0.6284	0.5008	0.5595	<0.001	0.889	0.1439	0.1428	0.7354	<0.001	0.0031	<0.001	0.0012	<0.001	0.0922	<0.001	<0.001	-																
PEA_752	34	0.0544	0.2994	0.5478	0.0397	0.5749	0.0752	0.9799	0.7079	0.8399	0.5008	0.6705	0.1586	<0.001	0.4402	0.4684	0.572	0.3318	0.4285	0.2521	0.0016	0.8429	0.0566	0.0164	0.9768	<0.001	<0.001	0.0255	<0.001	0.0577	0.4501	0.0039	<0.001	<0.001	-															
PEA_951	35	0.8912	0.4727	0.5172	0.5874	0.7547	0.5261	0.4773	0.1805	0.2195	0.7454	0.4468	0.3176	0.3442	0.1354	0.6353	0.8806	0.7981	0.1682	0.7905	0.003	0.5534	0.3083	0.3356	0.2876	<0.001	0.0868	<0.001	0.0052	<0.001	0.037	<0.001	0.0034	<0.001	0.0347	-														
PEA_952	36	0.4068	0.4238	0.0077	0.0552	0.6561	0.1302	0.8205	0.0177	0.099	0.1514	0.0775	0.6739	0.5901	0.0964	0.6304	0.7197	0.3217	0.9523	0.4648	0.0566	0.2043	0.5834	0.7992	0.0256	0.0242	0.1877	0.0064	<0.001	0.0027	<0.001	0.0146	0.0129	0.0178	0.1351	0.0018	-													
PHT	37	0.1594	0.9159	0.1104	0.0795	0.253	0.0953	0.4901	0.3358	0.9862	0.9	0.0911	0.091	0.0073	0.0348	0.0101	0.3025	0.8022	0.6379	0.1175	0.0235	0.352	0.52	0.8403	0.9923	0.2261	0.006	0.6982	0.4226	0.5482	0.8638	0.4771	0.0728	0.2873	0.0081	0.8042	0.8144	-												
PRN	38	0.0703	0.1435	0.9584	0.0113	0.7737	0.056	0.8205	0.5126	0.4865	0.1921	0.8773	0.9437	0.0982	0.0139	0.9465	0.9916	0.5491	0.0884	0.6118	0.7686	0.1188	0.7744	0.321	0.4065	0.8491	0.0841	0.4048	0.1373	0.5351	0.4883	0.6894	0.1794	0.8785	0.0996	0.411	0.4209	0.1011	-											
RCH	39	0.9359	0.7266	0.7518	0.0058	<0.001	<0.001	<0.001	0.9977	0.5931	0.8754	0.3403	0.7789	0.9347	0.2796	0.0253	<0.001	<0.001	0.2052	<0.001	<0.001	0.3119	0.9444	0.8897	0.8911	0.0089	0.0533	0.0598	0.2219	0.0704	0.0372	0.0396	0.0308	0.0153	0.0302	0.0507	0.1214	0.0943	0.6612	-										
Rb	40	0.5946	0.1184	0.4839	0.2947	0.4933	0.1052	0.4504	0.0653	0.0469	0.9663	0.6492	0.5751	0.2979	0.0491	0.5642	0.483	0.3449	0.6077	0.3842	0.8119	0.517	0.849	0.2586	0.2272	0.6895	0.3472	0.3503	0.1233	0.3905	0.4841	0.4472	0.2128	0.5175	0.3048	0.3207	0.0915	0.5705	0.7122	0.8571	-									
S	41	0.2498	0.0676	0.2565	0.7082	0.0955	0.7856	0.1271	0.1592	0.0134	0.0026	0.0069	0.3687	0.7407	0.4217	0.018	0.1068	0.8327	0.0162	0.1136	0.0894	<0.001	0.0263	0.0368	0.324	0.6717	0.4871	0.6076	0.3258	0.3598	0.6714	0.8288	0.4043	0.8134	0.4084	0.423	0.8679	0.1885	0.0418	0.071	0.6045	-								
Se	42	0.0377	0.0223	0.0651	0.2204	0.8022	0.3557	0.5537	0.992	0.159	0.8702	0.3795	0.6511	0.1753	0.6667	0.1435	0.6911	0.6001	0.3057	0.9519	0.2695	0.9019	0.0633	0.2442	0.2536	0.2327	0.2122	0.3925	0.0095	0.8984	0.2127	0.1643	0.0292	0.1683	0.0983	0.4985	0.0481	0.5838	0.4628	0.39	0.9826	0.1025	-							
Sr	43	0.5011	0.0796	<0.001	0.7058	0.4375	0.3853	0.4126	<0.001	0.2693	0.1445	0.6674	0.2285	0.8913	0.0026	0.6498	0.4208	0.4169	0.4275	0.3501	0.9965	0.2717	0.2657	0.2394	0.0024	0.5422	0.6487	0.1359	0.0249	0.1721	0.0071	0.2331	0.2695	0.3651	0.6745	0.1557	<0.001	0.1161	0.8424	0.8178	0.0124	0.8221	0.1357	-						
TGW	44	0.7801	0.0708	0.2939	0.2326	0.0894	0.3201	0.1083	0.6167	0.1765	0.6891	0.1679	0.2526	0.835	0.5795	0.5177	0.1113	0.1179	0.5549	0.1562	0.2809	0.4598	0.8591	0.7834	0.4629	0.7088	0.568	0.859	0.1608	0.5673	0.0286	0.8754	0.2244	0.7206	0.4225	0.4429	0.0363	0.7544	0.2297	0.1176	0.1081	0.8964	0.1524	0.4057	-					
TLAR	45	0.318	0.8089	0.6102	0.041	<0.001	0.0033	<0.001	0.8055	0.9701	0.5619	0.5908	0.4614	0.2089	0.5202	0.0037	<0.001	<0.001	0.0954	<0.001	<0.001	0.1372	0.4245	0.3073	0.8343	0.3334	0.6368	0.5366	0.6864	0.3617	0.1521	0.6307	0.6553	0.4494	0.6006	0.41	0.6859	0.4002	0.1393	<0.001	0.3508	0.0135	0.6826	0.4927	0.4775	-				
TLLR	46	0.8176	0.4643	0.2949	0.45	0.0154	0.207	0.0317	0.7535	0.92	0.4791	0.2698	0.7918	0.7588	0.3651	<0.001	0.0219	0.5706	<0.001	0.0105	0.0633	0.025	0.1031	0.6431	0.8187	0.7052	0.583	0.9168	0.2251	0.434	0.2909	0.9206	0.9012	0.7822	0.7324	0.8029	0.699	0.0084	0.4215	0.0204	0.9458	<0.001	0.1653	0.4273	0.9368	0.0032	-			
TLPR	47	0.3121	0.8149	0.6159	0.0413	<0.001	0.0034	<0.001	0.8012	0.97	0.5709	0.6065	0.4509	0.2023	0.5298	0.0042	<0.001	<0.001	0.1005	<0.001	<0.001	0.1438	0.4381	0.3087	0.8401	0.3331	0.6442	0.5331	0.6929	0.3625	0.1518	0.6286	0.6547	0.4486	0.605	0.407	0.6779	0.4221	0.1365	<0.001	0.3512	0.0147	0.6918	0.4989	0.4737	<0.001	0.0038	-		
WDR	48	0.377	0.8262	0.781	0.2173	0.9888	0.1755	0.596	0.4317	0.1388	0.3729	0.076	0.1002	0.0125	0.5089	0.9098	0.9258	0.6099	0.7781	0.4535	<0.001	0.2849	0.3309	0.3552	0.2294	<0.001	0.0014	<0.001	<0.001	<0.001	0.1659	<0.001	<0.001	<0.001	<0.001	<0.001	0.0083	0.0468	0.8945	0.0101	0.2134	0.3696	0.1423	0.3599	0.6268	0.3662	0.6944	0.3676	-	
Zn	49	0.045	0.8414	0.0068	0.3545	0.9358	0.4754	0.8438	0.2903	0.2875	<0.001	<0.001	0.0837	0.0182	0.0322	0.9276	0.6868	0.7423	0.8385	0.7478	0.3381	<0.001	0.1523	0.7949	<0.001	0.8083	0.4475	0.4754	0.0897	0.3577	0.214	0.816	0.1954	0.804	0.384	0.3206	0.0451	0.4336	0.7814	0.6053	0.5586	0.3583	0.1794	0.0661	0.5931	0.6582	0.6014	0.667	0.1208	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.4 Table Correlation coefficients between seedling root traits and grain yield, yield components and grain mineral composition traits of 36 Indian wheat genotypes at Kumarganj-reclaimed site. Seedling root traits data are mean of ~20 replications, yield & yield component traits data are mean of two replications per plot per genotype over two years at Kumarganj-reclaimed and mineral elements data are mean of one replicate per plot in 2013-14 and two replicates per plot per genotype in 2014-15 at Kumarganj-reclaimed site.

r values																									
As	1	-																							
BYD	2	0.0677	-																						
Ba	3	-0.1819	-0.2584	-																					
CHCRX	4	-0.1886	0.0895	0.2579	-																				
CHCRY	5	0.0801	0.0611	-0.0319	0.5797	-																			
CMRX	6	-0.1855	0.1233	0.2257	0.9302	0.6767	-																		
CMRY	7	0.1163	0.1224	-0.0413	0.5529	0.9823	0.6498	-																	
Ca	8	0.3035	0.0071	0.29	0.192	-0.094	0.1043	-0.1367	-																
Cs	9	-0.0082	0.5026	-0.0437	-0.0469	-0.3131	-0.1434	-0.2691	0.2063	-															
Cu	10	-0.0878	-0.3002	0.2031	0.2206	0.01	0.2762	-0.0299	0.0271	0.1375	-														
Fe	11	-0.0963	-0.0967	0.3726	0.0723	-0.1118	0.1198	-0.213	0.0795	0.0649	0.5737	-													
GYD	12	0.2686	0.8329	-0.3632	-0.0515	0.0927	0.0131	0.2032	-0.1799	0.3951	-0.2741	-0.3321	-												
HI_%	13	0.2583	-0.3009	-0.0792	-0.2371	0.1323	-0.18	0.2188	-0.3184	-0.2562	-0.03	-0.4232	0.253	-											
K	14	-0.241	-0.41	0.5181	-0.2718	-0.3343	-0.3247	-0.3304	0.2417	-0.1337	0.0858	0.1381	-0.4635	0.0121	-										
LRN	15	0.1603	0.2945	-0.2067	0.2849	0.6209	0.3099	0.6033	-0.0238	0.2489	-0.0784	-0.0004	0.1671	-0.1739	-0.4233	-									
MDR	16	0.141	0.0873	-0.0098	0.5596	0.9877	0.6577	0.9727	-0.0651	-0.3301	0.0164	-0.0809	0.1028	0.1079	-0.2851	0.6048	-								
MLAR	17	-0.1046	-0.0029	0.1524	0.6507	0.8679	0.7406	0.8638	-0.03	-0.4738	0.0501	-0.119	0.0091	0.1152	-0.0578	0.2404	0.8774	-							
MLLR	18	0.0666	-0.1045	-0.0508	-0.0498	0.1582	0.0959	0.109	-0.0141	0.0456	0.1165	0.2273	-0.0944	0.0658	-0.1516	0.3172	0.1609	-0.0138	-						
MLPR	19	-0.0216	0.0292	0.053	0.674	0.9635	0.7892	0.933	-0.0662	-0.3289	0.116	0.0347	-0.0074	0.006	-0.2854	0.5792	0.9502	0.8893	0.208	-					
MWR	20	-0.0479	-0.1804	0.1274	0.5224	0.5798	0.6137	0.4715	0.1432	-0.3856	0.4275	0.4832	-0.3956	-0.3456	-0.0623	0.3349	0.6079	0.6051	0.2119	0.7055	-				
Mg	21	-0.1832	-0.2759	-0.2049	0.0702	0.0666	0.0537	-0.0022	0.028	0.1581	0.5008	0.3627	-0.4284	-0.3319	0.0514	0.2606	0.0469	-0.0135	0.1167	0.1381	0.4788	-			
Mn	22	-0.2046	0.2493	0.1139	0.2573	0.2054	0.3469	0.1994	0.0925	0.262	-0.0384	0.0562	0.0327	-0.3367	-0.1974	0.3805	0.142	0.07	0.1792	0.2856	0.0008	-0.0619	-		
Mo	23	-0.1593	0.3511	-0.2229	0.1262	0.3904	0.2143	0.3779	-0.4657	-0.0402	-0.0963	0.0305	0.3736	0.0667	-0.4004	0.3576	0.3515	0.2087	0.0197	0.3532	0.1201	-0.0688	0.2168	-	
P	24	-0.1261	-0.2712	-0.0217	0.0026	0.0268	-0.0035	0.0465	-0.1737	0.1285	0.1712	0.0468	-0.2135	0.0494	0.24	0.1034	-0.0146	-0.0264	0.1	0.0877	-0.0445	0.2897	0.2002	0.2168	-
PEA_1001	25	-0.0459	-0.2044	0.4362	0.2959	0.0353	0.2539	-0.0821	0.333	-0.2439	0.3078	0.6467	-0.5209	-0.5342	0.1974	0.0101	0.0939	0.1417	0.1618	0.1708	0.7	0.269	-0.2186	-0.2105	-0.2138
PEA_1002	26	-0.4007	0.0704	0.283	0.4283	0.1336	0.3825	0.023	0.285	-0.0244	0.0843	0.3746	-0.3536	-0.6861	0.0682	0.2245	0.1379	0.1698	-0.1652	0.2392	0.5593	0.275	0.1814	0.001	-0.3407
PEA_251	27	0.0212	-0.3946	0.4011	0.0709	-0.1177	0.0649	-0.219	0.413	-0.2455	0.305	0.541	-0.5707	-0.2825	0.32	-0.1266	-0.0721	0.0167	0.2553	0.0139	0.591	0.2802	-0.3561	-0.3169	-0.0824
PEA_252	28	-0.3571	-0.2729	0.488	0.3916	-0.0583	0.2656	-0.1527	0.4238	-0.0848	0.2531	0.3323	-0.5298	-0.4121	0.2879	-0.232	-0.0736	0.1302	-0.2465	0.0389	0.4442	0.3222	-0.1163	-0.1938	-0.2224
PEA_301	29	0.0801	-0.3182	0.3941	0.1533	-0.0357	0.132	-0.106	0.3173	-0.1035	0.2093	0.4155	-0.455	-0.2385	0.1554	0.0298	-0.0038	0.0405	0.3008	0.0932	0.547	0.3102	-0.3007	-0.2749	-0.0331
PEA_302	30	0.2601	-0.2446	0.421	0.5023	0.3597	0.4403	0.3258	0.4225	-0.0736	0.1894	0.1612	-0.1937	0.1214	-0.1342	0.2251	0.3403	0.3248	0.1777	0.3789	0.3873	0.1649	0.0199	-0.1392	-0.215
PEA_501	31	-0.0566	-0.3475	0.4604	0.1371	-0.0964	0.1059	-0.2114	0.4225	-0.231	0.3067	0.6301	-0.6265	-0.4654	0.3836	-0.0913	-0.0458	0.0396	0.1951	0.0423	0.6177	0.3421	-0.2617	-0.3093	-0.0576
PEA_502	32	-0.4207	-0.1548	0.3878	0.4199	0.0826	0.331	-0.0358	0.29	-0.1549	0.1637	0.4225	-0.5105	-0.566	0.2236	0.0294	0.0789	0.2152	-0.1726	0.2066	0.6203	0.3514	-0.0382	-0.0892	-0.2535
PEA_751	33	-0.0667	-0.2462	0.4519	0.2556	-0.0102	0.2104	-0.1247	0.3837	-0.2246	0.306	0.6462	-0.5626	-0.5288	0.2854	-0.0018	0.0446	0.1066	0.1479	0.1283	0.676	0.3248	-0.2324	-0.2526	-0.1456
PEA_752	34	-0.4327	-0.0104	0.2638	0.4317	0.1234	0.3782	0.0056	0.2769	-0.1011	0.1068	0.3846	-0.4311	-0.686	0.1439	0.1591	0.1243	0.2119	-0.1735	0.2489	0.6207	0.3441	0.1139	-0.0297	-0.2507
PEA_951	35	0.0295	-0.2792	0.3664	0.1194	-0.0689	0.1393	-0.156	0.3516	-0.2062	0.2958	0.49	-0.4118	-0.2073	0.1655	-0.1045	-0.0332	0.0564	0.2974	0.0586	0.5899	0.2273	-0.3666	-0.2531	-0.2084
PEA_952	36	0.0418	-0.2761	0.4878	0.405	0.0981	0.3251	0.0501	0.5293	-0.0039	0.354	0.2874	-0.312	-0.0385	0.0632	-0.1059	0.0791	0.2162	-0.0132	0.1604	0.4029	0.2866	-0.1111	-0.2582	-0.24
PHT	37	-0.1003	0.4156	-0.3912	0.3385	0.2429	0.332	0.1786	0.0617	0.2908	-0.1166	0.1362	0.0576	-0.6772	-0.5357	0.5585	0.2093	0.0377	0.0782	0.3066	0.3381	0.3493	0.4634	0.3562	0.143
PRN	38	0.1689	-0.2397	-0.0163	-0.5183	-0.0634	-0.4038	-0.0501	-0.4209	-0.1435	0.2969	0.2144	-0.0672	0.3688	0.1985	0.0148	-0.0023	-0.1317	0.3633	-0.1117	0.0649	0.0962	-0.3462	0.1031	0.0687
RCH	39	0.0114	-0.1106	0.1215	0.5569	0.8049	0.6661	0.7189	0.0587	-0.4039	0.3111	0.3555	-0.2371	-0.1525	-0.1169	0.4651	0.8295	0.7815	0.2744	0.8736	0.9311	0.3461	0.0459	0.2182	-0.0359
Rb	40	-0.1607	0.5195	0.3214	0.0021	-0.2162	-0.0021	-0.2021	0.4345	0.6509	-0.0736	0.0801	0.2454	-0.4197	0.1848	0.1538	-0.2119	-0.2208	-0.0009	-0.1795	-0.2271	-0.2474	0.5324	-0.0751	-0.0521
S	41	0.2133	-0.1531	-0.2161	0.2523	0.4755	0.391	0.4404	-0.0106	-0.0963	0.3487	0.1639	-0.0994	0.0559	-0.1406	0.4575	0.492	0.3088	0.5367	0.5446	0.5434	0.3392	0.0785	0.2453	0.46
Se	42	-0.0152	-0.6225	0.1276	0.2026	0.3376	0.1566	0.2499	0.0331	-0.4742	0.1528	0.1043	-0.6579	-0.0036	0.1702	0.1571	0.3364	0.2608	0.3138	0.3515	0.4217	0.1958	-0.0069	0.1352	0.3998
Sr	43	0.1569	0.0876	0.657	0.271	-0.1086	0.1759	-0.0992	0.7918	0.2266	-0.0574	0.0312	-0.0558	-0.2006	0.3855	-0.186	-0.0729	0.0873	-0.1131	-0.0704	-0.0183	-0.2648	0.1084	-0.4797	-0.2069
TGW	44	0.2912	0.5144	-0.3738	-0.0871	-0.1088	-0.1047	-0.0077	-0.1115	0.3794	-0.2434	-0.3689	0.5909	0.0599	-0.4946	0.1002	-0.1053	-0.1999	-0.2935	-0.1879	-0.3228	-0.1594	-0.1432	-0.068	-0.3064
TLAR	45	0.0725	-0.0644	0.0619	0.4291	0.8814	0.5853	0.8564	-0.2055	-0.3559	0.2375	0.1226	-0.031	0.1526	-0.1893	0.5805	0.898	0.7773	0.356	0.9004	0.7154	0.1505	0.1183	0.3729	0.0954
TLLR	46	0.1329	0.1099	-0.2011	0.1656	0.4987	0.2733	0.4488	-0.084	0.1765	0.0566	0.197	0.0042	-0.1516	-0.4239	0.86	0.4754	0.1248	0.6963	0.5225	0.3933	0.3202	0.4623	0.3137	0.1791
TLPR	47	0.0718	-0.0663	0.0648	0.4287	0.8811	0.5845	0.8569	-0.2052	-0.3608	0.2375	0.1194	-0.0307	0.1573	-0.1833	0.5734	0.8984	0.7818	0.351	0.8996	0.7148	0.1475	0.1115	0.3698	0.0924
WDR	48	-0.1337	-0.2594	0.1726	0.2674	-0.0031	0.2926	-0.1167	0.2965	-0.2209	0.4801	0.5776	-0.5419	-0.5119	0.09	-0.025	0.0206	0.1123	0.0622	0.1644	0.7879	0.5613	-0.1484	-0.1271	-0.1213
Zn	49	-0.3522	-0.551	-0.0149	-0.0526	-0.1402	-0.0424	-0.1905	-0.1301	0.0127	0.5868	0.3449	-0.5529	-0.0605	0.2498	-0.1343	-0.1906	-0.1348	0.1816	-0.0355	0.1973	0.58	-0.0241	-0.0379	0.6854
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P

r values																										
PEA_1001	25	-																								
PEA_1002	26	0.601	-																							
PEA_251	27	0.8653	0.377	-																						
PEA_252	28	0.6161	0.7104	0.5568	-																					
PEA_301	29	0.7636	0.3285	0.9068	0.5014	-																				
PEA_302	30	0.3564	0.1661	0.3684	0.419	0.4942	-																			
PEA_501	31	0.9464	0.49	0.9444	0.6153	0.8169	0.3383	-																		
PEA_502	32	0.7381	0.9035	0.5937	0.8847	0.5395	0.3095	0.6819	-																	
PEA_751	33	0.9875	0.5884	0.8964	0.6327	0.782	0.3593	0.9781	0.7415	-																
PEA_752	34	0.6575	0.9741	0.4647	0.7636	0.4013	0.1656	0.5771	0.9553	0.6567	-															
PEA_951	35	0.8223	0.365	0.9616	0.563	0.9242	0.4371	0.8662	0.5847	0.8356	0.442	-														
PEA_952	36	0.4684	0.2849	0.5516	0.7172	0.595	0.8487	0.5024	0.51	0.4892	0.3212	0.6155	-													
PHT	37	0.09	0.4295	-0.0579	0.065	0.0443	-0.0822	-0.0044	0.2499	0.0665	0.4169	-0.05	-0.1015	-												
PRN	38	0.042	-0.3679	0.1824	-0.3195	0.1363	-0.1522	0.0881	-0.2901	0.0338	-0.3519	0.1801	-0.1764	-0.3836	-											
RCH	39	0.5326	0.4079	0.3982	0.2649	0.3841	0.4367	0.4318	0.451	0.4992	0.4523	0.4121	0.3323	0.2621	0.0965	-										
Rb	40	-0.0289	0.2802	-0.0671	0.0644	-0.0799	-0.1451	-0.0158	0.1049	-0.0121	0.2098	-0.0703	-0.0479	0.1968	-0.243	-0.2406	-									
S	41	0.1178	-0.0325	0.187	-0.1985	0.2282	0.055	0.123	-0.0833	0.115	-0.013	0.1696	-0.1156	0.2842	0.2161	0.5545	-0.2148	-								
Se	42	0.3486	0.0292	0.3257	0.1479	0.2228	0.1752	0.3762	0.1451	0.3476	0.0881	0.1899	0.0632	0.012	0.2002	0.4284	-0.3821	0.4699	-							
Sr	43	0.2849	0.227	0.3073	0.4563	0.3131	0.4471	0.3358	0.2918	0.3133	0.2229	0.3006	0.5423	-0.1848	-0.3756	-0.0288	0.5648	-0.269	-0.155	-						
TGW	44	-0.3833	-0.1318	-0.3387	-0.2232	-0.14	-0.1654	-0.4682	-0.2638	-0.4112	-0.2031	-0.1874	-0.132	0.2241	-0.1142	-0.3327	0.0773	-0.1927	-0.6714	-0.0555	-					
TLAR	45	0.2112	0.104	0.1358	-0.089	0.1994	0.3085	0.1059	0.0983	0.1659	0.1152	0.1805	0.0891	0.137	0.318	0.8759	-0.2338	0.6318	0.4121	-0.1961	-0.2101	-				
TLLR	46	0.0834	0.1208	0.0231	-0.2631	0.1715	0.2301	0.022	-0.0274	0.061	0.0754	0.0551	-0.0852	0.5321	0.1761	0.4801	0.0726	0.6203	0.2732	-0.2696	-0.0892	0.5874	-			
TLPR	47	0.2113	0.1017	0.137	-0.0871	0.1991	0.3087	0.1065	0.0985	0.1662	0.1139	0.1816	0.0915	0.1287	0.3201	0.8759	-0.2364	0.6274	0.411	-0.193	-0.211	0.9999	0.5785	-		
WDR	48	0.7977	0.6249	0.8031	0.6815	0.7183	0.2989	0.7979	0.7452	0.8091	0.7021	0.7941	0.5369	0.2794	0.0293	0.5248	-0.1286	0.2535	0.2353	0.0899	-0.2088	0.1976	0.0866	0.197	-	
Zn	49	0.1351	-0.1004	0.2798	0.1505	0.1781	-0.1667	0.2849	0.0676	0.1951	0.0016	0.1761	0.0451	0.0397	0.1897	0.0644	-0.2161	0.3722	0.4642	-0.3229	-0.3923	0.0246	0.0626	0.0224	0.3274	-
		25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.4 Table continued.

P values																																																		
As	1	-
BYD	2	0.7589	-
Ba	3	0.4062	0.2339	-
CHCRX	4	0.3887	0.6847	0.2349	-
CHCRY	5	0.7162	0.7819	0.8852	0.0037	-
CMRX	6	0.3968	0.5753	0.3005	<0.001	<0.001	-
CMRY	7	0.5972	0.578	0.8515	0.0062	<0.001	<0.001	-
Ca	8	0.1592	0.9745	0.1795	0.3801	0.6697	0.6357	0.5339	-
Cs	9	0.9703	0.0145	0.8431	0.8317	0.1457	0.5139	0.2144	0.3449	-
Cu	10	0.6905	0.164	0.3528	0.3118	0.964	0.202	0.8922	0.9022	0.5317	-
Fe	11	0.6619	0.6606	0.0799	0.7429	0.6114	0.586	0.3291	0.7183	0.7684	0.0042	-
GYD	12	0.2153	<0.001	0.0885	0.8155	0.6739	0.9527	0.3525	0.4113	0.0621	0.2057	0.1216	-
HI_%	13	0.2341	0.163	0.7193	0.276	0.5473	0.4111	0.3158	0.1387	0.2381	0.8921	0.0442	0.2441	-
K	14	0.2679	0.052	0.0113	0.2096	0.119	0.1306	0.1237	0.2666	0.5429	0.697	0.5297	0.0259	0.9564	-
LRN	15	0.4649	0.1726	0.3439	0.1877	0.0016	0.1501	0.0023	0.9143	0.2521	0.7221	0.9984	0.4462	0.4275	0.0441	-
MDR	16	0.521	0.6919	0.9645	0.0055	<0.001	<0.001	<0.001	0.7681	0.124	0.9407	0.7138	0.6408	0.6243	0.1874	0.0022	-
MLAR	17	0.6348	0.9896	0.4876	<0.001	<0.001	<0.001	<0.001	0.8918	0.0224	0.8204	0.5886	0.9673	0.6006	0.7932	0.2692	<0.001	-
MLLR	18	0.7627	0.635	0.8179	0.8215	0.4709	0.6634	0.6206	0.9491	0.8362	0.5965	0.297	0.6684	0.7656	0.4899	0.1403	0.4634	0.9503	-
MLPR	19	0.9221	0.8948	0.8103	<0.001	<0.001	<0.001	<0.001	0.7641	0.1254	0.5983	0.8749	0.9732	0.9784	0.1868	0.0038	<0.001	<0.001	0.341	-
MWR	20	0.8281	0.41	0.5625	0.0105	0.0037	0.0018	0.0231	0.5144	0.0692	0.0419	0.0195	0.0617	0.1063	0.7775	0.1183	0.0021	0.0022	0.3318	<0.001	-
Mg	21	0.4027	0.2025	0.3483	0.7501	0.7629	0.8077	0.9921	0.8991	0.4713	0.0149	0.0889	0.0414	0.1218	0.8158	0.2298	0.8316	0.9511	0.5958	0.5297	0.0208	-
Mn	22	0.3489	0.2513	0.6047	0.2358	0.3471	0.1048	0.3616	0.6747	0.2272	0.8619	0.7989	0.8823	0.1162	0.3667	0.0733	0.5181	0.7509	0.4133	0.1864	0.9973	0.7792	-
Mo	23	0.4677	0.1005	0.3065	0.5662	0.0655	0.3262	0.0754	0.0251	0.8554	0.6622	0.8902	0.0791	0.7622	0.0583	0.0939	0.1001	0.3392	0.9289	0.0983	0.5852	0.7553	0.3203	-
P	24	0.5664	0.2106	0.9216	0.9906	0.9036	0.9873	0.8333	0.428	0.5589	0.4349	0.832	0.3281	0.8229	0.2699	0.6388	0.9473	0.9047	0.65	0.6905	0.8401	0.18	0.3597	0.3204	-
PEA_1001	25	0.8352	0.3494	0.0374	0.1704	0.8731	0.2424	0.7096	0.1205	0.262	0.1531	<0.001	0.0108	0.0086	0.3665	0.9635	0.67	0.5188	0.4608	0.4359	<0.001	0.2145	0.3163	0.3351	0.3274	-
PEA_1002	26	0.0581	0.7496	0.1908	0.0415	0.5432	0.0716	0.9171	0.1875	0.9121	0.702	0.0782	0.0979	<0.001	0.7573	0.303	0.5303	0.4385	0.4512	0.2716	0.0055	0.2041	0.4075	0.9965	0.1117	0.0024	-
PEA_251	27	0.9237	0.0624	0.0578	0.7477	0.5928	0.7686	0.3154	0.0501	0.2588	0.1571	0.0077	0.0045	0.1915	0.1366	0.565	0.7437	0.9396	0.2398	0.9498	0.003	0.1953	0.0954	0.1407	0.7085	<0.001	0.0762	-
PEA_252	28	0.0944	0.2077	0.0182	0.0646	0.7918	0.2206	0.4868	0.0439	0.7005	0.2439	0.1213	0.0093	0.0507	0.1828	0.2867	0.7387	0.5536	0.2569	0.8601	0.0337	0.1338	0.5973	0.3755	0.3077	0.0017	<0.001	0.0058	-
PEA_301	29	0.7163	0.1389	0.0628	0.4849	0.8714	0.5482	0.6302	0.1402	0.6386	0.3378	0.0487	0.0292	0.2731	0.479	0.8928	0.9863	0.8544	0.1631	0.6724	0.0069	0.1497	0.1632	0.2042	0.8809	<0.001	0.1259	<0.001	0.0148	-
PEA_302	30	0.2307	0.2606	0.0454	0.0146	0.0919	0.0355	0.1293	0.0446	0.7386	0.3868	0.4625	0.3758	0.5811	0.5414	0.3018	0.1121	0.1304	0.4174	0.0746	0.0679	0.452	0.9281	0.5266	0.3246	0.0951	0.4488	0.0837	0.0466	0.0165	-
PEA_501	31	0.7974	0.1042	0.0271	0.5327	0.6618	0.6306	0.3329	0.0446	0.2889	0.1546	0.0013	0.0014	0.0252	0.0708	0.6786	0.8356	0.8578	0.3723	0.8479	0.0017	0.11	0.2278	0.151	0.7939	<0.001	0.0176	<0.001	0.0018	<0.001	0.1143	-
PEA_502	32	0.0456	0.4807	0.0675	0.0461	0.708	0.1229	0.8713	0.1794	0.4804	0.4555	0.0446	0.0128	0.0049	0.305	0.8941	0.7204	0.324	0.4311	0.3441	0.0016	0.1002	0.8625	0.6855	0.2432	<0.001	<0.001	0.0028	<0.001	0.0079	0.1507	<0.001	-
PEA_751	33	0.7624	0.2574	0.0304	0.2392	0.9632	0.3352	0.5707	0.0707	0.3029	0.1557	<0.001	0.0052	0.0095	0.1868	0.9934	0.8399	0.6284	0.5008	0.5595	<0.001	0.1305	0.2858	0.2448	0.5075	<0.001	0.0031	<0.001	0.0012	<0.001	0.0922	<0.001	<0.001	-
PEA_752	34	0.0392	0.9624	0.2239	0.0397	0.5749	0.0752	0.9799	0.2009	0.6463	0.6276	0.07	0.04	<0.001	0.5124	0.4684	0.572	0.3318	0.4285	0.2521	0.0016	0.1079	0.6047	0.8929	0.2485	<0.001	<0.001	0.0255	<0.001	0.0577	0.4501	0.0039	<0.001	<0.001	-
PEA_951	35	0.8939	0.197	0.0855	0.5874	0.7547	0.5261	0.4773	0.0999	0.3452	0.1705	0.0176	0.0509	0.3426	0.4505	0.6353	0.8806	0.7981	0.1682	0.7905	0.003	0.297	0.0853	0.244	0.34	<0.001	0.0868	<0.001	0.0052	<0.001	0.037	<0.001	0.0034	<0.001	0.0347	-
PEA_952	36	0.85	0.2023	0.0182	0.0552	0.6561	0.1302	0.8205	0.0094	0.986	0.0975	0.1835	0.1472	0.8615	0.7745	0.6304	0.7197	0.3217	0.9523	0.4648	0.0566	0.1849	0.6138	0.2342	0.27	0.0242	0.1877	0.0064	<0.001	0.0027	<0.001	0.0146	0.0129	0.0178	0.1351	0.0018	-
PHT	37	0.6488	0.0486	0.0649	0.1142	0.2641	0.1217	0.4149	0.7796	0.1783	0.5964	0.5355	0.7942	<0.001	0.0084	0.0056	0.3378	0.8644	0.7227	0.1548	0.1146	0.1023	0.026	0.0953	0.5151	0.683	0.0408	0.793	0.7684	0.8411	0.7092	0.984	0.2501	0.7631	0.0478	0.8207	0.6449	-
PRN	38	0.441	0.2706	0.9413	0.0113	0.7737	0.056	0.8205	0.0455	0.5137	0.1689	0.3259	0.7606	0.0833	0.3638	0.9465	0.9916	0.5491	0.0884	0.6118	0.7686	0.6623	0.1056	0.6397	0.7555	0.8491	0.0841	0.4048	0.1373	0.5351	0.4883	0.6894	0.1794	0.8785	0.0996	0.411	0.4209	0.0708	-
RCH	39	0.9587	0.6154	0.5809	0.0058	<0.001	<0.001	<0.001	0.7902	0.056	0.1484	0.096	0.2759	0.4872	0.5953	0.0253	<0.001	<0.001	0.2052	<0.001	<0.001	0.1057	0.8354	0.3173	0.871	0.0089	0.0533	0.0598	0.2219	0.0704	0.0372	0.0396	0.0308	0.0153	0.0302	0.0507	0.1214	0.2269	0.6612	-
Rb	40	0.4638	0.0111	0.1348	0.9925	0.3217	0.9925	0.3551	0.0383	<0.001	0.7385	0.7162	0.2591	0.0462	0.3986	0.4834	0.3317	0.3113	0.9968	0.4124	0.2974	0.2551	0.0089	0.7333	0.8133	0.8959	0.1953	0.7611	0.7703	0.7169	0.5089	0.9429	0.6337	0.9563	0.3367	0.75	0.8282	0.368	0.2639	0.2687	-
S	41	0.3284	0.4856	0.322	0.2455	0.0218	0.0651	0.0355	0.9617	0.662	0.1029	0.4548	0.6518	0.8001	0.5222	0.0282	0.0171	0.1517	0.0083	0.0072	0.0074	0.1134	0.7218	0.2593	0.0272	0.5924	0.883	0.3929	0.3638	0.2951	0.8032	0.576	0.7055	0.6013	0.9529	0.4391	0.5995	0.1888	0.322	0.006	0.325	-
Se	42	0.9451	0.0015	0.5619	0.3538	0.1152	0.4755	0.2501	0.8807	0.0223	0.4865	0.6359	<0.001	0.9869	0.4374	0.4742	0.1165	0.2294	0.1448	0.1	0.045	0.3706	0.9752	0.5385	0.0588	0.103	0.8949	0.1293	0.5006	0.3069	0.424	0.0769	0.509	0.1041	0.6894	0.3855	0.7746	0.9567	0.3597	0.0414	0.072	0.0237	-
Sr	43	0.4748	0.6909	<0.001	0.2109	0.6217	0.422	0.6523	<0.001	0.2986	0.7947	0.8875	0.8004	0.3588	0.0693	0.3955	0.7411	0.692	0.6075	0.7496	0.9339	0.2221	0.6225	0.0205	0.3435	0.1876	0.2976	0.1538	0.0286	0.1458	0.0324	0.1172	0.1767	0.1455	0.3066	0.1634	0.0075	0.3985	0.0774	0.8962	0.005	0.2145	0.48	-
TGW	44	0.1777	0.012	0.0789	0.6928	0.6213	0.6346	0.9721	0.6125	0.0742	0.263	0.0833	0.003	0.786	0.0164	0.6492	0.6324	0.3605	0.1741	0.3905	0.1331	0.4676	0.5145	0.758	0.155	0.071	0.5489	0.1139	0.306	0.5239	0.4508	0.0243	0.2239	0.0512	0.3527	0.3919	0.5482	0.304	0.6039	0.1209	0.726	0.3785	<0.001	0.8013	-
TLAR	45	0.7422	0.7703	0.7792	0.041	<0.001	0.0033	<0.001	0.3469	0.0956	0.2752	0.5773	0.8883	0.487	0.3869	0.0037	<0.001	<0.001	0.0954	<0.001	<0.001	0.493	0.5908	0.0797	0.6649	0.3334	0.6368	0.5366	0.6864	0.3617	0.1521	0.6307	0.6553	0.4494	0.6006	0.41	0.6859	0.5332	0.1393	<0.001	0.2829	0.0012	0.0507	0.3698	0.3359	-
TLLR	46	0.5454	0.6177	0.3576	0.45	0.0154	0.207	0.0317	0.7032	0.4204	0.7974	0.3677	0.9847	0.4898	0.0438	<0.001	0.0219	0.5706	<0.001	0.0105	0.0633	0.1364	0.0264	0.1449	0.4136	0.7052	0.583	0.9168	0.2251	0.434	0.2909	0.9206	0.9012	0.7822	0.7324	0.8029	0.699	0.009	0.4215	0.0204	0.7421	0.0016	0.2072	0.2135	0.6857	0.0032	-
TLPR	47	0.7448	0.7639	0.7691	0.0413	<0.001	0.0034	<0.001	0.3475	0.0908	0.2751	0.5873	0.8895	0.4734	0.4025	0.0042	<0.001	<0.001	0.1005	<0.001	<0.001	0.5018	0.6124	0.0824	0.6749	0.3331	0.6442	0.5331	0.6929	0.3625	0.1518	0.6286	0.6547	0.4486	0.605	0.407	0.6779	0.5585	0.1365	<0.001	0.2774	0.0014	0.0514	0.3776	0.3339	<0.001	0.0038	-
WDR	48	0.5432	0.2319	0.4309	0.2173	0.9888	0.1755	0.596	0.1695	0.3111	0.0204	0.0039	0.0076	0.0125	0.683	0.9098	0.9258	0.6099	0.7781	0.4535	<0.001	0.0053	0.4992	0.5633	0.5814	<0.001	0.0014	<0.001	<0.001	<0.001	0.1659	<0.001	<0.001	<0.001	<0.001	<0.001	0.0083	0.1967	0.8945	0.0101	0.5587	0.2432	0.2799	0.6832	0.339	0.3662	0.6944	0.3676	-
Zn	49	0.0993	0.0064	0.9462	0.8118	0.5235	0.8476	0.3838	0.5542	0.9543	0.0033	0.1071	0.0062	0.7841	0.2504	0.5412	0.3837	0.5397	0.4069	0.8723	0.367	0.0037	0.913	0.8637	<0.001	0.5388	0.6485	0.196	0.4932	0.4161	0.4471	0.1877	0.7593	0.3722	0.9943	0.4215	0.8381	0.8574	0.3861	0.7704	0.3219	0.0803	0.0257	0.1329	0.0641	0.9112	0.7767	0.9192	0.1272	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.5 Table Correlation coefficients between seedling root traits and grain yield, yield components and grain mineral composition traits of 36 Indian wheat genotypes at Kumarganj-sodic site. Seedling root traits data are mean of ~20 replications, yield & yield component traits data are mean of two replication per plot per genotypes over two years at Kumarganj-sodic and mineral elements data are mean of one replicates per plot in 2013-14 and two replicates per plot per genotype in 2014-15 at Kumarganj-sodic site.

r values																																																		
As	1	-																																																
BYD	2	-0.3674	-																																															
Ba	3	-0.2562	-0.273	-																																												
CHCRX	4	-0.0684	0.1022	0.0836	-																																										
CHCRY	5	0.0953	0.2263	0.1475	0.5797	-																																									
CMRX	6	-0.0421	0.1516	0.0787	0.9302	0.6767	-																																								
CMRY	7	0.1059	0.2236	0.173	0.5529	0.9823	0.6498	-																																							
Ca	8	-0.3505	0.352	0.3184	0.0697	0.1288	-0.0154	0.1459	-																																						
Cs	9	0.3415	0.0519	0.2276	0.1045	0.2164	0.0689	0.2346	0.0879	-																																					
Cu	10	0.0234	0.2798	-0.2858	0.193	-0.0376	0.1189	-0.025	0.3639	0.2124	-																																				
Fe	11	0.198	-0.0212	-0.2037	-0.063	0.0261	-0.0278	-0.0161	0.1163	0.0123	0.4085	-																																			
GYD	12	-0.3275	0.8831	-0.1802	-0.0403	0.2647	0.0381	0.2504	0.2661	0.1175	0.1728	-0.0806	-																																		
HI_%	13	0.0246	0.0878	-0.0187	-0.2458	0.1328	-0.1558	0.1192	-0.1278	0.1637	-0.0908	-0.0579	0.5279	-																																	
K	14	-0.1029	0.0852	0.0165	-0.1025	-0.0205	-0.0757	-0.0132	0.5896	0.0548	0.5482	0.3332	-0.0756	-0.3542	-																																
LRN	15	0.0473	0.5209	-0.1459	0.2849	0.6209	0.3099	0.6033	0.1636	0.1682	0.0238	0.0768	0.457	-0.0032	-0.0269	-																															
MDR	16	0.0568	0.2392	0.1767	0.5596	0.9877	0.6577	0.9727	0.1788	0.2082	-0.0316	0.0281	0.2785	0.1403	-0.0162	0.6048	-																														
MLAR	17	0.014	0.0246	0.2571	0.6507	0.8679	0.7406	0.8638	0.1866	0.1137	0.0046	0.0913	0.0573	0.0869	0.072	0.2404	0.8774	-																													
MLLR	18	-0.1764	0.256	-0.0241	-0.0498	0.1582	0.0959	0.109	0.0105	-0.2176	0.007	-0.0134	0.3285	0.1663	0.0717	0.3172	0.1609	-0.0138	-																												
MLPR	19	0.0178	0.1917	0.1486	0.674	0.9635	0.7892	0.933	0.0937	0.1282	-0.0017	0.0856	0.1912	0.0453	0.0342	0.5792	0.9502	0.8893	0.208	-																											
MWR	20	-0.1241	0.0502	0.128	0.5224	0.5798	0.6137	0.4715	0.0869	0.0148	0.0758	0.2681	0.0922	0.0919	0.0266	0.3349	0.6079	0.6051	0.2119	0.7055	-																										
Mg	21	0.1956	0.2143	-0.0599	0.0397	0.2429	0.0022	0.2755	0.4904	0.3699	0.6465	0.5726	0.1343	-0.0544	0.5286	0.3604	0.236	0.1724	0.0113	0.2369	0.1692	-																									
Mn	22	-0.3588	0.5203	0.0657	0.0293	0.2235	0.0863	0.267	0.6693	-0.0885	0.3918	0.1455	0.2987	-0.3361	0.7075	0.3367	0.2698	0.1958	0.1645	0.2604	0.1479	0.5067	-																								
Mo	23	0.4893	-0.1501	-0.3844	0.0813	0.0144	-0.0073	0.0228	-0.3199	0.3364	0.1955	0.4349	-0.2145	-0.0815	-0.1909	0.0177	-0.041	-0.0432	-0.4136	-0.0601	-0.2269	0.223	-0.4272	-																							
P	24	0.0215	0.3058	-0.1868	-0.0554	0.0432	-0.0686	0.0886	0.5417	0.2699	0.6759	0.3842	0.1072	-0.2945	0.8145	0.2102	0.0552	0.0161	0.0302	0.0524	-0.0316	0.7607	0.7593	0.0505	-																						
PEA_1001	25	-0.3215	-0.0766	0.2449	0.2959	0.0353	0.2539	-0.0821	0.0652	-0.201	-0.2014	0.0618	-0.0122	0.082	-0.2457	0.0101	0.0939	0.1417	0.1618	0.1708	0.7	-0.1856	-0.1086	-0.3853	-0.344	-																					
PEA_1002	26	-0.3822	0.3035	-0.0395	0.4283	0.1336	0.3825	0.023	0.137	-0.1313	0.0439	0.3175	0.2314	-0.0629	-0.098	0.2245	0.1379	0.1698	-0.1652	0.2392	0.5593	-0.0763	0.0268	0.0016	-0.1741	0.601	-																				
PEA_251	27	-0.3277	-0.2749	0.2529	0.0709	-0.1177	0.0649	-0.219	0.0398	-0.2095	-0.256	-0.0301	-0.1332	0.1675	-0.1238	-0.1266	-0.0721	0.0167	0.2553	0.0139	0.591	-0.2391	-0.164	-0.5105	-0.3178	0.8653	0.377	-																			
PEA_252	28	-0.3266	-0.142	0.3408	0.3916	-0.0583	0.2656	-0.1527	0.1336	0.0731	0.0481	0.1415	-0.0807	0.0434	-0.1091	-0.232	-0.0736	0.1302	-0.2465	0.0389	0.4442	-0.1039	-0.2383	-0.0532	-0.2633	0.6161	0.7104	0.5568	-																		
PEA_301	29	-0.2883	-0.2378	0.2712	0.1533	-0.0357	0.132	-0.106	-0.0561	-0.0547	-0.2381	0.018	-0.107	0.1773	-0.2347	0.0298	-0.0038	0.0405	0.3008	0.0932	0.547	-0.1255	-0.2117	-0.3886	-0.315	0.7636	0.3285	0.9068	0.5014	-																	
PEA_302	30	-0.0902	-0.1053	0.5106	0.5023	0.3597	0.4403	0.3258	0.12	0.1527	-0.1396	-0.2058	-0.1015	-0.0671	-0.1892	0.2251	0.3403	0.3248	0.1777	0.3789	0.3873	-0.0067	-0.1215	-0.2594	-0.294	0.3564	0.1661	0.3684	0.419	0.4942	-																
PEA_501	31	-0.2932	-0.1941	0.3135	0.1371	-0.0964	0.1059	-0.2114	0.1407	-0.1601	-0.2174	0.0394	-0.0939	0.0931	-0.0863	-0.0913	-0.0458	0.0396	0.1951	0.0423	0.6177	-0.17	-0.1041	-0.4826	-0.2796	0.9464	0.49	0.9444	0.6153	0.8169	0.3383	-															
PEA_502	32	-0.3215	-0.0212	0.1449	0.4199	0.0826	0.331	-0.0358	0.1077	-0.123	-0.0072	0.3418	0.0017	0.019	-0.1128	0.0294	0.0789	0.2152	-0.1726	0.2066	0.6203	-0.0586	-0.138	-0.0319	-0.2563	0.7381	0.9035	0.5937	0.8847	0.5395	0.3095	0.6819	-														
PEA_751	33	-0.3144	-0.1119	0.287	0.2556	-0.0102	0.2104	-0.1247	0.14	-0.1832	-0.1984	0.061	-0.046	0.061	-0.1673	-0.0018	0.0446	0.1066	0.1479	0.1283	0.676	-0.1556	-0.0835	-0.422	-0.3031	0.9875	0.5884	0.8964	0.6327	0.782	0.3593	0.9781	0.7415	-													
PEA_752	34	-0.2893	0.1596	-0.0296	0.4317	0.1234	0.3782	0.0056	0.137	-0.1358	0.0687	0.4081	0.113	-0.0525	-0.0374	0.1591	0.1243	0.2119	-0.1735	0.2489	0.6207	-0.011	-0.0023	0.0082	-0.1372	0.6575	0.9741	0.4647	0.7636	0.4013	0.1656	0.5771	0.9553	0.6567	-												
PEA_951	35	-0.3309	-0.2716	0.2507	0.1194	-0.0689	0.1393	-0.156	-0.0527	-0.2292	-0.2767	0.0024	-0.1122	0.236	-0.2579	-0.1045	-0.0332	0.0564	0.2974	0.0586	0.5899	-0.2479	-0.2365	-0.4346	-0.3892	0.8223	0.365	0.9616	0.563	0.9242	0.4371	0.8662	0.5847	0.8356	0.442	-											
PEA_952	36	-0.2175	-0.274	0.5298	0.405	0.0981	0.3251	0.0501	0.0869	0.157	-0.1002	-0.1476	-0.221	-0.0143	-0.1699	-0.1059	0.0791	0.2162	-0.0132	0.1604	0.4029	-0.0611	-0.2499	-0.2141	-0.3244	0.4684	0.2849	0.5516	0.7172	0.595	0.8487	0.5024	0.51	0.4892	0.3212	0.6155	-										
PHT	37	-0.1275	0.432	-0.3784	0.3365	0.1007	0.2717	0.0274	0.1449	0.0445	0.2856	0.3311	0.2382	-0.2557	0.026	0.309	0.0996	0.0418	0.2753	0.1774	0.2974	0.2932	0.131	0.2051	0.2133	0.2694	0.4247	0.1107	0.1858	0.2037	0.0046	0.1837	0.3096	0.2378	0.4143	0.1025	0.0272	-												
PRN	38	0.0063	-0.0511	0.1287	-0.5183	-0.0634	-0.4038	-0.0501	-0.1058	-0.0546	-0.0252	-0.0141	0.1646	0.3718	0.002	0.0148	-0.0023	-0.1317	0.3633	-0.1117	0.0649	-0.0094	0.0818	-0.2995	0.0155	0.042	-0.3679	0.1824	-0.3195	0.1363	-0.1522	0.0881	-0.2901	0.0338	-0.3519	0.1801	-0.1764	-0.3889	-										
RCH	39	-0.0491	0.0729	0.2195	0.5569	0.8049	0.6661	0.7189	0.1306	0.0587	-0.0045	0.2079	0.1355	0.1189	0.0191	0.4651	0.8295	0.7815	0.2744	0.8736	0.9311	0.1885	0.1839	-0.1934	-0.0412	0.5326	0.4079	0.3982	0.2649	0.3841	0.4367	0.4318	0.451	0.4992	0.4523	0.4121	0.3323	0.2108	0.0965	-										
Rb	40	-0.4121	0.5436	-0.1045	0.0179	0.1341	0.0192	0.1352	0.6914	-0.0572	0.3841	0.0065	0.4387	-0.047	0.6518	0.3131	0.1788	0.103	0.1481	0.1445	0.1709	0.3684	0.8109	-0.4858	0.6618	0.036	0.1335	0.0538	-0.0932	-0.0717	-0.0575	0.0772	-0.0019	0.0731	0.1104	-0.0496	-0.1412	0.0671	0.0563	0.1519	-									
S	41	0.1103	0.2972	-0.3584	0.0361	0.2692	0.0205	0.2722	0.3652	0.1914	0.6765	0.5769	0.1792	-0.1056	0.631	0.3725	0.2502	0.1551	0.1275	0.2717	0.1226	0.8569	0.5332	0.2986	0.8052	-0.294	-0.0619	-0.3559	-0.2634	-0.2918	-0.2453	-0.3068	-0.1311	-0.292	-0.0211	-0.393	-0.3422	0.3824	-0.0745	0.1609	0.4529	-								
Se	42	0.4183	0.0052	-0.2306	0.0222	0.0212	0.0756	0.0232	-0.107	0.428	0.5766	0.1811	-0.0991	-0.1922	0.2804	0.0133	0.0464	-0.0578	0.0546	0.0276	0.0831	0.3559	0.137	0.2146	0.4056	-0.2558	-0.2493	-0.2709	-0.2659	-0.2239	-0.1148	-0.2675	-0.3477	-0.2815	-0.2501	-0.3064	-0.1541	0.1966	0.0896	0.0471	-0.0202	0.3907	-							
Sr	43	-0.1095	-0.1174	0.6717	0.0808	0.0447	-0.0317	0.0926	0.6546	0.3671	0.0549	-0.027	-0.0908	-0.0805	0.1875	-0.1024	0.0626	0.1593	-0.222	-0.0286	-0.1323	0.2306	0.1143	-0.001	0.1276	-0.0534	-0.0263	-0.0364	0.3048	-0.039	0.2275	0.0483	0.0794	0.026	-0.0112	-0.0538	0.3342	-0.0594	-0.1769	-0.0343	0.005	-0.0533	-0.1498	-						
TGW	44	0.1077	-0.002	-0.1908	-0.2799	-0.3538	-0.258	-0.3902	-0.3004	-0.1085	-0.3399	-0.3262	0.1197	0.2847	-0.4364	-0.2252	-0.3503	-0.3257	-0.0664	-0.3789	-0.1195	-0.4632	-0.5103	-0.1501	-0.5858	0.1726	0.0573	0.2844	0.0482	0.2365	0.0863	0.2318	0.0444	0.1868	0.023	0.2463	0.1404	-0.0633	0.0869	-0.2282	-0.2494	-0.5447	-0.1326	-0.2656	-					
TLAR	45	-0.0192	0.1727	0.1665	0.4291	0.8814	0.5853	0.8564	0.0264	0.0797	-0.0325	0.0531	0.2697	0.2254	0.0087	0.5805	0.898	0.7773	0.356	0.9004	0.7154	0.1873	0.2752	-0.2124	0.0368	0.2112	0.104	0.1358	-0.089	0.1994	0.3085	0.1059	0.0983	0.1659	0.1152	0.1805	0.0891	0.0008	0.318	0.8759	0.1934	0.203	0.0367	-0.1476	-0.2951	-				
TLLR	46	-0.0124	0.47	-0.1616	0.1656	0.4987	0.2733	0.4488	0.0053	0.0252	0.0549	0.1322	0.4272	0.0038	0.0529	0.86	0.4754	0.1248	0.6963	0.5225	0.3933	0.2948	0.3225	-0.1461	0.1918	0.0834	0.1208	0.0231	-0.2631	0.1715	0.2301	0.022	-0.0274	0.061	0.0754	0.0551	-0.0852	0.3854	0.1761	0.4801	0.2464	0.3835	0.145	-0.3061	-0.2089	0.5874	-			
TLPR	47	-0.0197	0.1682	0.1708	0.4287	0.8811	0.5845	0.8569	0.0293	0.0793	-0.0326	0.0527	0.2668	0.2279	0.0095	0.5734	0.8984	0.7818	0.351	0.8996	0.7148	0.1864	0.2744	-0.2135	0.0357	0.2113	0.1017	0.137	-0.0871	0.1991	0.3087	0.1065	0.0985	0.1662	0.1139	0.1816	0.0915	-0.0047	0.3201	0.8759	0.1933	0.2002	0.0341	-0.1429	-0.2942	0.9999	0.5785	-		
WDR	48	-0.22	-0.0808	0.0624	0.2674	-0.0031	0.2926	-0.1167	0.0196	-0.063	0.0975	0.263	-0.0553	0.0376	-0.0202	-0.025	0.0206	0.1123	0.0622	0.1644	0.7879	0.042	-0.035	-0.2377	-0.0962	0.7977	0.6249	0.8031	0.6815	0.7183	0.2989	0.7979	0.7452	0.8091	0.7021	0.7941	0.5369	0.3047	0.0293	0.5248	0.0796	-0.0898	0.0238	-0.1273	0.1505	0.1976	0.0866	0.197	-	
Zn	49	-0.0875	0.3353	-0.3024	-0.0143	-0.0029	0.0252	0.0362	0.4361	0.0886	0.689	0.4113	0.1393	-0.2586	0.7147	0.167	0.0207	0.0346	-0.0178	0.0599	0.1431	0.6504	0.7487	-0.0386	0.887	-0.2127	0.0309	-0.1477	-0.1344	-0.1615	-0.3292	-0.1705	-0.082	-0.1785	0.064	-0.185	-0.2563	0.2556	0.0642	0.0402	0.6425	0.6682	0.4037	-0.0188	-0.4312	0.085	0.1593	0.0844	0.1734	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.5 Table continued.

P values																																																		
As	1	-																																															
BYD	2	0.0846	-																																														
Ba	3	0.2379	0.2075	-																																													
CHCRX	4	0.7566	0.6426	0.7045	-																																												
CHCRY	5	0.6655	0.2992	0.5017	0.0037	-																																											
CMRX	6	0.8488	0.49	0.7211	<0.001	<0.001	-																																										
CMRY	7	0.6306	0.3051	0.4298	0.0062	<0.001	<0.001	-																																									
Ca	8	0.101	0.0995	0.1387	0.752	0.5582	0.9443	0.5064	-																																								
Cs	9	0.1107	0.814	0.2963	0.6352	0.3212	0.7547	0.2813	0.6901	-																																							
Cu	10	0.9157	0.196	0.1862	0.3776	0.8648	0.5888	0.9099	0.0879	0.3305	-																																						
Fe	11	0.3652	0.9233	0.3513	0.7752	0.9057	0.8997	0.9417	0.5971	0.9556	0.053	-																																					
GYD	12	0.1272	<0.001	0.4107	0.8552	0.2223	0.8631	0.2493	0.2197	0.5933	0.4305	0.7147	-																																				
HI_%	13	0.9114	0.6904	0.9327	0.2582	0.5459	0.4777	0.5879	0.5612	0.4554	0.6803	0.793	0.0096	-																																			
K	14	0.6403	0.6992	0.9406	0.6416	0.9259	0.7315	0.9522	0.0031	0.8039	0.0068	0.1203	0.7316	0.0972	-																																		
LRN	15	0.8303	0.0108	0.5065	0.1877	0.0016	0.1501	0.0023	0.4558	0.443	0.9141	0.7276	0.0283	0.9884	0.9032	-																																	
MDR	16	0.7967	0.2717	0.42	0.0055	<0.001	<0.001	<0.001	0.4144	0.3403	0.8862	0.8986	0.1982	0.5232	0.9415	0.0022	-																																
MLAR	17	0.9496	0.9113	0.2363	<0.001	<0.001	<0.001	<0.001	0.3938	0.6054	0.9833	0.6786	0.7953	0.6934	0.744	0.2692	<0.001	-																															
MLLR	18	0.4207	0.2385	0.913	0.8215	0.4709	0.6634	0.6206	0.962	0.3187	0.9748	0.9516	0.1259	0.4482	0.745	0.1403	0.4634	0.9503	-																														
MLPR	19	0.9357	0.381	0.4987	<0.001	<0.001	<0.001	<0.001	0.6707	0.56	0.9939	0.6977	0.3823	0.8375	0.877	0.0038	<0.001	<0.001	0.341	-																													
MWR	20	0.5727	0.82	0.5605	0.0105	0.0037	0.0018	0.0231	0.6933	0.9465	0.7311	0.2161	0.6755	0.6767	0.9043	0.1183	0.0021	0.0022	0.3318	<0.001	-																												
Mg	21	0.371	0.3262	0.786	0.8571	0.2641	0.9922	0.2032	0.0175	0.0823	<0.001	0.0043	0.5412	0.8054	0.0095	0.0912	0.2784	0.4314	0.9591	0.2765	0.4403	-																											
Mn	22	0.0927	0.0109	0.7659	0.8943	0.3053	0.6954	0.2181	<0.001	0.6879	0.0644	0.5078	0.1662	0.1169	<0.001	0.1161	0.2132	0.3705	0.4533	0.2302	0.5008	0.0136	-																										
Mo	23	0.0178	0.4941	0.0702	0.7124	0.9481	0.9736	0.9177	0.1367	0.1165	0.3715	0.0381	0.3258	0.7117	0.3829	0.9363	0.8528	0.8448	0.0498	0.7854	0.2977	0.3065	0.042	-																									
P	24	0.9225	0.1559	0.3935	0.8016	0.845	0.7559	0.6878	0.0076	0.2129	<0.001	0.0703	0.6265	0.1725	<0.001	0.3357	0.8026	0.9417	0.8913	0.8122	0.8862	<0.001	<0.001	0.8189	-																								
PEA_1001	25	0.1347	0.7284	0.2601	0.1704	0.8731	0.2424	0.7096	0.7674	0.3578	0.3567	0.7794	0.9561	0.7099	0.2585	0.9635	0.67	0.5188	0.4608	0.4359	<0.001	0.3965	0.6219	0.0695	0.108	-																							
PEA_1002	26	0.0719	0.1591	0.8581	0.0415	0.5432	0.0716	0.9171	0.5331	0.5505	0.8423	0.1398	0.288	0.7757	0.6563	0.303	0.5303	0.4385	0.4512	0.2716	0.0055	0.7293	0.9033	0.9943	0.427	0.0024	-																						
PEA_251	27	0.1269	0.2043	0.2444	0.7477	0.5928	0.7686	0.3154	0.857	0.3373	0.2383	0.8917	0.5444	0.4448	0.5737	0.565	0.7437	0.9396	0.2398	0.9498	0.003	0.2719	0.4545	0.0128	0.1395	<0.001	0.0762	-																					
PEA_252	28	0.1282	0.5182	0.1115	0.0646	0.7918	0.2206	0.4868	0.5433	0.7403	0.8274	0.5196	0.7142	0.8442	0.6203	0.2867	0.7387	0.5536	0.2569	0.8601	0.0337	0.6372	0.2734	0.8096	0.2248	0.0017	<0.001	0.0058	-																				
PEA_301	29	0.1823	0.2745	0.2107	0.4849	0.8714	0.5482	0.6302	0.7993	0.8043	0.274	0.9352	0.6271	0.4182	0.2811	0.8928	0.9863	0.8544	0.1631	0.6724	0.0069	0.5683	0.3322	0.0669	0.1431	<0.001	0.1259	<0.001	0.0148	-																			
PEA_302	30	0.6822	0.6325	0.0128	0.0146	0.0919	0.0355	0.1293	0.5854	0.4866	0.5252	0.3462	0.6448	0.7611	0.3873	0.3018	0.1121	0.1304	0.4174	0.0746	0.0679	0.9757	0.5808	0.2319	0.1732	0.0951	0.4488	0.0837	0.0466	0.0165	-																		
PEA_501	31	0.1745	0.3748	0.1453	0.5327	0.6618	0.6306	0.3329	0.5221	0.4655	0.319	0.8584	0.6701	0.6728	0.6954	0.6786	0.8356	0.8578	0.3723	0.8479	0.0017	0.4381	0.6366	0.0197	0.1963	<0.001	0.0176	<0.001	0.0018	<0.001	0.1143	-																	
PEA_502	32	0.1347	0.9234	0.5093	0.0461	0.708	0.1229	0.8713	0.6246	0.5761	0.9739	0.1104	0.994	0.9316	0.6084	0.8941	0.7204	0.324	0.4311	0.3441	0.0016	0.7907	0.5299	0.8851	0.2378	<0.001	<0.001	0.0028	<0.001	0.0079	0.1507	<0.001	-																
PEA_751	33	0.144	0.6113	0.1842	0.2392	0.9632	0.3352	0.5707	0.5239	0.4027	0.3641	0.7821	0.8348	0.782	0.4455	0.9934	0.8399	0.6284	0.5008	0.5595	<0.001	0.4783	0.7047	0.0449	0.1597	<0.001	0.0031	<0.001	0.0012	<0.001	0.0922	<0.001	<0.001	-															
PEA_752	34	0.1806	0.4671	0.8933	0.0397	0.5749	0.0752	0.9799	0.5332	0.5368	0.7554	0.0532	0.6077	0.8119	0.8653	0.4684	0.572	0.3318	0.4285	0.2521	0.0016	0.9602	0.9917	0.9704	0.5325	<0.001	<0.001	0.0255	<0.001	0.0577	0.4501	0.0039	<0.001	<0.001	-														
PEA_951	35	0.123	0.21	0.2485	0.5874	0.7547	0.5261	0.4773	0.8112	0.2929	0.2013	0.9915	0.6101	0.2783	0.2348	0.6353	0.8806	0.7981	0.1682	0.7905	0.003	0.2542	0.2773	0.0383	0.0664	<0.001	0.0868	<0.001	0.0052	<0.001	0.037	<0.001	0.0034	<0.001	0.0347	-													
PEA_952	36	0.3188	0.2058	0.0093	0.0552	0.6561	0.1302	0.8205	0.6933	0.4744	0.6491	0.5016	0.3108	0.9483	0.4383	0.6304	0.7197	0.3217	0.9523	0.4648	0.0566	0.7818	0.2501	0.3266	0.131	0.0242	0.1877	0.0064	<0.001	0.0027	<0.001	0.0146	0.0129	0.0178	0.1351	0.0018	-												
PHT	37	0.5619	0.0396	0.075	0.1164	0.6477	0.2098	0.9011	0.5094	0.8402	0.1865	0.1227	0.2738	0.2389	0.9062	0.1514	0.6511	0.85	0.2037	0.4179	0.1682	0.1745	0.5514	0.3479	0.3284	0.2138	0.0434	0.6151	0.3961	0.3512	0.9834	0.4015	0.1505	0.2746	0.0494	0.6415	0.9021	-											
PRN	38	0.9771	0.8168	0.5585	0.0113	0.7737	0.056	0.8205	0.631	0.8046	0.9092	0.949	0.4529	0.0807	0.9926	0.9465	0.9916	0.5491	0.0884	0.6118	0.7686	0.9661	0.7106	0.165	0.9442	0.8491	0.0841	0.4048	0.1373	0.5351	0.4883	0.6894	0.1794	0.8785	0.0996	0.411	0.4209	0.0666	-										
RCH	39	0.824	0.7409	0.3142	0.0058	<0.001	<0.001	<0.001	0.5524	0.7901	0.9836	0.341	0.5377	0.5889	0.9309	0.0253	<0.001	<0.001	0.2052	<0.001	<0.001	0.389	0.401	0.3767	0.852	0.0089	0.0533	0.0598	0.2219	0.0704	0.0372	0.0396	0.0308	0.0153	0.0302	0.0507	0.1214	0.3342	0.6612	-									
Rb	40	0.0507	0.0073	0.6352	0.9355	0.5419	0.9307	0.5386	<0.001	0.7955	0.0704	0.9765	0.0363	0.8313	<0.001	0.1458	0.4144	0.6399	0.5	0.5105	0.4356	0.0837	<0.001	0.0188	<0.001	0.8704	0.5437	0.8075	0.6723	0.7449	0.7943	0.7263	0.9931	0.7402	0.6159	0.8222	0.5204	0.7609	0.7986	0.4891	-								
S	41	0.6162	0.1684	0.0931	0.8701	0.2141	0.926	0.2089	0.0866	0.3817	<0.001	0.004	0.4132	0.6314	0.0012	0.0801	0.2496	0.4797	0.5622	0.2097	0.5773	<0.001	0.0088	0.1663	<0.001	0.1733	0.779	0.0956	0.2245	0.1767	0.2593	0.1545	0.5509	0.1764	0.9238	0.0636	0.11	0.0718	0.7354	0.4634	0.03	-							
Se	42	0.047	0.9813	0.2897	0.92	0.9235	0.7318	0.9165	0.6271	0.0416	0.004	0.4083	0.6528	0.3796	0.195	0.9521	0.8336	0.7932	0.8046	0.9005	0.706	0.0956	0.533	0.3254	0.0548	0.2387	0.2513	0.2112	0.2201	0.3044	0.6018	0.2172	0.1041	0.1931	0.2498	0.155	0.4828	0.3687	0.6842	0.8309	0.9271	0.0653	-						
Sr	43	0.6188	0.5937	<0.001	0.7139	0.8395	0.8857	0.6742	<0.001	0.0849	0.8033	0.9025	0.6802	0.715	0.3916	0.6419	0.7767	0.4678	0.3087	0.897	0.5473	0.2898	0.6037	0.9963	0.5619	0.8086	0.9053	0.8691	0.1573	0.8599	0.2966	0.8269	0.7186	0.9061	0.9594	0.8073	0.1191	0.7878	0.4195	0.8765	0.9821	0.809	0.4951	-					
TGW	44	0.6247	0.9927	0.3831	0.1957	0.0977	0.2346	0.0657	0.1637	0.6223	0.1125	0.1288	0.5865	0.1879	0.0374	0.3014	0.1013	0.1294	0.7634	0.0746	0.587	0.026	0.0129	0.4941	0.0033	0.431	0.7952	0.1884	0.8271	0.2772	0.6956	0.2871	0.8404	0.3935	0.917	0.2572	0.5229	0.7741	0.6935	0.2949	0.2512	0.0072	0.5465	0.2207	-				
TLAR	45	0.9308	0.4306	0.4476	0.041	<0.001	0.0033	<0.001	0.9047	0.7176	0.883	0.8098	0.2133	0.3011	0.9687	0.0037	<0.001	<0.001	0.0954	<0.001	<0.001	0.3922	0.2037	0.3305	0.8675	0.3334	0.6368	0.5366	0.6864	0.3617	0.1521	0.6307	0.6553	0.4494	0.6006	0.41	0.6859	0.9972	0.1393	<0.001	0.3767	0.3529	0.8679	0.5016	0.1716	-			
TLLR	46	0.9552	0.0236	0.4612	0.45	0.0154	0.207	0.0317	0.9809	0.9092	0.8035	0.5478	0.042	0.9863	0.8106	<0.001	0.0219	0.5706	<0.001	0.0105	0.0633	0.172	0.1334	0.506	0.3807	0.7052	0.583	0.9168	0.2251	0.434	0.2909	0.9206	0.9012	0.7822	0.7324	0.8029	0.699	0.0693	0.4215	0.0204	0.2571	0.0708	0.5091	0.1555	0.3387	0.0032	-		
TLPR	47	0.929	0.4431	0.4359	0.0413	<0.001	0.0034	<0.001	0.8943	0.7191	0.8826	0.8111	0.2185	0.2957	0.9658	0.0042	<0.001	<0.001	0.1005	<0.001	<0.001	0.3944	0.2051	0.3281	0.8715	0.3331	0.6442	0.5331	0.6929	0.3625	0.1518	0.6286	0.6547	0.4486	0.605	0.407	0.6779	0.983	0.1365	<0.001	0.3769	0.3598	0.8772	0.5155	0.173	<0.001	0.0038	-	
WDR	48	0.3132	0.714	0.7771	0.2173	0.9888	0.1755	0.596	0.9291	0.7753	0.658	0.2254	0.802	0.8648	0.9273	0.9098	0.9258	0.6099	0.7781	0.4535	<0.001	0.8492	0.8741	0.2748	0.6624	<0.001	0.0014	<0.001	<0.001	<0.001	0.1659	<0.001	<0.001	<0.001	<0.001	<0.001	0.0083	0.1574	0.8945	0.0101	0.718	0.6838	0.9141	0.5626	0.4931	0.3662	0.6944	0.3676	-
Zn	49	0.6914	0.1178	0.1607	0.9484	0.9897	0.9091	0.8698	0.0375	0.6878	<0.001	0.0512	0.526	0.2335	<0.001	0.4463	0.9254	0.8754	0.9358	0.786	0.5149	<0.001	<0.001	0.861	<0.001	0.3298	0.8886	0.5012	0.5408	0.4615	0.125	0.4367	0.7099	0.4152	0.7718	0.3981	0.2379	0.2392	0.771	0.8556	<0.001	<0.001	0.0561	0.9321	0.04	0.6997	0.4679	0.7019	0.4287	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.6 Table Correlation coefficients between seedling root traits and grain yield, yield components and grain mineral composition traits of 36 Indian wheat genotypes at Malda site. Seedling root traits data are mean of ~20 replications, yield & yield components and grain mineral composition data are means of two replications per plot per genotype over two years at Malda site.

r values																																																		
As	1	-																																																
BYD	2	-0.0088	-																																															
Ba	3	-0.1288	-0.226	-																																														
CHCRX	4	-0.077	0.2235	0.2826	-																																													
CHCRY	5	0.0525	0.2459	0.0924	0.5797	-																																												
CMRX	6	-0.2333	0.2253	0.2918	0.9302	0.6767	-																																											
CMRY	7	0.0492	0.2233	0.1116	0.5529	0.9823	0.6498	-																																										
Ca	8	-0.1184	-0.3924	0.4364	0.1337	0.0446	0.0669	0.0365	-																																									
Cs	9	0.1499	-0.098	-0.1062	0.2053	-0.1381	0.0155	-0.124	0.3293	-																																								
Cu	10	-0.1786	-0.3325	0.4358	0.445	0.2198	0.3614	0.2315	0.5784	0.4222	-																																							
Fe	11	-0.0411	-0.3905	0.4129	0.2322	0.3204	0.2169	0.2618	0.615	0.1691	0.6108	-																																						
GYD	12	-0.1389	0.6866	-0.1045	-0.1153	0.0948	-0.033	0.1144	-0.4149	-0.3216	-0.4418	-0.5059	-																																					
HI_%	13	-0.1498	0.193	0.0341	-0.2642	0.0533	-0.1469	0.1069	-0.2687	-0.3436	-0.2914	-0.4145	0.8279	-																																				
K	14	0.0684	-0.6678	0.2133	-0.2491	-0.1455	-0.3139	-0.1068	0.5116	0.0155	0.3161	0.4617	-0.3057	0.0254	-																																		
LRN	15	0.0658	-0.0533	0.0124	0.2849	0.6209	0.3099	0.6033	0.2693	0.0923	0.3346	0.4501	-0.3722	-0.3147	-0.0678	-																																	
MDR	16	0.0635	0.2492	0.1157	0.5596	0.9877	0.6577	0.9727	0.0602	-0.1794	0.2363	0.3209	0.1178	0.0847	-0.0831	0.6048	-																																
MLAR	17	-0.016	0.2293	0.1947	0.6507	0.8679	0.7406	0.8638	0.0052	-0.1899	0.1869	0.2362	0.2068	0.1556	0.0033	0.2404	0.8774	-																															
MLLR	18	-0.1526	-0.1786	0.1441	-0.0498	0.1582	0.0959	0.109	0.1075	-0.2286	0.0437	0.0797	0.0052	0.2424	-0.1625	0.3172	0.1609	-0.0138	-																														
MLPR	19	-0.0371	0.203	0.1705	0.674	0.9635	0.7892	0.933	0.0779	-0.131	0.2547	0.3656	0.05	0.0061	-0.1405	0.5792	0.9502	0.8893	0.208	-																													
MWR	20	-0.034	0.0179	0.1776	0.5224	0.5798	0.6137	0.4715	0.2086	-0.1048	0.3112	0.5501	-0.1769	-0.2552	0.0371	0.3349	0.6079	0.6051	0.2119	0.7055	-																													
Mg	21	-0.1121	-0.4014	0.0956	0.1308	0.2207	0.0995	0.2811	0.3296	0.25	0.7025	0.4583	-0.4581	-0.2143	0.3229	0.5265	0.2272	0.067	0.1564	0.1839	0.0177	-																												
Mn	22	-0.1536	-0.2037	0.2358	0.2294	0.3623	0.2014	0.4263	0.4722	0.3036	0.5456	0.4763	-0.3542	-0.2407	0.2769	0.5475	0.3456	0.1823	-0.0209	0.3101	-0.0385	0.6877	-																											
Mo	23	0.147	-0.08	-0.114	0.1947	0.2995	0.0802	0.3534	0.202	0.1987	0.3706	0.1716	-0.2135	-0.1454	0.2134	0.3229	0.3219	0.2467	-0.121	0.1991	0.0126	0.6988	0.5118	-																										
P	24	0.023	-0.5637	0.1007	-0.0326	0.1391	-0.0652	0.2192	0.2822	0.2514	0.5592	0.3678	-0.4685	-0.1309	0.5222	0.3722	0.1587	0.0562	0.0163	0.0941	-0.0633	0.8905	0.6192	0.6905	-																									
PEA_1001	25	0.0259	-0.0392	0.3525	0.2959	0.0353	0.2539	-0.0821	0.2869	0.0571	0.18	0.4332	-0.2059	-0.2998	0.1072	0.0101	0.0939	0.1417	0.1618	0.1708	0.7	-0.2362	-0.2452	-0.2135	-0.2599	-																								
PEA_1002	26	-0.3028	-0.0403	0.1593	0.4283	0.1336	0.3825	0.023	0.3311	0.1173	0.3939	0.6119	-0.4235	-0.6025	0.1276	0.2245	0.1379	0.1698	-0.1652	0.2392	0.5593	0.1304	0.1841	-0.0129	-0.01	0.601	-																							
PEA_251	27	0.0451	-0.3278	0.3776	0.0709	-0.1177	0.0649	-0.219	0.3578	0.0514	0.1471	0.4184	-0.2875	-0.2174	0.2821	-0.1266	-0.0721	0.0167	0.2553	0.0139	0.591	-0.2144	-0.3098	-0.2256	-0.1155	0.8653	0.377	-																						
PEA_252	28	-0.0553	-0.2247	0.2686	0.3916	-0.0583	0.2656	-0.1527	0.2959	0.3037	0.4022	0.5048	-0.4088	-0.493	0.2143	-0.232	-0.0736	0.1302	-0.2465	0.0389	0.4442	-0.059	0.0357	-0.0422	-0.0831	0.6161	0.7104	0.5568	-																					
PEA_301	29	0.0451	-0.3563	0.3866	0.1533	-0.0357	0.132	-0.106	0.424	0.3278	0.327	0.5013	-0.3325	-0.214	0.2937	0.0298	-0.0038	0.0405	0.3008	0.0932	0.547	0.0539	-0.0463	-0.0511	0.1336	0.7636	0.3285	0.9068	0.5014	-																				
PEA_302	30	0.044	-0.0829	0.4509	0.5023	0.3597	0.4403	0.3258	0.4565	0.3186	0.4568	0.4239	-0.0716	0.0013	0.0901	0.2251	0.3403	0.3248	0.1777	0.3789	0.3873	0.0335	0.2902	0.0043	-0.0688	0.3564	0.1661	0.3684	0.419	0.4942	-																			
PEA_501	31	0.1097	-0.2546	0.387	0.1371	-0.0964	0.1059	-0.2114	0.3457	0.0417	0.1199	0.4333	-0.2831	-0.2625	0.2432	-0.0913	-0.0458	0.0396	0.1951	0.0423	0.6177	-0.2758	-0.3071	-0.2594	-0.2146	0.9464	0.49	0.9444	0.6153	0.8169	0.3383	-																		
PEA_502	32	-0.146	-0.1428	0.2254	0.4199	0.0826	0.331	-0.0358	0.2847	0.1934	0.3582	0.6273	-0.3973	-0.5255	0.2096	0.0294	0.0789	0.2152	-0.1726	0.2066	0.6203	0.0041	0.0191	-0.0515	-0.0591	0.7381	0.9035	0.5937	0.8847	0.5395	0.3095	0.6819	-																	
PEA_751	33	0.0622	-0.1515	0.3965	0.2556	-0.0102	0.2104	-0.1247	0.3445	0.0515	0.1798	0.4706	-0.2774	-0.3204	0.1853	-0.0018	0.0446	0.1066	0.1479	0.1283	0.676	-0.2279	-0.2432	-0.2083	-0.2219	0.9875	0.5884	0.8964	0.6327	0.782	0.3593	0.9781	0.7415	-																
PEA_752	34	-0.2074	-0.1029	0.1231	0.4317	0.1234	0.3782	0.0056	0.2659	0.1164	0.3322	0.6116	-0.4381	-0.5925	0.17	0.1591	0.1243	0.2119	-0.1735	0.2489	0.6207	0.0704	0.0675	-0.0341	-0.0306	0.6575	0.9741	0.4647	0.7636	0.4013	0.1656	0.5771	0.9553	0.6567	-															
PEA_951	35	-0.0937	-0.3172	0.376	0.1194	-0.0689	0.1393	-0.156	0.3153	0.0887	0.2044	0.436	-0.2773	-0.2018	0.2195	-0.1045	-0.0332	0.0564	0.2974	0.0586	0.5899	-0.1241	-0.223	-0.1784	-0.069	0.8223	0.365	0.9616	0.563	0.9242	0.4371	0.8662	0.5847	0.8356	0.442	-														
PEA_952	36	-0.0177	-0.1942	0.4364	0.405	0.0981	0.3251	0.0501	0.4587	0.3753	0.4607	0.4658	-0.2128	-0.194	0.1824	-0.1059	0.0791	0.2162	-0.0132	0.1604	0.4029	-0.078	0.1636	-0.0494	-0.1162	0.4684	0.2849	0.5516	0.7172	0.595	0.8487	0.5024	0.51	0.4892	0.3212	0.6155	-													
PHT	37	0.0386	0.0638	-0.2421	0.3502	0.1603	0.35	0.0767	0.0769	0.2334	0.0868	0.3365	-0.4945	-0.709	-0.2398	0.4309	0.1304	0.019	0.1261	0.2764	0.4795	0.18	0.1941	0.1239	0.0292	0.32	0.5191	0.1883	0.2524	0.2779	-0.013	0.2338	0.4151	0.2962	0.5323	0.2002	0.0462	-												
PRN	38	0.1599	-0.1237	0.0896	-0.5183	-0.0634	-0.4038	-0.0501	-0.1862	-0.3558	0.0121	-0.0684	0.1163	0.2868	0.1054	0.0148	-0.0023	-0.1317	0.3633	-0.1117	0.0649	0.1012	-0.2531	-0.0506	0.1499	0.042	-0.3679	0.1824	-0.3195	0.1363	-0.1522	0.0881	-0.2901	0.0338	-0.3519	0.1801	-0.1764	-0.3184	-											
RCH	39	0.006	0.1122	0.2195	0.5569	0.8049	0.6661	0.7189	0.1418	-0.1975	0.2878	0.5219	-0.0158	-0.0617	-0.0076	0.4651	0.8295	0.7815	0.2744	0.8736	0.9311	0.073	0.0842	0.0972	-0.0134	0.5326	0.4079	0.3982	0.2649	0.3841	0.4367	0.4318	0.451	0.4992	0.4523	0.4121	0.3323	0.3219	0.0965	-										
Rb	40	0.0211	-0.215	-0.0596	0.1758	0.0409	0.0283	0.0619	0.3408	0.7655	0.3274	0.3016	-0.3035	-0.2677	0.3719	0.1292	0.0163	0.0857	-0.4131	0.0461	-0.0016	0.2403	0.4737	0.2794	0.3984	0.0497	0.2728	0.0811	0.3568	0.314	0.2852	0.0603	0.3455	0.065	0.2898	0.1051	0.3657	0.1507	-0.421	-0.0347	-									
S	41	-0.0395	-0.2365	0.0949	0.1308	0.4303	0.108	0.4607	0.4539	0.357	0.7002	0.4842	-0.295	-0.1178	0.3119	0.5328	0.451	0.2387	0.1343	0.3677	0.1803	0.7791	0.6715	0.5773	0.7686	-0.0753	0.1336	-0.0869	-0.0062	0.149	0.1163	-0.1378	0.0344	-0.0974	0.0537	-0.0471	0.0132	0.0808	0.1324	0.2718	0.3808	-								
Se	42	0.0575	-0.132	0.0314	0.1126	0.1987	0.0266	0.1681	0.3135	0.2154	0.4657	0.4249	-0.4745	-0.4947	0.1258	0.4928	0.1855	0.0445	-0.0468	0.1759	0.1661	0.6005	0.5369	0.6023	0.5384	-0.0079	0.4119	-0.0875	0.1965	0.0122	-0.076	-0.0239	0.2944	0.0145	0.3603	-0.1342	-0.0309	0.4021	0.0061	0.1692	0.3138	0.5727	-							
Sr	43	-0.1934	-0.5352	0.7278	0.265	-0.0576	0.2039	-0.0046	0.7003	0.2045	0.5328	0.3377	-0.3167	-0.0143	0.5206	-0.0185	-0.0274	0.0858	0.0858	0.0104	0.0134	0.2431	0.4003	0.1042	0.3334	0.2113	0.0951	0.349	0.2781	0.417	0.4833	0.3056	0.1464	0.2794	0.0646	0.3513	0.5093	-0.2372	-0.1907	0.0021	0.3112	0.2435	0.0125	-						
TGW	44	-0.0294	0.064	-0.2245	0.1665	-0.1016	0.148	-0.1384	-0.1847	0.0661	-0.0496	0.0117	-0.2943	-0.4102	-0.4247	0.1482	-0.1352	-0.1683	0.1972	-0.1067	-0.0407	0.2179	-0.0878	0.1887	-0.025	0.0299	0.2107	-0.0415	0.0631	-0.0063	-0.1292	-0.0322	0.131	0.0157	0.2139	0.0534	-0.1248	0.4529	-0.198	-0.1006	-0.2108	-0.1842	0.0881	-0.2629	-					
TLAR	45	-0.0008	0.1134	0.2068	0.4291	0.8814	0.5853	0.8564	0.0288	-0.2426	0.2797	0.3338	0.0614	0.1016	-0.0671	0.5805	0.898	0.7773	0.356	0.9004	0.7154	0.2359	0.1939	0.1653	0.1832	0.2112	0.104	0.1358	-0.089	0.1994	0.3085	0.1059	0.0983	0.1659	0.1152	0.1805	0.0891	0.139	0.318	0.8759	-0.0899	0.4364	0.1725	-0.0348	-0.1902	-				
TLLR	46	-0.0448	-0.0844	0.0055	0.1656	0.4987	0.2733	0.4488	0.1944	-0.0181	0.2346	0.3652	-0.2511	-0.138	-0.1724	0.86	0.4754	0.1248	0.6963	0.5225	0.3933	0.4097	0.3608	0.0753	0.2179	0.0834	0.1208	0.0231	-0.2631	0.1715	0.2301	0.022	-0.0274	0.061	0.0754	0.0551	-0.0852	0.4826	0.1761	0.4801	-0.0963	0.4116	0.3355	-0.0804	0.1535	0.5874	-			
TLPR	47	0	0.1136	0.2088	0.4287	0.8811	0.5845	0.8569	0.0278	-0.2449	0.2793	0.3319	0.0656	0.1062	-0.0624	0.5734	0.8984	0.7818	0.351	0.8996	0.7148	0.2336	0.1909	0.167	0.1831	0.2113	0.1017	0.137	-0.0871	0.1991	0.3087	0.1065	0.0985	0.1662	0.1139	0.1816	0.0915	0.1312	0.3201	0.8759	-0.0892	0.4348	0.1693	-0.0323	-0.1938	0.9999	0.5785	-		
WDR	48	-0.0716	-0.2038	0.1514	0.2674	-0.0031	0.2926	-0.1167	0.2974	0.0804	0.273	0.4985	-0.4065	-0.4858	0.1497	-0.025	0.0206	0.1123	0.0622	0.1644	0.7879	-0.0924	-0.2089	-0.1327	-0.1376	0.7977	0.6249	0.8031	0.6815	0.7183	0.2989	0.7979	0.7452	0.8091	0.7021	0.7941	0.5369	0.5236	0.0293	0.5248	0.0696	-0.0672	0.0974	0.1045	0.0919	0.1976	0.0866	0.197	-	
Zn	49	-0.0739	-0.4664	0.117	0.0382	0.0423	-0.009	0.1204	0.2845	0.1444	0.5343	0.3353	-0.4832	-0.2267	0.3277	0.3575	0.0373	-0.0413	0.0844	0.0092	-0.2075	0.8909	0.6334	0.6635	0.8339	-0.3958	0.0111	-0.3232	-0.1163	-0.1346	-0.1747	-0.3585	-0.1167	-0.3493	-0.0348	-0.2788	-0.1806	0.1247	-0.028	-0.1473	0.1626	0.5949	0.6006	0.3046	0.248	-0.0046	0.2297	-0.0062	-0.2438	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.6 Table continued.

P values																																																		
As	1	-																																																
BYD	2	0.9683	-																																															
Ba	3	0.5579	0.2998	-																																												
CHCRX	4	0.7271	0.3052	0.1914	-																																											
CHCRY	5	0.8118	0.2581	0.675	0.0037	-																																										
CMRX	6	0.2841	0.3012	0.1767	<0.001	<0.001	-																																									
CMRY	7	0.8237	0.3057	0.6121	0.0062	<0.001	<0.001	-																																								
Ca	8	0.5906	0.064	0.0373	0.5431	0.8398	0.7618	0.8688	-																																							
Cs	9	0.4947	0.6563	0.6297	0.3474	0.5297	0.9441	0.5729	0.125	-																																						
Cu	10	0.4148	0.1211	0.0377	0.0333	0.3136	0.0902	0.2879	0.0038	0.0448	-																																					
Fe	11	0.8524	0.0654	0.0502	0.2864	0.1361	0.3202	0.2276	0.0018	0.4404	0.002	-																																				
GYD	12	0.5272	<0.001	0.6352	0.6003	0.667	0.881	0.6032	0.049	0.1345	0.0348	0.0138	-																																			
HI_%	13	0.4952	0.3775	0.8774	0.2232	0.8091	0.5036	0.6274	0.2151	0.1084	0.1773	0.0492	<0.001	-																																		
K	14	0.7565	<0.001	0.3285	0.2518	0.5077	0.1446	0.6278	0.0126	0.9441	0.1417	0.0266	0.156	0.9085	-																																	
LRN	15	0.7653	0.8091	0.9552	0.1877	0.0016	0.1501	0.0023	0.2141	0.6753	0.1186	0.0312	0.0803	0.1435	0.7585	-																																
MDR	16	0.7735	0.2514	0.5991	0.0055	<0.001	<0.001	<0.001	0.785	0.4126	0.2777	0.1354	0.5926	0.7009	0.7063	0.0022	-																															
MLAR	17	0.9423	0.2925	0.3734	<0.001	<0.001	<0.001	<0.001	0.9813	0.3855	0.3931	0.2778	0.3438	0.4785	0.9882	0.2692	<0.001	-																														
MLLR	18	0.4869	0.415	0.512	0.8215	0.4709	0.6634	0.6206	0.6254	0.2942	0.8431	0.7178	0.9812	0.2651	0.4587	0.1403	0.4634	0.9503	-																													
MLPR	19	0.8665	0.3528	0.4366	<0.001	<0.001	<0.001	<0.001	0.7239	0.5513	0.2409	0.0862	0.8208	0.9781	0.5227	0.0038	<0.001	<0.001	0.341	-																												
MWR	20	0.8776	0.9355	0.4176	0.0105	0.0037	0.0018	0.0231	0.3394	0.6341	0.1484	0.0065	0.4194	0.2398	0.8665	0.1183	0.0021	0.0022	0.3318	<0.001	-																											
Mg	21	0.6106	0.0576	0.6644	0.552	0.3115	0.6515	0.1939	0.1246	0.2499	<0.001	0.0278	0.0279	0.3262	0.1329	0.0098	0.2972	0.7612	0.4761	0.4008	0.936	-																										
Mn	22	0.484	0.3512	0.2788	0.2923	0.0894	0.3567	0.0425	0.0229	0.159	0.0071	0.0216	0.0972	0.2687	0.2009	0.0068	0.1063	0.4052	0.9246	0.1498	0.8617	<0.001	-																									
Mo	23	0.5034	0.7169	0.6045	0.3734	0.1651	0.7159	0.0981	0.3554	0.3633	0.0817	0.4336	0.3281	0.5081	0.3282	0.1329	0.1341	0.2565	0.5823	0.3624	0.9545	<0.001	0.0125	-																								
P	24	0.9169	0.0051	0.6475	0.8826	0.5267	0.7676	0.3149	0.1921	0.2472	0.0055	0.0842	0.0241	0.5515	0.0106	0.0803	0.4696	0.799	0.941	0.6693	0.7742	<0.001	0.0016	<0.001	-																							
PEA_1001	25	0.9068	0.8591	0.099	0.1704	0.8731	0.2424	0.7096	0.1843	0.7957	0.4113	0.0389	0.3458	0.1646	0.6265	0.9635	0.67	0.5188	0.4608	0.4359	<0.001	0.278	0.2594	0.3279	0.231	-																						
PEA_1002	26	0.1602	0.8552	0.4678	0.0415	0.5432	0.0716	0.9171	0.1228	0.5941	0.0629	0.0019	0.044	0.0023	0.5617	0.303	0.5303	0.4385	0.4512	0.2716	0.0055	0.5532	0.4005	0.9533	0.9639	0.0024	-																					
PEA_251	27	0.8381	0.1267	0.0757	0.7477	0.5928	0.7686	0.3154	0.0937	0.8158	0.5031	0.0469	0.1834	0.3191	0.1922	0.565	0.7437	0.9396	0.2398	0.9498	0.003	0.326	0.1503	0.3006	0.5998	<0.001	0.0762	-																				
PEA_252	28	0.802	0.3026	0.2153	0.0646	0.7918	0.2206	0.4868	0.1704	0.1589	0.0571	0.014	0.0528	0.0168	0.326	0.2867	0.7387	0.5536	0.2569	0.8601	0.0337	0.7893	0.8716	0.8484	0.7062	0.0017	<0.001	0.0058	-																			
PEA_301	29	0.8382	0.0952	0.0684	0.4849	0.8714	0.5482	0.6302	0.0438	0.1268	0.1277	0.0148	0.1211	0.3268	0.1738	0.8928	0.9863	0.8544	0.1631	0.6724	0.0069	0.8069	0.834	0.817	0.5433	<0.001	0.1259	<0.001	0.0148	-																		
PEA_302	30	0.8421	0.7068	0.0308	0.0146	0.0919	0.0355	0.1293	0.0286	0.1384	0.0284	0.0439	0.7455	0.9952	0.6827	0.3018	0.1121	0.1304	0.4174	0.0746	0.0679	0.8793	0.1792	0.9844	0.7551	0.0951	0.4488	0.0837	0.0466	0.0165	-																		
PEA_501	31	0.6184	0.2411	0.0681	0.5327	0.6618	0.6306	0.3329	0.1061	0.8503	0.5857	0.0389	0.1906	0.2262	0.2634	0.6786	0.8356	0.8578	0.3723	0.8479	0.0017	0.2027	0.1541	0.232	0.3256	<0.001	0.0176	<0.001	0.0018	<0.001	0.1143	-																	
PEA_502	32	0.5063	0.5156	0.301	0.0461	0.708	0.1229	0.8713	0.188	0.3765	0.0933	0.0014	0.0605	0.01	0.3371	0.8941	0.7204	0.324	0.4311	0.3441	0.0016	0.9851	0.9312	0.8155	0.7887	<0.001	<0.001	0.0028	<0.001	0.0079	0.1507	<0.001	-																
PEA_751	33	0.778	0.4902	0.061	0.2392	0.9632	0.3352	0.5707	0.1075	0.8153	0.4116	0.0234	0.2001	0.1361	0.3972	0.9934	0.8399	0.6284	0.5008	0.5595	<0.001	0.2956	0.2636	0.3403	0.3089	<0.001	0.0031	<0.001	0.0012	<0.001	0.0922	<0.001	<0.001	-															
PEA_752	34	0.3424	0.6402	0.5758	0.0397	0.5749	0.0752	0.9799	0.2201	0.5968	0.1215	0.0019	0.0365	0.0029	0.4382	0.4684	0.572	0.3318	0.4285	0.2521	0.0016	0.7496	0.7594	0.8771	0.8899	<0.001	<0.001	0.0255	<0.001	0.0577	0.4501	0.0039	<0.001	<0.001	-														
PEA_951	35	0.6708	0.1402	0.077	0.5874	0.7547	0.5261	0.4773	0.1428	0.6873	0.3495	0.0376	0.2001	0.3559	0.3143	0.6353	0.8806	0.7981	0.1682	0.7905	0.003	0.5727	0.3064	0.4155	0.7543	<0.001	0.0868	<0.001	0.0052	<0.001	0.037	<0.001	0.0034	<0.001	0.0347	-													
PEA_952	36	0.9362	0.3746	0.0374	0.0552	0.6561	0.1302	0.8205	0.0277	0.0776	0.0269	0.0251	0.3297	0.3751	0.4048	0.6304	0.7197	0.3217	0.9523	0.4648	0.0566	0.7236	0.4558	0.823	0.5974	0.0242	0.1877	0.0064	<0.001	0.0027	<0.001	0.0146	0.0129	0.0178	0.1351	0.0018	-												
PHT	37	0.8613	0.7723	0.2657	0.1014	0.4649	0.1016	0.7281	0.7273	0.2837	0.6938	0.1164	0.0165	<0.001	0.2704	0.0401	0.553	0.9314	0.5664	0.2017	0.0206	0.4112	0.3748	0.5733	0.8947	0.1366	0.0111	0.3895	0.2453	0.1992	0.9531	0.283	0.0489	0.17	0.0089	0.3596	0.8344	-											
PRN	38	0.4661	0.5738	0.6843	0.0113	0.7737	0.056	0.8205	0.3951	0.0957	0.9561	0.7566	0.5971	0.1846	0.6323	0.9465	0.9916	0.5491	0.0884	0.6118	0.7686	0.646	0.2439	0.8186	0.4947	0.8491	0.0841	0.4048	0.1373	0.5351	0.4883	0.6894	0.1794	0.8785	0.0996	0.411	0.4209	0.1387	-										
RCH	39	0.9784	0.6102	0.3142	0.0058	<0.001	<0.001	<0.001	0.5186	0.3665	0.183	0.0106	0.9429	0.7796	0.9726	0.0253	<0.001	<0.001	0.2052	<0.001	<0.001	0.7405	0.7025	0.659	0.9517	0.0089	0.0533	0.0598	0.2219	0.0704	0.0372	0.0396	0.0308	0.0153	0.0302	0.0507	0.1214	0.1342	0.6612	-										
Rb	40	0.9239	0.3246	0.7871	0.4224	0.8529	0.8979	0.779	0.1115	<0.001	0.1273	0.162	0.1592	0.2169	0.0805	0.557	0.9412	0.6973	0.0501	0.8347	0.9943	0.2693	0.0224	0.1966	0.0597	0.822	0.2079	0.7131	0.0946	0.1445	0.1871	0.7845	0.1064	0.7682	0.1798	0.6331	0.0862	0.4925	0.0454	0.8752	-									
S	41	0.8581	0.2774	0.6666	0.552	0.0404	0.6238	0.027	0.0296	0.0945	<0.001	0.0192	0.1717	0.5924	0.1474	0.0089	0.0308	0.2728	0.5413	0.0843	0.4103	<0.001	<0.001	0.0039	<0.001	0.7328	0.5435	0.6934	0.9776	0.4976	0.5971	0.5305	0.8761	0.6584	0.8078	0.8312	0.9523	0.714	0.547	0.2096	0.073	-								
Se	42	0.7943	0.5482	0.8868	0.6089	0.3634	0.9041	0.4433	0.1452	0.3237	0.0251	0.0433	0.0221	0.0164	0.5673	0.0169	0.3969	0.8403	0.8321	0.422	0.4487	0.0024	0.0083	0.0024	0.008	0.9716	0.0508	0.6914	0.3688	0.956	0.7304	0.9138	0.1726	0.9475	0.0913	0.5414	0.8888	0.0572	0.978	0.4403	0.1448	0.0043	-							
Sr	43	0.3766	0.0085	<0.001	0.2217	0.7941	0.3508	0.9834	<0.001	0.3493	0.0089	0.1151	0.1409	0.9484	0.0109	0.9333	0.9013	0.6971	0.697	0.9625	0.9517	0.2638	0.0584	0.6363	0.12	0.3332	0.6659	0.1026	0.1989	0.0478	0.0195	0.1561	0.505	0.1967	0.7697	0.1002	0.0131	0.2759	0.3833	0.9922	0.1484	0.2628	0.9549	-						
TGW	44	0.8942	0.7719	0.3031	0.4476	0.6445	0.5004	0.5289	0.3989	0.7644	0.8221	0.9579	0.1729	0.0519	0.0434	0.4999	0.5385	0.4427	0.367	0.6281	0.8538	0.318	0.6905	0.3886	0.9098	0.8922	0.3346	0.8508	0.7747	0.9774	0.5567	0.8842	0.5512	0.9434	0.327	0.8088	0.5705	0.03	0.3651	0.6478	0.3344	0.4002	0.6895	0.2256	-					
TLAR	45	0.997	0.6066	0.3437	0.041	<0.001	0.0033	<0.001	0.8961	0.2646	0.1962	0.1195	0.7808	0.6447	0.7611	0.0037	<0.001	<0.001	0.0954	<0.001	<0.001	0.2786	0.3754	0.4511	0.4028	0.3334	0.6368	0.5366	0.6864	0.3617	0.1521	0.6307	0.6553	0.4494	0.6006	0.41	0.6859	0.527	0.1393	<0.001	0.6835	0.0373	0.4311	0.8749	0.3848	-				
TLLR	46	0.8391	0.7017	0.9802	0.45	0.0154	0.207	0.0317	0.3741	0.9347	0.2812	0.0866	0.2478	0.5301	0.4316	<0.001	0.0219	0.5706	<0.001	0.0105	0.0633	0.0522	0.0908	0.7328	0.3179	0.7052	0.583	0.9168	0.2251	0.434	0.2909	0.9206	0.9012	0.7822	0.7324	0.8029	0.699	0.0197	0.4215	0.0204	0.6621	0.051	0.1175	0.7153	0.4844	0.0032	-			
TLPR	47	0.9999	0.6058	0.3391	0.0413	<0.001	0.0034	<0.001	0.8998	0.26	0.1968	0.1218	0.7662	0.6297	0.7772	0.0042	<0.001	<0.001	0.1005	<0.001	<0.001	0.2833	0.3829	0.4463	0.4031	0.3331	0.6442	0.5331	0.6929	0.3625	0.1518	0.6286	0.6547	0.4486	0.605	0.407	0.6779	0.5507	0.1365	<0.001	0.6857	0.0382	0.4398	0.8836	0.3757	<0.001	0.0038	-		
WDR	48	0.7456	0.3509	0.4903	0.2173	0.9888	0.1755	0.596	0.1682	0.7154	0.2076	0.0155	0.0542	0.0188	0.4953	0.9098	0.9258	0.6099	0.7781	0.4535	<0.001	0.6751	0.3387	0.5462	0.5313	<0.001	0.0014	<0.001	<0.001	<0.001	0.1659	<0.001	<0.001	<0.001	<0.001	<0.001	0.0083	0.0103	0.8945	0.0101	0.7522	0.7607	0.6583	0.6351	0.6766	0.3662	0.6944	0.3676	-	
Zn	49	0.7376	0.0249	0.595	0.8626	0.8481	0.9675	0.5841	0.1883	0.5108	0.0086	0.1178	0.0195	0.2981	0.1269	0.094	0.8659	0.8516	0.7016	0.9668	0.3421	<0.001	0.0012	<0.001	<0.001	0.0616	0.96	0.1325	0.5972	0.5402	0.4254	0.093	0.5958	0.1023	0.8746	0.1977	0.4096	0.5709	0.8992	0.5025	0.4585	0.0028	0.0024	0.1575	0.2539	0.9835	0.2918	0.9775	0.2622	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.7 Table Correlation coefficients between seedling root traits and grain yield, yield components and grain mineral composition traits of 36 Indian wheat genotypes at Pundibari site. Seedling root traits data are mean of ~20 replications, yield & yield component traits data are mean of two replication per plot per genotype over two years and mineral elements data are mean of two replicates per plot per genotype in 2014-15 at Pundibari site.

r values																																																		
As	1	-																																																
BYD	2	0.1642	-																																															
Ba	3	-0.065	-0.0548	-																																													
CHCRX	4	-0.2242	-0.1679	0.0105	-																																												
CHCRY	5	-0.1335	-0.0501	-0.1632	0.5797	-																																											
CMRX	6	-0.223	-0.162	-0.073	0.9302	0.6767	-																																										
CMRY	7	-0.0931	-0.0313	-0.146	0.5529	0.9823	0.6498	-																																									
Ca	8	-0.1036	-0.3382	0.5423	0.0909	0.019	0.0764	0.0114	-																																								
Cs	9	-0.108	-0.1242	0.3537	-0.1635	-0.2017	-0.2669	-0.1932	0.7088	-																																							
Cu	10	-0.0444	-0.287	0.3049	-0.0785	-0.0808	-0.0195	-0.0259	0.628	0.4006	-																																						
Fe	11	-0.0246	0.273	0.3662	-0.0316	-0.0941	0.0152	-0.0796	0.3127	0.334	0.5764	-																																					
GYD	12	0.0279	0.4508	-0.0724	-0.3647	-0.0101	-0.329	0.037	-0.5007	-0.1124	-0.1434	0.079	-																																				
HI_%	13	-0.1332	-0.6935	0.0232	-0.1625	-0.0474	-0.1422	-0.0189	-0.0773	-0.0694	0.2506	-0.1855	0.2695	-																																			
K	14	0.0823	-0.0875	0.3155	-0.3876	-0.0817	-0.4079	-0.0181	0.6563	0.5776	0.5555	0.1292	0.0395	0.1467	-																																		
LRN	15	-0.226	0.2729	-0.1746	0.2849	0.6209	0.3099	0.6033	0.1408	0.0204	0.116	0.2727	-0.0855	-0.4115	0.0956	-																																	
MDR	16	-0.138	-0.0645	-0.1003	0.5596	0.9877	0.6577	0.9727	0.0512	-0.2022	-0.0635	-0.1021	-0.0106	-0.0446	-0.0671	0.6048	-																																
MLAR	17	-0.1394	-0.2051	-0.0674	0.6507	0.8679	0.7406	0.8638	0.0374	-0.1775	-0.1497	-0.2354	-0.0909	0.0451	-0.1698	0.2404	0.8774	-																															
MLLR	18	0.017	0.0762	-0.0457	-0.0498	0.1582	0.0959	0.109	0.0725	-0.01	0.1683	0.2732	0.1527	-0.0403	-0.1476	0.3172	0.1609	-0.0138	-																														
MLPR	19	-0.1821	-0.0713	-0.1449	0.674	0.9635	0.7892	0.933	0.0807	-0.1604	-0.0459	0.0097	-0.113	-0.1139	-0.1798	0.5792	0.9502	0.8893	0.208	-																													
MWR	20	-0.3066	-0.2765	-0.0676	0.5224	0.5798	0.6137	0.4715	0.3352	0.0879	0.0647	0.0059	-0.3864	-0.1553	-0.1805	0.3349	0.6079	0.6051	0.2119	0.7055	-																												
Mg	21	0.2472	0.1583	0.1371	-0.158	0.0666	-0.1547	0.138	0.4958	0.5431	0.5252	0.4413	-0.005	-0.2221	0.5863	0.4717	0.0649	-0.1946	0.2282	0.0455	-0.0548	-																											
Mn	22	-0.1039	0.2988	0.2963	-0.1308	-0.1384	-0.2546	-0.0512	0.3214	0.3668	0.3638	0.3472	0.0355	-0.2538	0.5034	0.342	-0.1548	-0.3443	-0.1115	-0.1855	-0.372	0.5925	-																										
Mo	23	-0.1	0.1132	-0.015	0.2151	0.1719	0.0729	0.2322	-0.0615	-0.0659	-0.0288	-0.1478	-0.0663	-0.1347	0.14	0.3737	0.1891	0.0963	-0.4227	0.042	-0.214	0.0774	0.1896	-																									
P	24	0.3042	0.4009	0.0955	-0.2664	-0.1155	-0.3299	-0.0505	0.2826	0.3804	0.2803	0.255	0.0889	-0.3692	0.5267	0.4051	-0.1128	-0.3831	0.0334	-0.187	-0.2544	0.848	0.6013	0.2821	-																								
PEA_1001	25	-0.4637	-0.3051	0.3193	0.2959	0.0353	0.2539	-0.0821	0.4568	0.2568	0.0797	0.0384	-0.4603	-0.0971	-0.1253	0.0101	0.0939	0.1417	0.1618	0.1708	0.7	-0.1655	-0.2492	-0.2369	-0.2794	-																							
PEA_1002	26	-0.5967	-0.1081	-0.0045	0.4283	0.1336	0.3825	0.023	0.1331	0.097	-0.2132	0.0433	-0.4779	-0.3322	-0.389	0.2245	0.1379	0.1698	-0.1652	0.2392	0.5593	-0.3178	-0.1821	0.0897	-0.2953	0.601	-																						
PEA_251	27	-0.3081	-0.3481	0.3131	0.0709	-0.1177	0.0649	-0.219	0.5389	0.3585	0.2378	-0.001	-0.4528	-0.0307	0.0334	-0.1266	-0.0721	0.0167	0.2553	0.0139	0.591	-0.0788	-0.2031	-0.3528	-0.1609	0.8653	0.377	-																					
PEA_252	28	-0.3946	-0.4483	0.1325	0.3916	-0.0583	0.2656	-0.1527	0.3144	0.3745	-0.0563	-0.1173	-0.485	0.0236	-0.1868	-0.232	-0.0736	0.1302	-0.2465	0.0389	0.4442	-0.3632	-0.237	-0.1197	-0.4367	0.6161	0.7104	0.5568	-																				
PEA_301	29	-0.4126	-0.3177	0.2559	0.1533	-0.0357	0.132	-0.106	0.4771	0.405	0.2342	0.021	-0.3788	-0.032	-0.011	0.0298	-0.0038	0.0405	0.3008	0.0932	0.547	0.051	-0.0328	-0.2508	-0.0612	0.7636	0.3285	0.9068	0.5014	-																			
PEA_302	30	-0.3889	-0.528	0.1991	0.5023	0.3597	0.4403	0.3258	0.4616	0.1977	0.247	-0.0715	-0.2819	0.3011	0.1612	0.2251	0.3403	0.3248	0.1777	0.3789	0.3873	0.0129	0.1193	-0.0669	-0.1343	0.3564	0.1661	0.3684	0.419	0.4942	-																		
PEA_501	31	-0.3242	-0.3548	0.3141	0.1371	-0.0964	0.1059	-0.2114	0.5564	0.3657	0.146	0.0319	-0.5294	-0.0792	-0.0014	-0.0913	-0.0458	0.0396	0.1951	0.0423	0.6177	-0.1215	-0.2582	-0.3062	-0.2356	0.9464	0.49	0.9444	0.6153	0.8169	0.3383	-																	
PEA_502	32	-0.5727	-0.2622	0.0388	0.4199	0.0826	0.331	-0.0358	0.2186	0.265	-0.1768	-0.0455	-0.4805	-0.1732	-0.3109	0.0294	0.0789	0.2152	-0.1726	0.2066	0.6203	-0.3702	-0.2739	-0.0574	-0.401	0.7381	0.9035	0.5937	0.8847	0.5395	0.3095	0.6819	-																
PEA_751	33	-0.4125	-0.3263	0.3136	0.2556	-0.0102	0.2104	-0.1247	0.5273	0.3217	0.115	0.0446	-0.534	-0.1203	-0.0585	-0.0018	0.0446	0.1066	0.1479	0.1283	0.676	-0.1243	-0.2377	-0.2297	-0.2333	0.9875	0.5884	0.8964	0.6327	0.782	0.3593	0.9781	0.7415	-															
PEA_752	34	-0.5551	-0.135	-0.0575	0.4317	0.1234	0.3782	0.0056	0.1419	0.1379	-0.2444	-0.0169	-0.5059	-0.3312	-0.3803	0.1591	0.1243	0.2119	-0.1735	0.2489	0.6207	-0.3514	-0.2635	0.0287	-0.3488	0.6575	0.9741	0.4647	0.7636	0.4013	0.1656	0.5771	0.9553	0.6567	-														
PEA_951	35	-0.4132	-0.3178	0.266	0.1194	-0.0689	0.1393	-0.156	0.4823	0.3414	0.2594	-0.0147	-0.3515	0.0031	0.0031	-0.1045	-0.0332	0.0564	0.2974	0.0586	0.5899	-0.0746	-0.1784	-0.3667	-0.1687	0.8223	0.365	0.9616	0.563	0.9242	0.4371	0.8662	0.5847	0.8356	0.442	-													
PEA_952	36	-0.3582	-0.5467	0.3042	0.405	0.0981	0.3251	0.0501	0.5913	0.4663	0.278	-0.0667	-0.3344	0.2455	0.2138	-0.1059	0.0791	0.2162	-0.0132	0.1604	0.4029	-0.0687	0.0283	-0.1696	-0.1961	0.4684	0.2849	0.5516	0.7172	0.595	0.8487	0.5024	0.51	0.4892	0.3212	0.6155	-												
PHT	37	-0.1361	0.6449	-0.2842	0.1239	0.0753	0.1212	0.0199	-0.1724	0.0463	-0.3845	0.1259	0.0026	-0.7475	-0.2614	0.3748	0.0341	-0.0849	-0.0699	0.137	0.1888	0.0742	0.1699	0.0492	0.2058	0.066	0.4046	-0.0583	0.0912	0.0638	-0.2335	-0.0034	0.2819	0.0476	0.4047	-0.0348	-0.1643	-											
PRN	38	0.165	-0.1497	0.0987	-0.5183	-0.0634	-0.4038	-0.0501	0.0764	0.1148	0.4485	0.2277	0.2472	0.3301	0.2535	0.0148	-0.0023	-0.1317	0.3633	-0.1117	0.0649	0.2328	-0.1324	-0.1502	0.1053	0.042	-0.3679	0.1824	-0.3195	0.1363	-0.1522	0.0881	-0.2901	0.0338	-0.3519	0.1801	-0.1764	-0.4221	-										
RCH	39	-0.2619	-0.2157	-0.0466	0.5569	0.8049	0.6661	0.7189	0.262	-0.0011	0.0149	-0.0084	-0.2164	-0.0821	-0.1297	0.4651	0.8295	0.7815	0.2744	0.8736	0.9311	-0.0285	-0.3662	-0.1072	-0.2436	0.5326	0.4079	0.3982	0.2649	0.3841	0.4367	0.4318	0.451	0.4992	0.4523	0.4121	0.3323	0.0946	0.0965	-										
Rb	40	0.0063	0.158	0.3809	-0.4366	-0.1447	-0.466	-0.1038	0.5058	0.7466	0.3817	0.3642	0.2845	-0.0347	0.7308	0.0443	-0.1235	-0.2169	-0.0845	-0.1814	-0.0779	0.5413	0.5424	-0.1494	0.4443	-0.0408	-0.1978	0.0628	-0.0165	0.0983	0.0296	0.0255	-0.1098	-0.0171	-0.1916	0.0701	0.2061	0.0885	0.2878	-0.0806	-									
S	41	0.059	-0.1229	0.1288	-0.1342	0.424	-0.0084	0.4955	0.1593	0.036	0.4907	0.3007	0.3046	0.3601	0.3593	0.3152	0.4423	0.2285	0.2847	0.3669	0.0586	0.4909	0.3403	-0.1824	0.2056	-0.2227	-0.4834	-0.1572	-0.4794	-0.0276	0.1985	-0.2479	-0.4939	-0.2548	-0.5319	-0.1201	-0.0669	-0.303	0.4637	0.2299	0.3771	-								
Se	42	0.1852	0.3752	0.0552	-0.0624	0.1182	-0.0812	0.1747	-0.0449	0.0699	0.1281	0.3323	0.3276	-0.1113	0.2694	0.2094	0.1279	0.0111	-0.3059	0.0044	-0.2579	0.2018	0.0832	0.5044	0.2957	-0.3985	-0.0408	-0.5417	-0.2015	-0.6194	-0.3429	-0.4485	-0.198	-0.3898	-0.112	-0.5405	-0.3161	0.0498	0.0392	-0.1097	0.2516	0.0275	-							
Sr	43	-0.2324	-0.3329	0.8071	0.0914	-0.13	0.0186	-0.1324	0.844	0.5698	0.5222	0.2345	-0.2969	0.087	0.5173	-0.1056	-0.0631	-0.0046	0.0328	-0.0859	0.1972	0.1949	0.268	-0.0494	0.0748	0.5262	0.1149	0.5858	0.3742	0.5203	0.507	0.5733	0.2364	0.5554	0.108	0.5633	0.6566	-0.3425	0.1154	0.1436	0.4577	0.0772	-0.0812	-						
TGW	44	0.0052	0.0844	0.186	-0.1068	-0.1791	-0.1342	-0.2193	-0.367	-0.123	-0.3638	-0.0165	0.1591	0.003	-0.5303	-0.1201	-0.1825	-0.2157	0.3708	-0.1695	-0.1242	-0.1637	-0.1973	-0.202	-0.1072	0.1094	0.036	0.1512	0.0593	0.2762	-0.054	0.0827	0.0768	0.065	0.0166	0.198	-0.0813	0.0453	0.1728	-0.1205	-0.2253	-0.1186	-0.3391	-0.1196	-					
TLAR	45	-0.1596	-0.1227	-0.0816	0.4291	0.8814	0.5853	0.8564	0.1208	-0.1106	0.1809	0.1196	-0.0173	0.0165	-0.0688	0.5805	0.898	0.7773	0.356	0.9004	0.7154	0.136	-0.2004	-0.0004	-0.126	0.2112	0.104	0.1358	-0.089	0.1994	0.3085	0.1059	0.0983	0.1659	0.1152	0.1805	0.0891	-0.0343	0.318	0.8759	-0.0586	0.5476	-0.0021	-0.0085	-0.0881	-				
TLLR	46	-0.1529	0.2322	-0.2049	0.1656	0.4987	0.2733	0.4488	0.0977	0.0037	0.1466	0.3941	0.0117	-0.3216	-0.0596	0.86	0.4754	0.1248	0.6963	0.5225	0.3933	0.4425	0.1888	-0.0613	0.2744	0.0834	0.1208	0.0231	-0.2631	0.1715	0.2301	0.022	-0.0274	0.061	0.0754	0.0551	-0.0852	0.338	0.1761	0.4801	0.0239	0.3877	-0.0643	-0.1335	0.1088	0.5874	-			
TLPR	47	-0.1592	-0.1274	-0.0793	0.4287	0.8811	0.5845	0.8569	0.1212	-0.1101	0.1808	0.1142	-0.0164	0.0221	-0.0667	0.5734	0.8984	0.7818	0.351	0.8996	0.7148	0.1314	-0.2042	0.001	-0.1303	0.2113	0.1017	0.137	-0.0871	0.1991	0.3087	0.1065	0.0985	0.1662	0.1139	0.1816	0.0915	-0.0416	0.3201	0.8759	-0.0582	0.547	-0.0014	-0.0053	-0.0906	0.9999	0.5785	-		
WDR	48	-0.3161	-0.3517	0.0007	0.2674	-0.0031	0.2926	-0.1167	0.4478	0.3095	0.1565	-0.0029	-0.5573	-0.174	-0.113	-0.025	0.0206	0.1123	0.0622	0.1644	0.7879	-0.0853	-0.2711	-0.3368	-0.1927	0.7977	0.6249	0.8031	0.6815	0.7183	0.2989	0.7979	0.7452	0.8091	0.7021	0.7941	0.5369	0.2095	0.0293	0.5248	0.0221	-0.2747	-0.4302	0.3521	-0.0553	0.1976	0.0866	0.197	-	
Zn	49	-0.0631	-0.0995	-0.0613	-0.1238	0.0318	-0.0136	0.062	0.2603	0.2378	0.6029	0.607	-0.1131	0.0788	0.1913	0.3238	0.0103	-0.1162	0.2991	0.134	0.1584	0.5712	0.234	-0.2254	0.3214	0.0357	-0.0886	0.1438	-0.2421	0.221	0.0171	0.0885	-0.0893	0.0735	-0.0785	0.1344	-0.1151	-0.0855	0.3636	0.1145	0.1591	0.5107	-0.0782	-0.0113	-0.0896	0.3035	0.4528	0.2993	0.1304	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

S4.7 Table continued.

P values																																																		
As	1	-																																																
BYD	2	0.4541	-																																															
Ba	3	0.7682	0.8038	-																																														
CHCRX	4	0.3038	0.4438	0.9621	-																																													
CHCRY	5	0.5436	0.8205	0.4567	0.0037	-																																												
CMRX	6	0.3063	0.4603	0.7405	<0.001	<0.001	-																																											
CMRY	7	0.6726	0.8872	0.5062	0.0062	<0.001	<0.001	-																																										
Ca	8	0.6382	0.1144	0.0075	0.6799	0.9314	0.7289	0.9588	-																																									
Cs	9	0.6236	0.5723	0.0978	0.4559	0.356	0.2183	0.3772	<0.001	-																																								
Cu	10	0.8406	0.1843	0.1571	0.722	0.714	0.9297	0.9065	0.0013	0.0582	-																																							
Fe	11	0.9114	0.2076	0.0857	0.8863	0.6693	0.9451	0.7179	0.1463	0.1193	0.004	-																																						
GYD	12	0.8994	0.0309	0.7428	0.0871	0.9634	0.1253	0.867	0.015	0.6095	0.514	0.7201	-																																					
HI_%	13	0.5446	<0.001	0.9164	0.4589	0.8298	0.5174	0.9318	0.726	0.7531	0.2487	0.3969	0.2136	-																																				
K	14	0.7089	0.6915	0.1425	0.0677	0.7111	0.0533	0.9345	<0.001	0.0039	0.0059	0.5568	0.8579	0.5041	-																																			
LRN	15	0.2997	0.2077	0.4255	0.1877	0.0016	0.1501	0.0023	0.5216	0.9263	0.5983	0.208	0.698	0.0511	0.6644	-																																		
MDR	16	0.5299	0.7701	0.6488	0.0055	<0.001	<0.001	<0.001	0.8167	0.3548	0.7735	0.6429	0.9618	0.8399	0.761	0.0022	-																																	
MLAR	17	0.5257	0.3479	0.76	<0.001	<0.001	<0.001	<0.001	0.8656	0.4178	0.4954	0.2796	0.6801	0.8382	0.4387	0.2692	<0.001	-																																
MLLR	18	0.9385	0.7296	0.8361	0.8215	0.4709	0.6634	0.6206	0.7424	0.964	0.4427	0.2072	0.4868	0.855	0.5016	0.1403	0.4634	0.9503	-																															
MLPR	19	0.4058	0.7464	0.5096	<0.001	<0.001	<0.001	<0.001	0.7142	0.4648	0.8354	0.9649	0.6078	0.6047	0.4116	0.0038	<0.001	<0.001	0.341	-																														
MWR	20	0.1548	0.2016	0.7594	0.0105	0.0037	0.0018	0.0231	0.118	0.6901	0.7693	0.9787	0.0686	0.4792	0.41	0.1183	0.0021	0.0022	0.3318	<0.001	-																													
Mg	21	0.2554	0.4706	0.5328	0.4714	0.7629	0.4809	0.53	0.0161	0.0074	0.0101	0.035	0.9818	0.3084	0.0033	0.0231	0.7687	0.3736	0.2949	0.8366	0.8037	-																												
Mn	22	0.6372	0.166	0.1699	0.552	0.5288	0.241	0.8164	0.1348	0.0851	0.088	0.1046	0.8722	0.2426	0.0143	0.1102	0.4806	0.1077	0.6124	0.3969	0.0805	0.0029	-																											
Mo	23	0.6498	0.607	0.9459	0.3242	0.4328	0.7408	0.2863	0.7803	0.7651	0.8964	0.5009	0.7639	0.54	0.5241	0.079	0.3876	0.6619	0.0445	0.8491	0.3269	0.7254	0.3863	-																										
P	24	0.1581	0.058	0.6648	0.2191	0.5999	0.1242	0.8188	0.1914	0.0733	0.1952	0.2403	0.6867	0.0829	0.0098	0.0552	0.6084	0.0712	0.8799	0.393	0.2414	<0.001	0.0024	0.1921	-																									
PEA_1001	25	0.0258	0.1569	0.1375	0.1704	0.8731	0.2424	0.7096	0.0284	0.2368	0.7177	0.8619	0.0271	0.6594	0.569	0.9635	0.67	0.5188	0.4608	0.4359	<0.001	0.4504	0.2515	0.2764	0.1966	-																								
PEA_1002	26	0.0026	0.6234	0.9836	0.0415	0.5432	0.0716	0.9171	0.5449	0.6596	0.3287	0.8444	0.0211	0.1214	0.0665	0.303	0.5303	0.4385	0.4512	0.2716	0.0055	0.1395	0.4055	0.6841	0.1713	0.0024	-																							
PEA_251	27	0.1526	0.1035	0.1458	0.7477	0.5928	0.7686	0.3154	0.008	0.093	0.2745	0.9962	0.03	0.8895	0.8797	0.565	0.7437	0.9396	0.2398	0.9498	0.003	0.7207	0.3525	0.0987	0.4632	<0.001	0.0762	-																						
PEA_252	28	0.0624	0.0319	0.5467	0.0646	0.7918	0.2206	0.4868	0.144	0.0783	0.7986	0.594	0.019	0.915	0.3933	0.2867	0.7387	0.5536	0.2569	0.8601	0.0337	0.0884	0.2763	0.5865	0.0372	0.0017	<0.001	0.0058	-																					
PEA_301	29	0.0504	0.1396	0.2386	0.4849	0.8714	0.5482	0.6302	0.0213	0.0552	0.2822	0.9241	0.0747	0.8847	0.9603	0.8928	0.9863	0.8544	0.1631	0.6724	0.0069	0.8171	0.882	0.2483	0.7814	<0.001	0.1259	<0.001	0.0148	-																				
PEA_302	30	0.0667	0.0096	0.3624	0.0146	0.0919	0.0355	0.1293	0.0266	0.3659	0.2559	0.7457	0.1925	0.1626	0.4626	0.3018	0.1121	0.1304	0.4174	0.0746	0.0679	0.9534	0.5878	0.7615	0.5413	0.0951	0.4488	0.0837	0.0466	0.0165	-																			
PEA_501	31	0.1313	0.0967	0.1444	0.5327	0.6618	0.6306	0.3329	0.0058	0.0861	0.5063	0.8852	0.0094	0.7194	0.9949	0.6786	0.8356	0.8578	0.3723	0.8479	0.0017	0.5806	0.2342	0.1553	0.2791	<0.001	0.0176	<0.001	0.0018	<0.001	0.1143	-																		
PEA_502	32	0.0043	0.2267	0.8606	0.0461	0.708	0.1229	0.8713	0.3163	0.2216	0.4197	0.8367	0.0203	0.4295	0.1488	0.8941	0.7204	0.324	0.4311	0.3441	0.0016	0.0821	0.2061	0.7949	0.0579	<0.001	<0.001	0.0028	<0.001	0.0079	0.1507	<0.001	-																	
PEA_751	33	0.0504	0.1286	0.1451	0.2392	0.9632	0.3352	0.5707	0.0097	0.1344	0.6014	0.8397	0.0087	0.5846	0.7909	0.9934	0.8399	0.6284	0.5008	0.5595	<0.001	0.5722	0.2747	0.2917	0.2841	<0.001	0.0031	<0.001	0.0012	<0.001	0.0922	<0.001	<0.001	-																
PEA_752	34	0.006	0.539	0.7945	0.0397	0.5749	0.0752	0.9799	0.5183	0.5304	0.2611	0.9392	0.0138	0.1227	0.0735	0.4684	0.572	0.3318	0.4285	0.2521	0.0016	0.1001	0.2245	0.8966	0.1029	<0.001	<0.001	0.0255	<0.001	0.0577	0.4501	0.0039	<0.001	<0.001	-															
PEA_951	35	0.05	0.1394	0.2199	0.5874	0.7547	0.5261	0.4773	0.0198	0.1108	0.2319	0.947	0.1	0.9887	0.9886	0.6353	0.8806	0.7981	0.1682	0.7905	0.003	0.7351	0.4153	0.0853	0.4417	<0.001	0.0868	<0.001	0.0052	<0.001	0.037	<0.001	0.0034	<0.001	0.0347	-														
PEA_952	36	0.0933	0.0069	0.1581	0.0552	0.6561	0.1302	0.8205	0.003	0.0249	0.1991	0.7625	0.1189	0.2588	0.3274	0.6304	0.7197	0.3217	0.9523	0.4648	0.0566	0.7554	0.8979	0.4391	0.37	0.0242	0.1877	0.0064	<0.001	0.0027	<0.001	0.0146	0.0129	0.0178	0.1351	0.0018	-													
PHT	37	0.5358	<0.001	0.1887	0.5734	0.7328	0.5817	0.9283	0.4316	0.8337	0.0701	0.567	0.9905	<0.001	0.2283	0.078	0.8773	0.7002	0.7513	0.533	0.3883	0.7367	0.4383	0.8237	0.3461	0.7648	0.0555	0.7917	0.679	0.7726	0.2837	0.9876	0.1925	0.8293	0.0555	0.8749	0.4537	-												
PRN	38	0.4519	0.4955	0.6541	0.0113	0.7737	0.056	0.8205	0.729	0.6019	0.0318	0.2961	0.2555	0.124	0.2431	0.9465	0.9916	0.5491	0.0884	0.6118	0.7686	0.2851	0.5469	0.4938	0.6324	0.8491	0.0841	0.4048	0.1373	0.5351	0.4883	0.6894	0.1794	0.8785	0.0996	0.411	0.4209	0.0448	-											
RCH	39	0.2274	0.323	0.8329	0.0058	<0.001	<0.001	<0.001	0.2272	0.9959	0.9463	0.9697	0.3214	0.7095	0.5554	0.0253	<0.001	<0.001	0.2052	<0.001	<0.001	0.8972	0.0857	0.6263	0.2627	0.0089	0.0533	0.0598	0.2219	0.0704	0.0372	0.0396	0.0308	0.0153	0.0302	0.0507	0.1214	0.6677	0.6612	-										
Rb	40	0.9772	0.4715	0.073	0.0372	0.5099	0.025	0.6375	0.0138	<0.001	0.0723	0.0875	0.1882	0.8752	<0.001	0.8408	0.5745	0.3201	0.7016	0.4075	0.7239	0.0076	0.0075	0.4964	0.0337	0.8532	0.3657	0.7759	0.9405	0.6554	0.8932	0.908	0.6178	0.9381	0.3811	0.7505	0.3453	0.688	0.1831	0.7148	-									
S	41	0.789	0.5763	0.5581	0.5414	0.0438	0.9697	0.0162	0.468	0.8704	0.0174	0.1632	0.1576	0.0914	0.0922	0.1429	0.0346	0.2943	0.1879	0.0851	0.7904	0.0174	0.1121	0.4049	0.3467	0.3071	0.0194	0.4737	0.0206	0.9006	0.3639	0.2541	0.0166	0.2406	0.009	0.5852	0.7616	0.1599	0.0258	0.2913	0.0761	-								
Se	42	0.3974	0.0777	0.8026	0.7773	0.5913	0.7127	0.4252	0.8386	0.7513	0.5603	0.1213	0.1271	0.6133	0.2138	0.3375	0.561	0.9599	0.1558	0.9839	0.2347	0.3559	0.7057	0.0141	0.1707	0.0597	0.8534	0.0076	0.3565	0.0016	0.1092	0.0318	0.3652	0.066	0.6108	0.0077	0.1417	0.8215	0.8589	0.6183	0.2469	0.9008	-							
Sr	43	0.286	0.1206	<0.001	0.6782	0.5542	0.933	0.5471	<0.001	0.0045	0.0106	0.2814	0.1688	0.6929	0.0115	0.6315	0.775	0.9834	0.8818	0.6968	0.3671	0.3729	0.2163	0.8228	0.7344	0.0099	0.6017	0.0033	0.0786	0.0109	0.0135	0.0042	0.2774	0.0059	0.6238	0.0051	<0.001	0.1096	0.6	0.5134	0.0281	0.7264	0.7125	-						
TGW	44	0.9813	0.7017	0.3955	0.6276	0.4135	0.5417	0.3147	0.0849	0.5759	0.0879	0.9403	0.4684	0.9893	0.0092	0.5852	0.4046	0.3228	0.0815	0.4393	0.5723	0.4556	0.3668	0.3554	0.6265	0.6191	0.8705	0.491	0.7881	0.2021	0.8068	0.7075	0.7276	0.7683	0.9401	0.3651	0.7122	0.8375	0.4304	0.5839	0.3013	0.5898	0.1134	0.5867	-					
TLAR	45	0.467	0.577	0.7112	0.041	<0.001	0.0033	<0.001	0.583	0.6154	0.4087	0.5866	0.9376	0.9404	0.7552	0.0037	<0.001	<0.001	0.0954	<0.001	<0.001	0.5361	0.3592	0.9985	0.5668	0.3334	0.6368	0.5366	0.6864	0.3617	0.1521	0.6307	0.6553	0.4494	0.6006	0.41	0.6859	0.8765	0.1393	<0.001	0.7906	0.0068	0.9926	0.9692	0.6893	-				
TLLR	46	0.4862	0.2864	0.3483	0.45	0.0154	0.207	0.0317	0.6574	0.9866	0.5045	0.0627	0.9579	0.1345	0.7869	<0.001	0.0219	0.5706	<0.001	0.0105	0.0633	0.0345	0.3882	0.781	0.2051	0.7052	0.583	0.9168	0.2251	0.434	0.2909	0.9206	0.9012	0.7822	0.7324	0.8029	0.699	0.1146	0.4215	0.0204	0.9139	0.0676	0.7706	0.5437	0.6212	0.0032	-			
TLPR	47	0.4682	0.5623	0.7191	0.0413	<0.001	0.0034	<0.001	0.5816	0.6169	0.409	0.6038	0.9406	0.9203	0.7625	0.0042	<0.001	<0.001	0.1005	<0.001	<0.001	0.5502	0.35	0.9963	0.5536	0.3331	0.6442	0.5331	0.6929	0.3625	0.1518	0.6286	0.6547	0.4486	0.605	0.407	0.6779	0.8504	0.1365	<0.001	0.7921	0.0069	0.9951	0.9809	0.6811	<0.001	0.0038	-		
WDR	48	0.1417	0.0998	0.9974	0.2173	0.9888	0.1755	0.596	0.0322	0.1507	0.4759	0.9895	0.0057	0.4272	0.6078	0.9098	0.9258	0.6099	0.7781	0.4535	<0.001	0.6989	0.2108	0.1161	0.3785	<0.001	0.0014	<0.001	<0.001	<0.001	0.1659	<0.001	<0.001	<0.001	<0.001	<0.001	0.0083	0.3373	0.8945	0.0101	0.9204	0.2045	0.0405	0.0994	0.802	0.3662	0.6944	0.3676	-	
Zn	49	0.775	0.6516	0.7811	0.5735	0.8855	0.9509	0.7788	0.2303	0.2745	0.0023	0.0021	0.6074	0.7207	0.3819	0.1317	0.9629	0.5976	0.1656	0.5422	0.4703	0.0044	0.2825	0.301	0.1348	0.8716	0.6878	0.5127	0.2657	0.3109	0.9382	0.6879	0.6852	0.739	0.7219	0.5408	0.6009	0.6982	0.0881	0.6029	0.4684	0.0128	0.7227	0.9593	0.6844	0.1591	0.03	0.1653	0.5531	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
		As	BYD	Ba	CHCRX	CHCRY	CMRX	CMRY	Ca	Cs	Cu	Fe	GYD	HI_%	K	LRN	MDR	MLAR	MLLR	MLPR	MWR	Mg	Mn	Mo	P	PEA_1001	PEA_1002	PEA_251	PEA_252	PEA_301	PEA_302	PEA_501	PEA_502	PEA_751	PEA_752	PEA_951	PEA_952	PHT	PRN	RCH	Rb	S	Se	Sr	TGW	TLAR	TLLR	TLPR	WDR	Zn

CHAPTER 5. CHARACTERISATION OF *THINOPYRUM BESSARABICUM* X BREAD/DURUM WHEAT DERIVED AMPHIDIPLOIDS FOR GRAIN YIELD, YIELD COMPONENTS AND GRAIN MINERAL COMPOSITION TRAITS UNDER SALINE SOILS

5.1 Abstract

Background: Salt-affected soils constrain wheat production globally and modern wheat varieties are not salt tolerant. A wild relative of wheat, *Thinopyrum bessarabicum* and its derivatives is tolerant of high external NaCl concentrations, but has not been yet tested in field conditions. The aim of this study was to study the performance of amphidiploids derived from *Th. bessarabicum* for grain yield, yield components and grain mineral composition traits under normal and saline soil conditions and also tested the relationships between juvenile root traits and grain yield, yield components and mineral composition traits.

Methods: Field experiments were conducted at Karnal (soil $pH_{(water)}$ =7.3) and Hisar ($pH_{(water)}$ =8.3) sites in 2014-15 and 2015-16 in India. Grain yield and component traits were measured at each site on eight amphidiploids (*Th. bessarabicum* x bread/durum wheat). Grain samples were analysed using inductively coupled plasma-mass spectrometry (ICP-MS). Juvenile traits were measured by growing seeds on germination paper based 'pouch & wick' system.

Results: Yield and yield component traits of amphidiploids were typically greater at Karnal than Hisar. The GYD was greater at Karnal (1.6 t ha^{-1}) than

Hisar (1.2 t ha^{-1}) in 2014-15 however, GYD was greater at Hisar site (1.7 t ha^{-1}) than Karnal (1.1 t ha^{-1}) in 2015-16. There was a positive relationship in GYD between Karnal and Hisar in both years, however, some amphidiploids had greater GYD at Hisar than Karnal. Mean grain Zn concentration of eight amphidiploids, averaged across sites and years varied from 36-43 mg kg^{-1}. Juvenile root angle traits did not correlate with GYD at Karnal and Hisar, however, maximum width of root (MWR) and root width & depth ratio (WDR) correlated with GYD at Karnal. Narrow root angle traits correlated with grain iron (Fe) and manganese (Mn) concentration at Karnal.

Conclusions: Some amphidiploids derived from *Th. bessarabicum* showed greater GYD and grain Zn concentration under saline soils (Hisar) than normal soils (Karnal). These might be potential new sources for the development of salt tolerant wheat varieties with increased grain Zn concentration under salt affected soils.

5.2 Introduction

Salt affected soils constrain wheat production in many countries. It is estimated that more than 831 million hectares (Mha) is salt affected globally, with 10 Mha of cultivated land lost annually (Pessarakli and Szabolcs 2010; Hasegawa, 2013). In India, 6.7 Mha is affected by salt across 15 out of 29 states (Mandal *et al*., 2010; Sharma *et al.,* 2012). Salinity affects wheat grain yield (Rahnama *et al*., 2011; Khokhar *et al*., 2017) and grain quality traits, e.g. grain zinc (Zn) concentration (Frossard *et al*., 2000). Some variation for salt tolerance in modern 36 Indian wheat genotypes have been reported under hostile soils in India (Khokhar *et al*., 2017), but there is need to develop high salt tolerant varieties to improve the grain yield and grain quality under hostile soils.

A number of wheat wild relatives, for example, *Aegilops tauschii* (DD) and *Triticum urartu* (AA), and their derivatives have shown salinity tolerance when grown in saline hydroponic solutions (Gorham, 1990; Gorham 1991; Mujeeb-Kazi and De Leon, 2002). A greater salinity tolerance has been reported in *Thinopyrum bessarabicum* from the tertiary gene pool (i.e. species not share any genomes with bread wheat). *Thinopyrum bessarabicum* (2n=14; JJ) is a tall wheat grass from tribe *Triticeae* which grows in coastal areas of the Crimea, and shows greater level of salt tolerance than wheat when grown under high saline hydroponic culture (Gorham *et al*., 1985; King *et al*., 1997a). The plants of *Th. bessarabicum* have shown salinity tolerance up to 350 mol m^{-3} NaCl solution culture when grown up to 10 months in glasshouse condition (Gorham *et al.,* 1985) and this species could potentially be used to develop salt tolerant genotypes (King *et al*., 1997a; Qi *et al*., 2010). Salinity tolerance in *Th. bessarabicum* plants is thought to be due to regulation of sodium (Na) and

chloride (Cl) ions to maintain adequate potassium (K) ions concentration in plant leaf and synthesis of glycinebetaine which confer the salt tolerance (Gorham *et al*., 1985; Colmer *et al*., 2006). *Thinopyrum bessarabicum* got more attention because of its combining ability with wheat homoeologous lacking the 5B chromosome and conferred salt tolerance in wheat background when grown in different level of salt solutions until maturity (Forster *et al*., 1987; King *et al*., 1993). Octaploid amphidiploids (AABBDDJJ) developed by crossing *Th. bessarabicum* (JJ) and Chinese spring wheat (AABBDD) showed better vegetative growth when grown in 150 mM NaCl nutrient solution than wheat parents They have shown less reduction in grain yield, better exclusion capacity of Na^+ ions from leaves (40% less) and more accumulation of glycinebetaine (5 fold greater) than Chinese spring (Gorham *et al*., 1986). Similarly, hexaploid amphidiploids (AABBJJ) developed by crossing of *Th. bessarabicum* with durum wheat cultivars (AABB) showed greater salt tolerance and increased fertility than octaploid amphidiploids when tested in different levels of salt (NaCl) concentrations in hydroculture till maturity (King *et al*., 1997b).

The grain mineral composition of *Th. bessarabicum* derivatives have not been studied except by Ardalani *et al*., 2016, who studied grain Zn and Fe concentrations. There is a deficiency of Zn and Fe in the global food system, affecting the human health, particularly in developing countries (Gregory *et al*., 2017; Khokhar *et al*., submitted). Ardalani *et al*., 2016, screened amphidiploid and translocation lines derived from *Th. bessarabicum* under normal soil field conditions in Kurdistan and reported greater grain Zn and Fe concentration in *Th. bessarabicum* derivatives than wheat cultivars. However, derivatives of *Th. elongatum (2n=2x=14; EE),* a close relative of *Th. bessarabicum*, have also

shown greater grain concentration of calcium (Ca), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), phosphorus (P) and zinc (Zn) concentrations than wheat cultivars under rainfed field trails in Washington State University (Murphy *et al*., 2009).

The aim of this study was to study the performance of eight amphidiploids derived from *Th. bessarabicum* for grain yield, yield components and grain mineral composition traits under normal and saline soil conditions in India, and to test the relationships between juvenile root traits and grain yield, yield components and mineral composition traits measured in different hostile soils. The hypothesis being tested is that juvenile root traits, for example, narrow root angle, lateral root length and number related traits, wider root angle and maximum width of root traits are predicted to work best for saline soils for yield components and grain mineral composition traits (Chapter 4).

5.3 Materials and methods

5.3.1 Field locations

The field experiments were conducted at two sites in the North Western Plains Zone (NWPZ) of India, during the *rabi* (winter) seasons in 2014-15 and 2015-16 (**Table 5.1**). The sites were, (1) the Indian Institute of Wheat & Barley Research (IIWBR), Karnal, Haryana, which represents a 'normal soil' of pH 7.3; and (2) IIWBR, Hisar, Haryana, which represents a 'saline soil' of pH 8.3. Further soil characteristics of these sites have been described in Khokar *et al*., 2017. The experiments were conducted at both the sites with the permission of the institute's director and the study received permission from the Indian

Council of Agriculture Research (ICAR) and the Department of Biotechnology (DBT), India under a collaborative project between India and the University of Nottingham, United Kingdom (UK), grand number BT/IN/UK/12/IS/2012.

Table 5.1 Sowing dates and cropping pattern of field experiments in India.

Site	Growing zone	Grid	Sowing	Harvesting	Year	Soil type	Cropping pattern
IIWBR, Karnal	NWPZ	29.70° N	18.11.14	20.04.15	2014-15	Normal	Rice-Wheat
		76.99° E	12.11.15	23.04.16	2015-16		
IIWBR, Hisar	NWPZ	29.18° N	27.11.14	24.04.15	2014-15	Saline	Cotton-Wheat
		75.70° E	24.11.15	22.04.16	2015-16		

5.3.2 Planting material

Grain of eight amphidiploids were provided by Ian King's group who developed these amphidiploids through crossing of *Th. bessarabicum* as the male parent with different durum (*Triticum turgidum*; AABB) and bread (*T. aestivum*; AABBDD) wheat cultivars at the BBSRC-UoN Wheat Research Centre (WRC), University of Nottingham, UK (**Table 5.2**).The resulting hybrids from these crosses were converted into fertile lines by doubling the chromosome numbers. This was achieved when F_1 hybrid plants reached the four tiller stage after vernalisation (exposure to low temperature to induce flowering). The roots and base of the tillers were dipped in a colchicine or caffeine solution, covered with a clean plastic bag and left over (16 h) at room temperature. Colchicine is an extract from bulb of *Colchicum autumnale*, an autumn crocus, which prevent the chromosome segregation during meiosis by binding to tubulin and stop micro-tubule polymerisation (Dhooghe *et al*., 2011). Caffeine is extracted from *Coffea arabica* and it inhibit the division of the cytoplasm of the parental cell further into daughter cells after nuclear division (Thomas *et al.*, 1997). After treatment,

washed root plants were re-potted and grown in the glasshouse. Before anthesis plants were covered with perforated poly bags to avoid any cross pollination and at maturity seeds were threshed manually.

Table 5.2 Amphidiploids used in field trials in 2014-15 and 2015-16 in India.

Amphidiploids	**Pedigree**
EC 787007	*Triticum turgidum* L. cv. Langdon x *Thinopyrum bessarabicum*
EC 787008	*Triticum turgidum* L. cv. Macoun x *Thinopyrum bessarabicum*
EC 787009	*Triticum turgidum* L. cv. Karim x *Thinopyrum bessarabicum*
EC 787010	*Triticum turgidum* L. cv. Neodur x *Thinopyrum bessarabicum*
EC 787011	*Triticum turgidum* L. cv. Creso x *Thinopyrum bessarabicum*
EC 787012	*Triticum turgidum* L. cv. Azaziah x *Thinopyrum bessarabicum*
EC 787013	*Triticum turgidum* L. cv. Stewart x *Thinopyrum bessarabicum*
EC 787014	*Triticum aestivum* L. cv. Chinese spring x *Thinopyrum bessarabicum*

5.3.3 Experimental managements

Field experiments were conducted in *rabi* (winter) season in 2014-15 and 2015-16 at two sites (**Table 5.1**). After conventional operations, including field preparation, fertilising, disking, levelling and furrowing, seeds were manually placed in three rows per plot with an inter-row spacing of 25 cm. The plot length was 1.5 m in 2014-15 and 2.5 m in 2015-16. The experiment was laid out as a randomised block design with three replications. Fertilisers were applied at a rate of 150 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1} as urea, triple super phosphate (TSP) and muriate of potash (MOP), respectively. All fertilisers, including one third of the N, were applied uniformly in the field during final land preparation. One third of the N was top dressed at nodal root initiation (NRI) stage, ~21 days after sowing (DAS), and the remaining N was applied at the time of second

irrigation, ~45 DAS. Experiments were irrigated when required to avoid water stress to the plants, typically on three occasions, to bring the soil moisture close to the field capacity during NRI, booting and grain filling stages. Weeds were controlled manually when required and then crops were protected from pests and disease as required. Crops were harvested at maturity, sun-dried and then threshed manually.

5.3.4 Supplementary lighting

Thinopyrum bessarabicum derived amphidiploids showed perennial and photosensitive nature in the field, hence supplementary lighting was provided to overcome the problem of fertility and flowering. Supplementary lighting was provided in the field using 1000 W tungsten halogen tube-lamps, to give a photoperiod of 16 h d^{-1} light at Karnal (**Figure 5.1**A) and Hisar (**Figure 5.1**B) sites. Supplementary lighting was provided from 45 DAS, corresponding with the period of late vegetative growth to anthesis. At the onset of maturity, plants in each plot were covered with netting bags of 2 $feet^2$ to avoid the falling off spikelets from the spike. In each plot 7-10 netting bags were used.

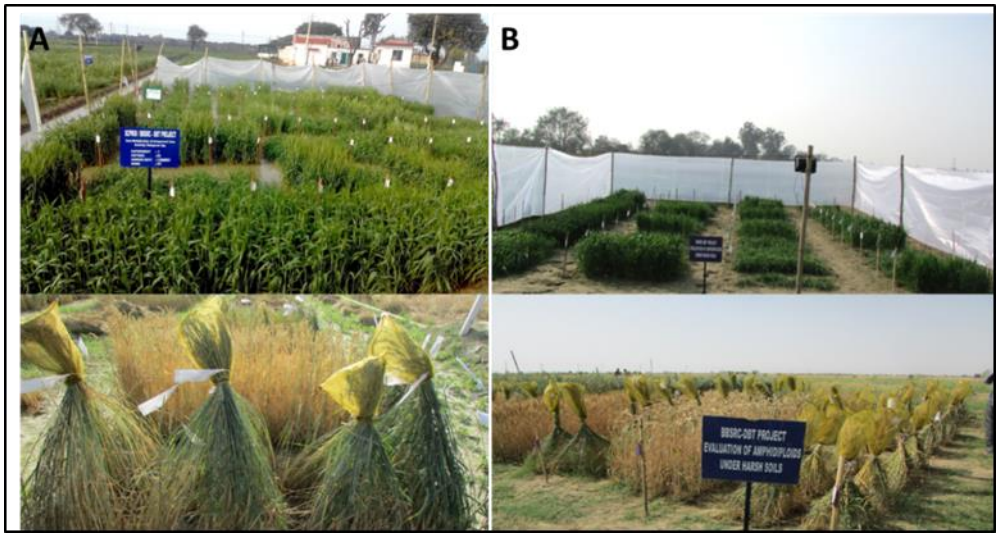


Figure 5.1 Supplementary lightning and covering of spikes with net bags at A) IIWBR, Karnal and, B) IIWBR Hisar sites.

5.3.5 Trait measurements

Pre-harvest traits, for example, Grain number per spike (GNS); Grain weight per spike (GWS, g) and Plant height at maturity (PHT, cm), were recorded on five randomly selected plants per plot, which were tagged for subsequent measurements at maturity, alongside plot-scale measurements. The data were recorded on the following traits: Grain yield per plot at 12-13% dry weight (GYD, g); GNS; GWS; 1000 grain weight (TGW, g); Productive tillers per meter (PTM); Biological yield per plot (BYD, g); Harvest index (HI, %); Days to 75% heading (DTH, d); Days to anthesis (DTA, d); Days to 75% maturity (DTM, d) and PHT.

5.3.6 Grain mineral concentration

Grain samples from two replications were used from Hisar site in 2014-15 while grain samples from three replications were used from Karnal and Hisar sites in

2015-16 for grain mineral analysis. Details of grain sampling, digestion, data validation and mineral analysis by ICP-MS are described in Khokhar *et al*., submitted (Chapter 3). Briefly, grain samples were crushed inside a paper bag and subsamples (~0.200 g, DW) were then used for microwave digestion. Crushed grain samples were digested in 2 mL 70% Trace Analysis Grade (TAG) HNO_3, 1 mL Milli-Q water (18.2 MΩ cm; Fisher Scientific UK Ltd, Loughborough, UK), and 1 mL H_2O_2. Prior to digestion, the samples were soaked in this solution for one hour at room temperature. Two operational blanks, duplicate samples of certified reference material (CRM) of wheat flour (Wheat SRM 1567b, NIST, Gaithersburg, MD, USA) and duplicate laboratory reference material (LRM), Paragon, were used for each digestion run. Following digestion, each tube was made up to a final volume of 15 mL by adding 11 mL Milli-Q water, then transferred to a 25 mL universal tube (Sarstedt Ltd., Nümbrecht, Germany) and stored at room temperature. Samples were further diluted 1:5 with Milli-Q water into 13 ml tubes (Sarstedt Ltd.) for determination of grain Zn concentration and 30 other elements by ICP-MS (Thermo Fisher Scientific iCAPQ, Thermo Fisher Scientific, Bremen, Germany). In total, 64 grain samples were analysed in two runs, excluding blank, CRM and LRM samples.

5.3.7 Root phenotyping of amphidiploids

A two dimensional high throughput phenotyping (HTP) 'pouch and wick' system was used to study the root architecture of seven amphidiploids, except EC 787014, due to non-availability of seeds. Experimental methods are based on Atkinson *et al*. (2015), Thomas *et al*. (2016), Xie *et al*. (2017) and Chapter 4. Briefly, seeds were sterilized by 5% (v/v) sodium hypochloride for 15 minutes

and then rinsed three times with sterilized water. Seeds were placed on pre-soaked germinated paper, crease side down, and incubated at 4°C for 96 hours. Seeds were grown on germinated paper in hydroponic condition for nine days. The imaging and processing of roots using RootNav software and measurement of different root traits have been described in Chapter 4.

5.3.8 Statistical analysis

Variance components were calculated for yield, yield components, mineral composition and root traits. The analysis of variance (ANOVA) was used to test the differences in yield and component traits due to genotype and site factors, for each site and year while differences in mean of mineral composition traits at each site. Means of grain yield, yield components and grain mineral composition traits were compared using Least Significant Difference (LSD) for each site. Differences between sites and genotypes for grain yield were considered significant at $P<0.01$. Pearson correlation coefficients were calculated to study the correlation among yield and yield components for each site and between the sites. Correlations coefficients were also measured between yield, yield components, mineral composition traits and juvenile root traits. All data analyses were conducted using GenStat 17th Edition (VSN International Ltd, Hemel Hempstead, UK).

5.4 Results

This study reported the performance of eight amphidiploids derived from crosses between *Th. bessarabicum* x bread/durum wheat, for grain yield, yield components and grain mineral composition traits under different hostile soil

environments and quantified the association between seedling root traits and grain yield, yield components and grain mineral composition traits measured in hostile soil field conditions.

Grains of eight amphidiploids were observed visually and found that *Th. bessarabicum* x durum wheat derived amphidiploids, from EC-787007 to EC-787013, had longer and more brownish grains than *Th. bessarabicum* x Chinese Spring derived amphidiploid (EC-787014). Grain colour of EC-787014 was similar to wheat parent, Chinese spring (**Figure 5.2**).



Figure 5.2 Comparison of grain size and colour of eight amphidiploids. Left to right: EC-787007 (*Th. bessarabicum* x Langdon), EC-787008 (*Th. bessarabicum* x Macoun), EC-787009 (*Th. bessarabicum* x Karim), EC-787010 (*Th. bessarabicum* x Neodur), EC-787011 (*Th. bessarabicum* x Creso), EC-787012 (*Th. bessarabicum* x Azaziah), EC-787013 (*Th. bessarabicum* x Stewart), EC-787014 (*Th. bessarabicum* x Chinese spring) and Chinese spring.

5.4.1 Differences in grain yield of eight amphidiploids at Karnal (normal) and Hisar (saline) sites

The GYD differed between amphidiploids in both 2014-15 and 2015-16 ($P<0.001$). The mean GYD of eight amphidiploids, averaged across sites, varied from 0.8 to 2.9 t ha^{-1} in 2014-15 (**Figure 5.3**a) and from 0.8 to 2.5 t ha^{-1} in 2015-16 (**Figure 5.3**b). The EC 787014 amphidiploid had the greatest GYD in both years. The EC 787012 and EC 787008 amphidiploids had the smallest GYD in 2014-15 and 2015-16, respectively.

There was a positive relationships in GYD between Karnal and Hisar in both 2014-15 ($r=0.82$) and 2015-16 ($r=0.89$). In 2014-15, the mean GYD of eight amphidiploids varied from 0.9 to 2.8 t ha^{-1} at Karnal and from 0.7 to 3.0 t ha^{-1} at Hisar site (**Figure 5.3**c). In 2015-16, the mean GYD of eight amphidiploids varied from 0.6 to 2 t ha^{-1} at Karnal and from 0.7 to 3.0 t ha^{-1} at Hisar site (**Figure 5.3**d).

The EC 787014 amphidiploid had the greatest GYD at Hisar in both years (**Figure 5.4**). In 2014-15, the EC 787014 amphidiploid had the greatest GYD at Karnal (2.8 t ha^{-1}) and Hisar (3.0 t ha^{-1}) sites and the EC 787012 amphidiploid had the smallest GYD at Karnal (0.9 t ha^{-1}) and Hisar (0.7 t ha^{-1}) sites. In 2015-16, the EC 787014 amphidiploid had the greatest GYD at Karnal (2 t ha^{-1}) and Hisar (3.1 t ha^{-1}) sites and the EC 787013 (0.6 t ha^{-1}) and EC 787008 (0.7 t ha^{-1}) had the smallest GYD at Karnal and Hisar sites, respectively.

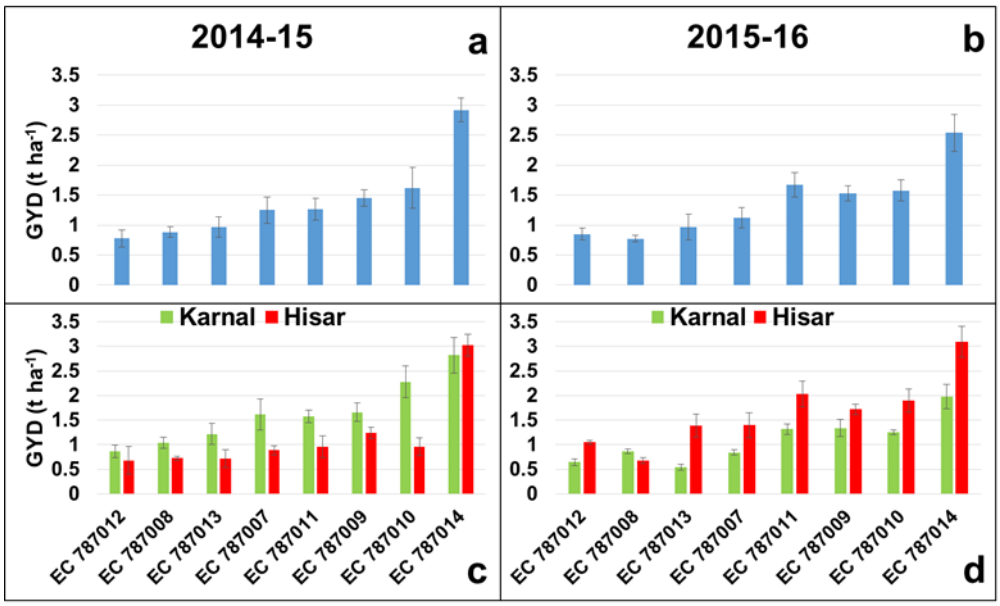


Figure 5.3 Mean grain yield of eight amphidiploids harvested in 2014-15 and 2015-16 at Karnal and Hisar sites. In panels (a) and (b), data are means of each amphidiploid across sites, while in (c) and (d) data are means of three replicate plots per amphidiploid per site in 2014-15 and 2015-16, respectively (± standard error of the mean). Green and red bars represent 'normal' and 'saline' soils, respectively.



Figure 5.4 Amphidiploid, EC 787014 (*Th. bessarabicum* x Chinese spring) growing at Hisar (saline) sites.

5.4.2 Differences in grain yield and yield component traits between Karnal (normal) and Hisar (saline) sites

Yield and yield component traits were typically greater at Karnal than Hisar site (**Figure 5.5**). The GYD was greater at Karnal (1.6 t ha^{-1}) than Hisar (1.2 t ha^{-1}) in 2014-15 (LSD=0.22) while in 2015-16 it was greater at Hisar (1.7 t ha^{-1}) than Karnal (1.1 t ha^{-1}) (LSD=0.17). BYD was greater at Hisar than Karnal in both years. In 2014-15, BYD was 2012 and 2312 g at Karnal and Hisar sites, respectively (LSD=222.7). In 2015-16, BYD was 3566 and 4702 g at Karnal and Hisar sites, respectively (LSD=330.7). TGW and GWS did not differ between sites in 2015-16 but was greater at Karnal in both years. In 2014-15, TGW was 32.7 and 26.3 g at Karnal and Hisar sites, respectively (LSD=1.74). In 2015-16, TGW was 26.5 and 25.6 g at Karnal and Hisar, respectively (LSD=1.53). In 2014-15, GWS was 1.2 and 0.8 g at Karnal and Hisar sites, respectively (LSD=0.16). In 2015-16, GWS was 1.0 and 0.9 g at Karnal and Hisar sites, respectively (LSD=0.1). The HI differ significantly between sites in both years. In 2014-15, HI was 10 and 6.4% at Karnal and Hisar, respectively (LSD=1.0). In 2015-16, HI was 7.8 and 9.3% at Karnal and Hisar, respectively (LSD=0.8).

The PTM did not differ between sites in 2014-15. However, the PTM was greater at Hisar than Karnal in both years. In 2014-15, PTM was 85 and 86 at Karnal and Hisar sites, respectively (LSD=10.22). In 2015-16, PTM was 104 and 113 at Karnal and Hisar sites, respectively (LSD=8). The PHT differed between sites in both years and was greater at Karnal in both years. In 2014-15, PHT was 109 and 105 at Karnal and Hisar sites, respectively (LSD=3.35). In 2015-16, PHT was 125 and 105 at Karnal and Hisar sites, respectively (LSD=3.16).

The DTM differed between sites in both years. In 2014-15, DTM was 152 and 163 days at Karnal and Hisar sites, respectively (LSD=1.11). In 2015-16, DTM was 164 and 152 days at Karnal and Hisar sites, respectively (LSD=0.89) (**Figure 5.5**).

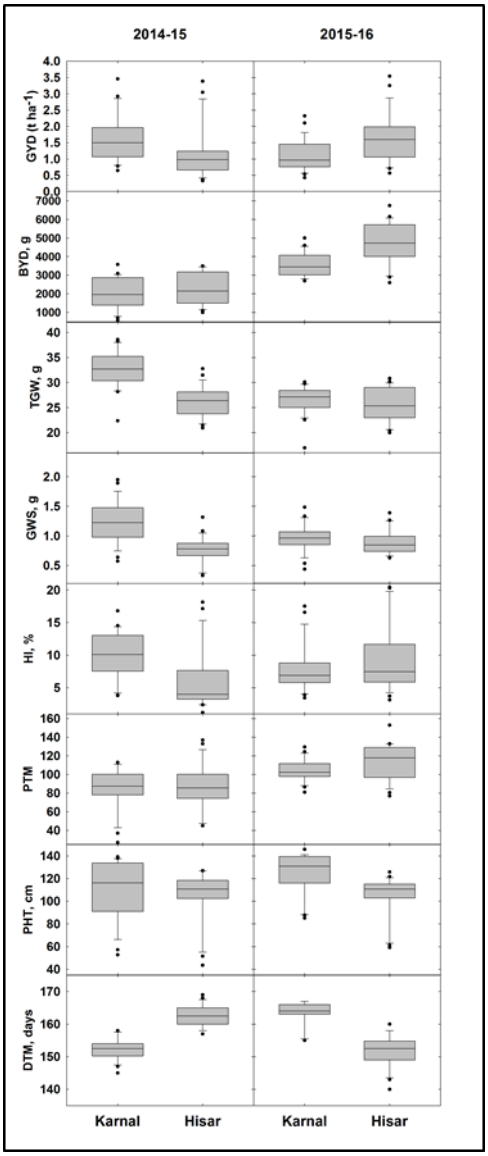


Figure 5.5 Yield and yield component traits at Karnal and Hisar sites in 2014-15 and 2015-16. Data represent three replicate plots per site of eight amphidiploids (n=24) in 2014-15 and 2015-16. Boxes represent the two quartiles with median drawn; whiskers are the 95% confidence limits plus outliers. Traits: GYD (grain yield, t ha^{-1}), BYD (biological yield, g), TGW (1000 grain weight, g), GWS (grain weight per spike, g), HI (harvest index, %), PTM (productive tillers per meter), PHT (plant height at maturity, cm), DTM (days to maturity, days).

5.4.3 Comparison of grain yield reduction between Karnal (normal) and Hisar (saline) sites, in 36 Indian wheat genotypes and eight amphidiploids

The amphidiploids showed less reduction in GYD on the saline site than a panel of 36 genotypes in a previous study (Khokhar *et al*., 2017). Mean GYD of 36 Indian wheat genotypes, averaged across years, showed 6 to 59% reduction under saline soil (Hisar) than normal soil (Karnal) (S5.1 Table). All 36 wheat genotypes showed lower GYD under saline soil (Hisar) than normal soil (Karnal), except KRL 3-4, which showed 92% greater GYD at Hisar (saline) than Karnal (normal) (Khokhar *et al*., 2017). Mean GYD of eight amphidiploids, averaged across years, showed 1 to 26% reduction under saline soil (Hisar) than normal soil (Karnal) (S5.2 Table). Out of eight, four amphidiploids showed 3 to 28% higher GYD under saline soil (Hisar) than normal soil (Karnal).

5.4.4 Variance components associated with grain yield and component traits

The contribution of Genotype (G), Environment (E) and G*E interactions (G*E) to variation in GYD and yield component traits of eight amphidiploids was determined (**Table 5.3**). Genotype was associated with most of the variation in yield and yield component traits in both years (**Table 5.3**). For example, 68 and 64% of the variation in GYD was associated with genotype in 2014-15 and 2015-16, respectively. Genotype was also associated with most of the variation in BYD (78 and 42%) and PHT (88 and 66%) in 2014-15 and 2015-16, respectively. DTM was associated with E (72 and 68%) to a greater extent than G (15 and 27%) or G*E interaction (3 and 6%) in 2014-15 and 2015-16,

respectively. Site had much greater influence on TGW, GWS and HI in 2014-15 than in 2015-16.

Table 5.3 The contribution of G, E and G*E interaction to variation in grain yield and yield component traits of eight amphidiploid grown at two sites in India during 2014-15 and 2015-16.

Traits	Variation (%)							
	G		E		G*E		Residual	
	2015	2016	2015	2016	2015	2016	2015	2016
Grain yield per plot (GYD)	67.7	63.7	9.8	16.7	7.2	7.0	15.3	12.6
Biological yield (BYD)	77.5	41.6	3.1	27.3	6.2	13.3	13.2	17.8
Germination % (Germ. %)	67.0	67.1	4.9	14.5	13.9	4.4	14.1	14.0
1000 grain weight (TGW)	18.8	25.1	49.3	2.0	4.4	26.0	27.6	46.8
Grain weight per spike (GWS)	13.2	50.6	41.5	2.5	9.8	4.7	35.5	42.2
Harvest Index (HI)	58.0	84.8	16.2	3.1	15.5	5.5	10.2	6.6
Productive tillers per meter (PTM)	45.9	23.1	0.1	8.1	15.4	22.9	38.6	46.0
Plant height at maturity (PHT)	88.3	65.6	0.8	23.9	7.2	5.7	3.7	4.7
Days to maturity (DTM)	15.0	26.8	71.9	67.5	6.9	2.9	6.2	2.8
Degrees of freedom (d.f.)	*7*		*1*		*7*		*32*	

5.4.5 Correlation among grain yield and yield component traits at Karnal (normal) and Hisar (saline) sites

At Karnal, there was a significant positive correlation between GYD and TGW (r=0.49), HI (r=0.62), GWS (r=0.48) and a significant negative correlation between GYD and DTM (r=-0.59); GYD did not correlate with BYD, PTM and PHT. At Hisar, there was a significant positive correlation between GYD and GWS (r=0.59), HI (r=0.88), PTM (0.31) and a significant negative correlation between GYD and DTM (r=-0.53); GYD did not correlate with BYD, PHT and TGW.

5.4.6 Variation in wheat grain Zn concentration and the grain ionome

The mean grain Zn concentration across all plots and years (n=64) was 39.7 mg kg^{-1} and ranged from 21.2 to 58.9 mg kg^{-1} across all plots (**Table 5.4**). Among the macronutrients, the mean grain concentration of calcium (Ca), potassium (K), magnesium (Mg), potassium (P) and sulphur (S) across all plots were 636, 5520, 1650, 5160 and 2180 mg kg^{-1}, respectively. Among micronutrients, the mean grain concentration of copper (Cu), iron (Fe), manganese (Mn) and molybdenum (Mo) across all plots were 7, 50.1, 47.8 and 1.3 mg kg^{-1}, respectively. Among non-essential trace elements, the mean grain concentration of arsenic (As), cadmium (Cd) and selenium (Se) was 0.0154, 0.0351 and 0.331 mg kg^{-1}, respectively (**Table 5.4**).

Table 5.4 Grain concentration of Zn and other mineral elements of amphidiploid wheat. Data are in mg kg^{-1}, summarised across all plots (n=64).

Elements	Mean	Median	SD	Min	Max	LOD
Zn	39.7	40.0	8.20	21.2	58.9	0.572
As	0.0154	0.0106	0.0146	0.0016	0.0646	0.00319
Al	11.1	11.1	4.22	2.26	26.3	4.53
Ba	9.47	8.2	6.1	2	24.1	0.0291
Ca	636	631	94.8	273	819	7.65
Cd	0.0351	0.033	0.0196	0.00634	0.0999	0.00121
Cs	0.0102	0.00586	0.00853	0.000271	0.0302	0.000542
Cu	7.01	7	1.44	3.53	9.99	0.355
Fe	50.1	49.3	8.33	22.1	72.8	4.76
K	5520	5660	843	2920	7140	2.02
Mg	1650	1670	217	643	1950	0.942
Mn	47.8	47.8	9.24	18.9	69.8	0.238
Mo	1.34	1.3	0.33	0.609	2.36	0.077
Na	42.3	34.2	25.4	13	103	5.39
P	5160	5220	657	2530	6590	1.84
Rb	5.78	4.45	3.77	0.468	15.2	0.00599
S	2180	2170	257	947	2620	106
Se	0.331	0.289	0.206	0.0912	0.911	0.00342
Sr	10.1	9.66	3.92	4.18	18.4	0.0886
Ti	0.46	0.456	0.117	0.126	0.736	0.251
V	0.0212	0.0201	0.00833	0.00251	0.0468	0.00503

5.4.7 Differences in grain Zn concentration and the grain ionome between Karnal (normal) and Hisar (saline) sites

Grain Zn concentration differed between sites (<0.001). The mean grain Zn concentration varied from 34.9 (Karnal) to 42.7 (Hisar) mg kg^{-1}, averaged across eight amphidiploids and both years (LSD=3.83). Among the macronutrients, grain Ca, K, P and S concentrations differed significantly, except Mg. Mean grain concentration of Ca, K, Mg, P and S, averaged across eight amphidiploids and years, were 667, 5182, 1641, 4820 and 2091 mg kg^{-1} at Karnal; 617, 5727,

1650, 5358 and 2229 mg kg^{-1} at Hisar, respectively. (**Figure 5.6**). Among the micronutrients, the mean grain Cu, Fe, Mn and Mo concentrations were 6.2, 48.1, 43.5 and 1.1 mg kg^{-1} at Karnal; 7.5, 51.3, 50.4 and 1.5 mg kg^{-1} at Hisar, respectively. Among the non-essential trace elements, the mean grain arsenic (As) concentration varied from 0.007 (Karnal) to 0.021 (Hisar) mg kg^{-1} (LSD=0.007). The mean grain Se concentration varied from 0.5 (Karnal) to 0.2 (Hisar) mg kg^{-1} (LSD=0.07).

Most of the grain mineral composition traits differed between sites ($P<0.01$) except grain aluminium (Al), cadmium (Cd), Fe and Mg concentrations. The mean grain concentration of most of the mineral composition traits were greater at Hisar than Karnal site except of grain concentration of Ba, Ca, Cd, Cs, Rb, Se and Tl (**Figure 5.6**).

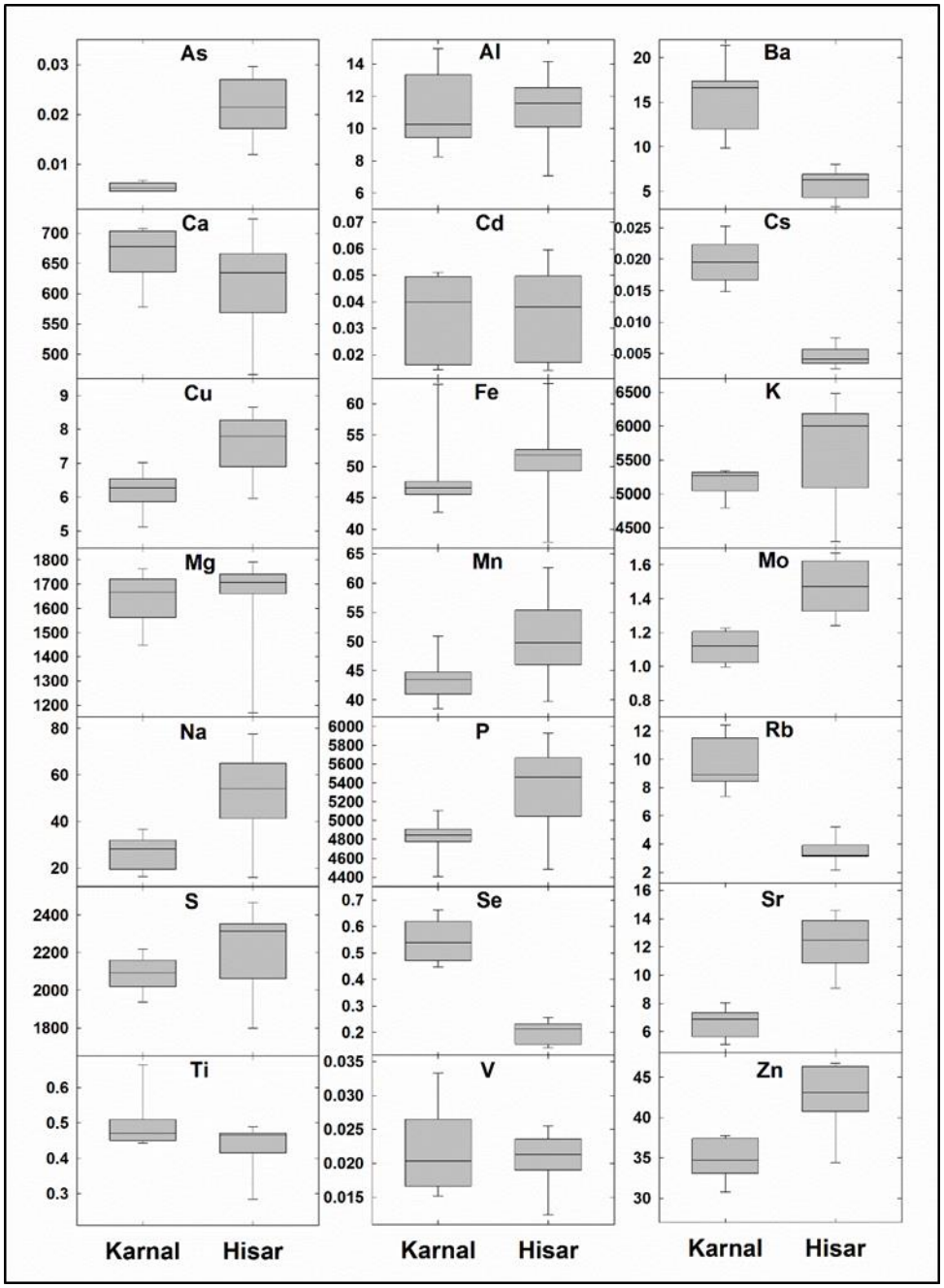


Figure 5.6 Grain element concentration of eight amphidiploids at Karnal and Hisar sites over two years. Data represent the mean of two replicate plots per amphidiploid at Hisar site in 2014-15 and three replicate plots per amphidiploid at Karnal and Hisar sites in 2015-16. Boxes represent the two quartiles with the median drawn; whiskers are the 95% confidence limits; circles are the outliers.

5.4.8 Differences in grain Zn concentration of eight amphidiploids between Karnal (normal) and Hisar (saline) sites

Grain Zn concentration did not differ significantly between eight amphidiploids (P=0.49). The mean grain Zn concentration of eight amphidiploids varied from 35.7 to 43.2 mg kg^{-1}, averaged across sites and years (**Figure 5.7**a). The EC 787013 and EC 787009 had the greatest and smallest grain Zn concentration, respectively. There were no significant relationship in mean grain Zn concentration of eight amphidiploids, averaged across years, between Karnal and Hisar sites (r=0.24; P=0.57). The mean grain Zn concentration of eight amphidiploids, averaged across years, varied from 30.8 to 37.8 mg kg^{-1} at Karnal and from 34.5 to 46.7 mg kg^{-1} at Hisar site. The EC 787009 and EC 787007 had the greatest grain Zn concentration at Karnal and Hisar sites, respectively. The EC 787008 and EC 787009 amphidiploids had the smallest grain Zn concentration at Karnal and Hisar sites, respectively (**Figure 5.7**b).

All the amphidiploids have shown greater grain Zn concentration at Hisar than Karnal site, except EC 787009, however, 13 out of 36 Indian wheat genotypes showed lower grain Zn concentration at Hisar than Karnal, averaged across years.

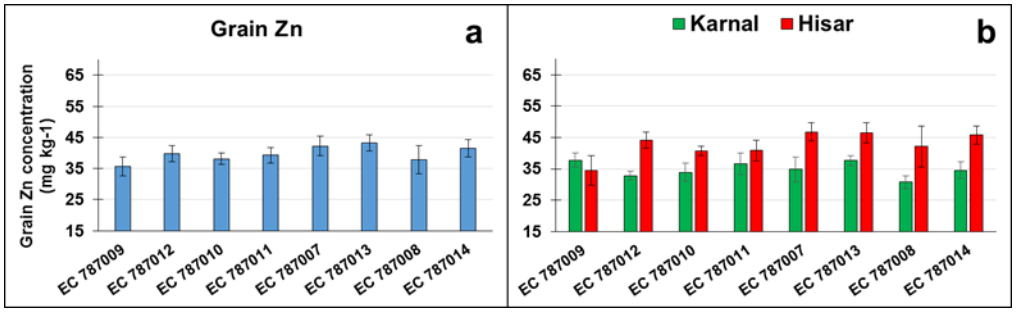


Figure 5.7 Grain Zn concentration of eight amphidiploids grown at two sites over two years. In panel (a) data are means of each amphidiploid averaged across site and years. In panel (b) data represent two replicate plots per amphidiploid at Hisar site in 2014-15 and three replicate plots per amphidiploid at Karnal and Hisar sites in 2015-16 (± standard error of the mean). Green and red bars represent 'normal' and 'saline' soils, respectively).

5.4.9 Correlations between grain Zn concentration and the grain ionome and grain yield

The grain Zn concentration showed positive significant relationships with grain concentration of Ca, Mg, Mn, P, S and Sr (r=0.88, 0.81, 0.94, 0.87, 0.85 and 0.96, respectively). However, grain Zn concentration not correlated with grain concentration of Al, As, Ba, Cd, Cs, Cu, Fe, K, Mo, Na, Rb, Se, Ti and V. There was no relationship between grain Zn concentration and GYD.

5.4.10 Variance components associated with grain ionome

Genotype (G) and site (E) terms were associated with 8 and 22% of the variation in grain Zn concentration, respectively. The residual term (R) was associated with 62% of the variation in grain Zn concertation and these variation could be due to year, plot-to-plot variation between replicates, and technical/measurement errors.

Genotype (G) was typically associated with a greater proportion of the variation in the grain concentration of other minerals compared to Zn (S5.3 Table). Among the macronutrients, 42, 32, 46, 22 and 35% of the variation in grain Ca, K, Mg, P and S concentration was associated with G; 7, 10, 0, 16 and 7% of the variation was associated with E, respectively.

Among the micronutrients, 15, 46, 27 and 10% of variation in grain cupper (Cu), iron (Fe), manganese (Mn) and molybdenum (Mo) was associated with G; 21, 3, 13, 29% of variation was associated with E, respectively. Among non-essential trace elements, 29 and 65% of the variation in grain arsenic (As) and selenium (Se) concentration, respectively, was associated with E, with just 6 and 4% of the variation associated with G, respectively (S5.3 Table).

5.4.11 Relationships between juvenile root traits and grain yield, yield components and grain mineral composition traits

The hypothesis being tested are that GYD and BYD not correlated with any root traits, narrow root angle traits correlated with HI, lateral root length/number correlated with PHT and wider root angle traits correlated with TGW of 36 Indian wheat genotypes under saline soil (Hisar), whilst, narrow root angle traits correlated with GYD and HI of 36 Indian wheat genotypes at Karnal (normal) site in India (Chapter 4).

The present study showed that juvenile root traits not correlated with GYD of seven amphidiploids, averaged across years, at Hisar (saline) site. Among length related root traits, total length of all roots (TLAR; r=0.86), total length of primary roots (TLPR; r=0.86) and maximum depth of roots (MDR; r=0.78) correlated with BYD of seven amphidiploids, averaged across years, at Hisar

site. The productive tillers per meter (PTM) of seven amphidiploids, averaged across years correlated with TLAR (r=0.82) and TLPR (r=0.83) at Hisar site (S5.5 Table). Under normal soil (Karnal), maximum width of root (MWR) and width depth ratio (WDR), which represent the wider and deeper root system correlated with GYD of seven amphidiploids, averaged across years, at Karnal (normal soil) site, (r=0.77, 0.90, respectively). The wider root angle traits correlated with BYD and DTM of seven amphidiploids, averaged across years, at Karnal. Among length related root traits, TLAR (r=0.80) and TLPR (r=0.80) correlated with BYD of seven amphidiploids, averaged across years, at Karnal (S5.4 Table).

Wider root angle traits have shown association with grain Fe and Mg concentration of 36 Indian wheat genotypes under normal soil (Karnal) and length related root traits, for example, TLLR, TLPR and MWR have shown association with grain concentration of Fe, Mg and S of 36 wheat genotypes under saline soil (Hisar), India (Chapter 4). Our results showed that narrow root angle which potentially represent a steep root system correlated with grain Fe, K and Mn concentration of seven amphidiploids, averaged across years, at Karnal (normal soil) site. However, lateral root number and total length of lateral roots correlated negatively with grain concentration of Fe and Mn of seven amphidiploids, averaged across years at Karnal site. (S5.6 Table). Juvenile root traits were not correlated with grain macronutrients and micronutrients traits of seven amphidiploids, averaged across year at Hisar site (S5.7 Table).

In general, the total length of all roots (TLAR) and total length of primary roots (TLPR, **Figure 5.8**A) correlated with both BYD and DTM of seven

amphidiploids, averaged across sites and years. Wider root angle traits correlated with BYD, percentage germination, DTM and PTM traits of seven amphidiploids, averaged across sites and years. For example, the wider root angle trait, PEA 252, correlated with grain BYD (**Figure 5.8**B) of seven amphidiploids, averaged across sites and years. The wider root angle which potentially represent the shallow root system, showed positive relationships with grain Zn concentration (r=0.76) of seven amphidiploids, averaged across sites and years (**Figure 5.8**C).

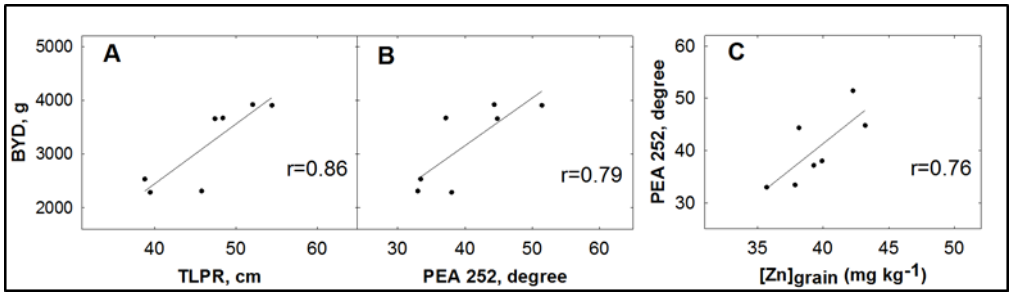


Figure 5.8 Relationships between field traits and seedling root traits and between root angle trait and grain Zn concentration of seven amphidiploids grown at two sites over two years. A) Correlation between BYD (g) and TLPR (cm); B) correlation between BYD (g) and PEA 252 (degree); C) correlation between PEA 252 (degree) and grain Zn concentration (mg kg^{-1}).The BYD data are mean of three replicate plots per amphidiploid averaged across sites and years. Grain Zn concentration data are means of two replicate plots per amphidiploid at Hisar in 2014-15 and three replicate plots per amphidiploid at Karnal and Hisar in 2015-16. Seedling root traits data are means of 12 to 19 replicates of seven amphidiploids.

5.5 Discussion

Wheat grain production and quality is greatly affected by salt affected soils. Therefore, there is scope to explore the salt tolerant wild wheat species to

harness the diversity for grain yield, yield components and nutrient traits. In present study, eight amphidiploids derived from *Th. bessarabicum*, a salt tolerant wheatgrass, were studied under hostile soil environments for grain yield, yield components and mineral composition traits. Further hypothesis tested based on Chapter4 that juvenile root traits correlated with grain yield, yield components and grain mineral composition traits under normal and saline soils.

5.5.1 Significant performance of amphidiploids for grain yield and yield components under saline soils

Thinopyrum bessarabicum crossed with seven durum wheat varieties, Langdon, Macoun, Karim, Neodur, Creso, Azaziah and Stewart and with one bread wheat, Chinese spring. Amphidiploids with durum wheat parents (EC 787007 to EC787013) had longer grains than the amphidiploid, EC 787014 with bread wheat parent. All of the amphidiploids showed photosensitive and perennial nature under field conditions which are in agreement with Hassani *et al*., 2000, who reported perennial nature of these amphidiploids under greenhouse growing conditions. Most of the amphidiploids showed suppressed awning traits, however some variation was observed, for example EC 787009 had awns which are consistent with King *et al*., 1997b who reported awn traits in this amphidiploid under glasshouse growing condition. A panel of 36 Indian wheat genotypes showed reduction in GYD up to 59% under saline soil (Hisar) than normal soil (Karnal) (Khokhar *et al*., 2017). In the present study, the *Th. bessarabicum* derived eight amphidiploids showed less reduction in GYD up to 26% under saline soil (Hisar) than normal soil (Karnal) and most of the amphidiploids showed greater GYD under saline soil. It indicates the presence

of salt tolerance genes/traits in these amphidiploids which support their better performance under saline soil conditions.

The mean of BYD, PTM and percentage germination, averaged across amphidiploids and years, were greater under saline soils (Hisar) than normal soil (Karnal). Our results are consistent with King *et al*., 1997b, who reported greater number of heads per plant and better germination of *Th. bessarabicum* derived amphidiploids than wheat parents under salt (NaCl) solution of 200 mol m^{-3} concentration. Whilst, salinity reduced the TGW, GWS, HI, PHT and DTM of amphidiploids. Forster *et al*., 1987, reported reduction in grain weight and plant height of *Th. bessarabicum* x Chinese spring derived amphidiploid when grown under 250 mol m^{-3} salt solution until maturity. Javed *et al*., 2003, reported that soil salinity shortened the grain filling duration which possibly cause reduction in grain weight. King *et al*., 1997b also reported reduced height of *Th. bessarabicum* derived amphidiploids when grown under salt (NaCl) solution culture. Our results are also consistent with Noori *et al*., 2010; Turki *et al*., 2012; Akbarpour *et al*., 2015; Chamekh *et al*., 2016 and Khokhar *et al*., 2017, who reported reduction in TGW HI and GWS in modern wheat genotypes when grown under saline field conditions.

Grain yield of amphidiploids correlated positively with PTM at Hisar (saline), not at Karnal; EC 787011, EC 787012, EC 787013 and EC 787014 had the greater GYD at Hisar than Karnal. Given that GYD of amphidiploids associated positively with GWS, HI and PTM under saline soils, therefore selection based on these traits could improve the GYD under saline soils. DTM had negative relationship with GYD under saline soil (Hisar) which are in agreement with

Khokhar *et al*., 2017, who reported early maturity of 36 Indian wheat genotypes under saline soils. The amphidiploid, EC 787014 showed earliness in physiological maturity at both sites than other amphidiploids which are consistent with Hassani *et al*., 2000 and King *et al*., 1997b, who reported early physiological maturity of this amphidiploid in comparison to other amphidiploids under normal soil field condition and salt solution culture, respectively. It indicates that early maturity might favour GYD under saline soil or a way to escape salt stresses (McDonald *et al*., 2013).

Notably, some amphidiploids performed better for GYD and component traits under saline soils. For example, EC 787014 (*Th. bessarabicum* x Chinese spring) amphidiploid had the highest GYD, HI, TGW and GWS under saline soil (Hisar). It may be due to the presence of an extra D genome in this amphidiploid as compared to others. Other amphidiploids, for example, EC 787011 (*Th. bessarabicum* x Creso), EC 787012 (*Th. bessarabicum* x Azaziah) and EC 787013 (*Th. bessarabicum* x Stewart) also had greater GYD under saline soil. Hassani *et al*., 2000 reported that *Th. bessarabicum* x Chinese spring (CS) and *Th. bessarabicum* x Stewart derived amphidiploids had greater tiller numbers and TGW than other *Th. bessarabicum* derived amphidiploids under normal soil field conditions.

The better performance of these amphidiploids for GYD and component traits under saline soil might be due to salt tolerance mechanism introgressed from *Th. bessarabicum*, which is known as a salt tolerant wild species and shows salt tolerance by limiting leaf Na^+ and Cl^- concentration, maintain high K^+, K^+/Na^+ concentrations and synthesize glycinebetaine for osmotic adjustment and

protecting the plant from toxic effect of excessive salt in the soil, it is the subject of further studies for breeding salt tolerance (Colmer *et al*., 2006; Munns and Tester., 2008; Munns *et al*., 2011; Zhu *et al*., 2016). All of the amphidiploids showed fragile spikes and spikelets which is consistent with King *et al*., 1997b; Hassani *et al*., 2000; Stoyanov H, 2012. The presence of these undesirable agronomic traits could be due to the presence of genes from *Th. bessarabicum* (King *et al*., 1997b). But, the genes responsible for these undesirable traits can be removed by hybridization of amphidiploids with hexaploid wheat lines and continue selections for wheat components (Hassani *et al*., 2000; Marais *et al*., 2014; Ghazali *et al*., 2015).

5.5.2 Characterisation of amphidiploids for grain Zn concentration and the grain ionome

Wheat is an important dietary source of Zn for people of developing countries, particularly India. The modern wheat varieties had less variation for grain Zn concentration, for example, a panel of 36 Indian wheat genotypes showed grain Zn concentration from 26-32 mg kg^{-1} under field conditions in India (Khokhar *et al*., submitted). A similar range of grain Zn concentration have been reported in field grown wheat at global scale which showed 10 to 20 mg kg^{-1} less grain Zn concentration than the target of 40 mg kg^{-1} for human diet (Chen *et al*., 2017). In the present study, *Th. bessarabicum* derived eight amphidiploids showed grain Zn concentration from 36 to 43 mg kg^{-1}. Our result are consistent with Ardalani *et al*., 2016, who reported mean grain Zn concentration of 35 mg kg^{-1} in *Th. bessarabicum* derived hexaploid amphidiploid under field condition in Kurdistan. The HarvestPlus has used the wild wheat relatives, for example, *Aegilops tauschii*, wild *Triticum dicoccon* and *Triticum spelta* for the developed

high-Zn wheat varieties with 7 to 14 mg kg^{-1} greater Zn than the notional baseline grain Zn concentration of 25 mg kg^{-1} for India and Pakistan (Singh and Velu, 2017). Given the low soil Zn conditions in this study, amphidiploids showed greater grain Zn concentration than a panel of 36 Indian wheat genotypes. It indicates the potential of *Th. bessarabicum* derived amphidiploids to be a new source for variation in grain Zn concentration in breeding programmes.

Most of the amphidiploids had greater grain Zn concentration at Hisar (saline) than Karnal (normal). Accordingly, Kharchia 65, a salt tolerant wheat genotypes, showed greater grain Zn concentration under saline soils than normal soil (Khokhar *et al*., submitted). There was no evidence of a yield dilution effect on grain Zn concentration in this study. This observation support the argument that these amphidiploids can be used to increase the grain Zn concentration of locally adapted high yielding wheat varieties. Our result is therefore consistent with findings of Welch and Graham, 2004; Joshi *et al*., 2010 and Khokhar *et al*., submitted, who reported no trade- off between grain Zn and GYD concentration in wheat.

The concentration of mineral elements would decrease if an increase in size was due to only increase in the endosperm, not the bran or germ, where most of the minerals are located (Cakmak *et al*., 2010; Ajiboye *et al*., 2015). Further research is required to understand the storage of Zn in different parts of the grain. Visual observations showed that the grains of amphidiploids were longer with deeper crease than Chinese spring (**Figure 5.2**) and other wheat varieties grown

in field (data not shown here). Most of the amphidiploids had brown colour grains except EC 787014, which showed wheat like colour.

5.5.3 Significant association between seedling root traits of *Thinopyrum bessarabicum* derived amphidiploids and grain yield, yield components and grain mineral composition traits

Juvenile root traits, for example, narrow root angle traits have shown association with GYD and HI and wider root angle traits showed association with grain Fe and Mg of 36 Indian wheat genotypes under normal soil at Karnal site. Similarly, juvenile root angle traits have shown association with HI; TLLR and LRN with PHT; wider root angle traits with TGW and, TLLR, TLPR and MWR with grain concentration of Fe, Mg and S of 36 Indian genotypes under saline soils at Hisar. (Chapter 4).

Our study showed that MWR and WDR was associated with GYD in seven amphidiploids at Karnal, but not with narrow root angle traits as described in Chapter 4. This contrasting observation could be due to the less variation for wider and deeper root traits in spring wheat Indian genotypes as compared to *Th. bessarabicum* derived amphidiploids, although warrants further study. Our results are consistent with Xie *et al*., 2017, who reported positive association between maximum width of root and GYD of winter wheat genotypes measured in field trials in United Kingdom. Wider root angle traits, longer primary roots and total root length, altogether represent a larger root system, associated with BYD and DTM of seven amphidiploids at Karnal (normal soil) site. The vigorous root system of amphidiploids might be due the presence of extra chromosomes from *Th. bessarabicum*. Xie *et al*., 2017, reported that larger root

system delayed the physiological maturity of wheat genotypes in field condition. It indicates that larger root system may extended the grain filling period through improved water and nutrient uptake even after anthesis and keep the plants green (Pinto and Reynolds, 2015). Biological yield and productive tillers per meter (PTM) of seven amphidiploids, averaged across years, associated with TLAR, TLPR and MDR at Hisar (saline) site, which are again contradictory with correlation of juvenile root traits and field traits of 36 Indian wheat genotypes under saline soil (Hisar) studied in Chapter 4. However, Xie *et al*., 2017, reported association between juvenile roots total length and biomass m^{-2} of wheat genotypes measured in field conditions. Therefore, there is potential that longer and deeper roots can explore water and nutrient from deeper layers of soil, in turn increase the biomass and number of tillers which could help in the improvement of grain yield (Richard *et al*., 2015).

Narrow root angle which potentially represent the steeper root system associated with grain iron (Fe), potassium (K) and manganese (Mn) concentrations of amphidiploids measured in normal soil (Karnal) while wider root system have shown association with grain Fe concentration of 36 Indian wheat genotypes at Karnal (Chapter 4). Juvenile root traits not associated with macronutrients and micronutrients of amphidiploids at Hisar.

This study showed that juvenile root traits of *Th. bessarabicum* derived amphidiploids did not behave similarly to 36 Indian wheat genotypes. Possible reasons for this might be the genes responsible for different root architecture present on the extra set of chromosomes of introgressed in to these amphidiploids from *Th. bessarabicum*. Haudry *et al*., 2007, reported that genetic

diversity in bread wheat and durum wheat have been reduced to ~70 and 84%, respectively, as compared to wild wheat relatives. Interestingly, modern wheat varieties have root biomass less than two-third of the mean of wheat landraces (Waines and Ehdaie, 2007). *Thinopyrum bessarabicum*, is a salt tolerant wild wheat grass which are known to be adaptable on marginal soils, it is possible that root traits might have played important role in its adaptability to some extent. Placido *et al*., 2013, have introgressed root traits from wild wheat relative, *Agropyron elongatum*, into bread wheat and showed increased root biomass under drought conditions. Therefore, there is scope to re-introduction of beneficial root traits from *Th. bessarabicum* derived amphidiploids into modern wheat genotypes to improve root traits and yield. However, juvenile root traits should be explored further in wheat breeding.

5.5.4 Conclusion:

Wild relatives of wheat have shown their superiority than the cultivated wheat cultivars in term of mineral composition, disease tolerance, salinity tolerance and other traits. *Th. bessarabicum* is also well known for salinity tolerance. *Th. bessarabicum* derived amphidiploids in present study showed generally better performance for GYD and yield components under saline soils than normal soil. Therefore there is a considerable potential to use these amphidiploids in breeding programme to introgress the salt tolerant traits into modern wheat varieties. Moreover, amphidiploids showed greater grain Zn concentration and might be useful to increase the grain Zn concentration of modern wheat through using them in genetic biofortification programs. Amphidiploids also showed robust root system on germination paper based ‘pouch & wick’ system, further screening under different salt level is required to quantify the root traits and

genes for salinity tolerance. However, presence of many undesirable traits for example, brittle rachis, late maturity and hard threshing ability in amphidiploids can be removed by further backcrossing and selection in breeding programmes.

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5.7 Supplementary tables

S5.1 Table. Grain yield reduction (percentage) of 36 Indian wheat genotypes at Hisar (saline) site compared to Karnal (normal) site. Data are means of two replicate plots per genotype at each site over two years, 2013-14 and 2014-15.

Genotypes	n	Karnal	Hisar	Reduction (%) at Hisar
BH_1146	4	4.33	2.99	30.93
CBW_38	4	6.35	4.54	28.57
DBW_14	4	5.31	2.80	47.25
DBW_16	4	4.94	3.78	23.48
DBW_17	4	5.46	3.84	29.58
DBW_39	4	6.91	4.52	34.57
DBW_46	4	5.81	3.56	38.69
DBW_51	4	5.99	3.85	35.82
DBW_71	4	6.11	3.76	38.53
DPW_621-50	4	6.83	4.33	36.63
GW_322	4	5.23	3.13	40.12
HD_2009	4	5.22	3.15	39.80
HD_2733	4	4.41	4.12	6.55
HD_2932	4	5.33	3.55	33.41
HD_2967	4	6.18	4.77	22.90
HI_1563	4	4.54	3.07	32.47
HI_8498	4	4.87	4.02	17.41
HW_2044	4	5.71	3.03	46.92
K_0307	4	5.28	3.36	36.30
KHARCHIA_65	4	1.75	1.64	6.45
KRL_1-4	4	6.05	2.49	58.91
KRL_19	4	4.25	1.91	55.02
KRL_210	4	6.81	5.57	18.28
KRL_213	4	5.86	3.43	41.45
KRL_3-4	4	1.51	2.90	-91.67
MACS_6222	4	5.52	3.80	31.27
NW_1067	4	5.88	4.65	20.90
NW_4018	4	6.35	3.20	49.63
NW_4092	4	6.17	2.98	51.69
PDW_314	4	6.18	4.08	34.05
RAJ_4229	4	4.87	3.24	33.50
RAJ_4238	4	4.39	3.61	17.74
RW_3684	4	7.51	4.32	42.55
UP_262	4	4.10	3.10	24.36
WH_1021	4	6.19	3.99	35.59
WH_1105	4	6.80	5.09	25.05

S5.2 Table. Grain yield reduction (percentage) of eight amphidiploids (*Th. bessarabicum* x bread/durum wheat) at Hisar (saline) site compared to Karnal (normal) site. Data are means of three replicate plots per amphidiploids at each site, over two years, 2014-15 and 2015-16.

Genotype	n	Karnal	Hisar	Reduction (%) at Hisar
EC 787007	**6**	1.23	1.14	7.31
EC 787008	**6**	0.95	0.70	26.37
EC 787009	**6**	1.50	1.48	1.27
EC 787010	**6**	1.77	1.43	19.28
EC 787011	**6**	1.45	1.50	-3.24
EC 787012	**6**	0.76	0.87	-14.53
EC 787013	**6**	0.88	1.05	-19.16
EC 787014	**6**	2.40	3.06	-27.70

S5.3 Table. The contribution of G, E and G*E and residual factors to variation percentage (%) in grain Zn concentration and the grain ionome of eight amphidiploids grown at two sites in 2014-15 and 2015-16, in India.

		Variation (%)			
Elements	**n**	**G**	**E**	**G*E**	**Residual**
Zn	64	8.4	21.5	8.5	61.6
As	64	5.6	29	3.6	61.8
Al	64	11.1	0	13.2	75.7
Ba	64	10.2	60.5	5.8	23.5
Ca	64	42.4	6.8	3.5	47.4
Cd	64	64.7	0	0.7	34.5
Cs	64	3.9	74.3	3.4	18.4
Cu	63	15.2	20.7	9.8	54.4
Fe	64	46	3.3	10.5	40.2
K	64	32.2	10	14.3	43.5
Mg	64	46.2	0	7.9	45.8
Mn	64	27	13.3	9.7	50
Mo	64	9.6	28.6	6.1	55.7
Na	64	28.4	23.4	5.8	42.4
P	64	21.9	16	7.5	54.7
Rb	64	3	63.3	7.5	26.2
S	64	35.4	6.8	9.1	48.7
Se	64	4.2	64.7	2.8	28.3
Sr	64	10.7	47.7	3.2	38.4
Ti	64	21.3	6	9.8	62.9
V	64	14.8	0.6	16	68.5
d.f.		***7***	***1***	***7***	***64***

S5.4. Table. Correlation coefficients between seedling root traits and grain yield and yield components of seven amphidiploids measured at Karnal site. Root traits data are means of ~20 replications and yield and yield components data are means of three replicate plots per amphidiploids at Karnal site over two years, 2014-15 and 2015-16.

r values																																													
CHCRX	1	-																																												
CHCRY	2	0.5725	-																																												
CMRX	3	0.9656	0.6469	-																																											
CMRY	4	0.555	0.9758	0.6661	-																																									
LRN	5	0.3264	0.2504	0.2418	0.1398	-																																							
MDR	6	0.6063	0.9914	0.6935	0.9743	0.2974	-																																							
MLAR	7	0.3812	0.6038	0.5337	0.7435	-0.4654	0.5957	-																																						
MLLR	8	0.4099	0.4999	0.3757	0.3567	0.8744	0.5427	-0.3246	-																																					
MLPR	9	0.6699	0.9535	0.7677	0.9753	0.294	0.9688	0.6733	0.4624	-																																				
MWR	10	0.4677	0.6032	0.481	0.6157	0.6658	0.6504	0.2491	0.5292	0.7015	-																																			
Mg	11	0.4022	0.4765	0.3595	0.3166	0.1947	0.4494	-0.0911	0.5832	0.3075	-0.1612	-																																		
Mn	12	-0.469	0.0442	-0.3133	0.1855	-0.7927	-0.0084	0.6173	-0.7201	0.0198	-0.2914	-0.3587	-																																	
Mo	13	-0.3791	-0.5506	-0.3714	-0.4734	0.2691	-0.5196	-0.3827	-0.1155	-0.3608	0.062	-0.6487	-0.0543	-																																
P	14	0.0193	-0.1716	0.008	-0.2904	0.1595	-0.1139	-0.4942	0.4262	-0.2674	-0.3178	0.5355	-0.5082	-0.3173	-																																
PEA_251	15	0.6593	0.1312	0.6096	0.1417	0.7117	0.2098	-0.0765	0.4792	0.3475	0.6671	-0.1312	-0.6808	0.3605	-0.0628	-																															
PEA_252	16	0.6865	0.9098	0.7406	0.8422	0.4515	0.9381	0.3615	0.7401	0.8739	0.583	0.6373	-0.2954	-0.559	0.1981	0.3083	-																															
PEA_301	17	0.6297	-0.002	0.5298	-0.043	0.726	0.0801	-0.2933	0.5339	0.156	0.5345	-0.0033	-0.8607	0.2199	0.2161	0.9359	0.2719	-																														
PEA_302	18	0.4495	-0.0076	0.3114	-0.1491	0.8389	0.0424	-0.6261	0.7786	0.0256	0.2843	0.4032	-0.9824	0.1311	0.4823	0.6858	0.3251	0.8274	-																														
PEA_501	19	0.8432	0.6402	0.9051	0.6822	0.4778	0.7118	0.4587	0.4924	0.8141	0.756	0.1064	-0.3443	-0.083	-0.1038	0.783	0.726	0.6429	0.36	-																												
PEA_502	20	0.8936	0.5959	0.9436	0.5812	0.3333	0.6637	0.3512	0.5467	0.6902	0.4034	0.5001	-0.4436	-0.3923	0.312	0.5773	0.8001	0.563	0.4523	0.8584	-																											
PEA_751	21	0.6911	0.5824	0.7619	0.6318	0.5483	0.6673	0.3854	0.5043	0.7565	0.8715	-0.0683	-0.3337	0.0128	-0.1089	0.7879	0.6659	0.6561	0.3336	0.9572	0.7329	-																									
PEA_752	22	0.985	0.5612	0.9278	0.5171	0.4716	0.5997	0.2481	0.534	0.6464	0.5332	0.4273	-0.5968	-0.3441	0.082	0.7193	0.7124	0.7166	0.5771	0.8418	0.8824	0.7145	-																								
PEA_951	23	0.5386	-0.0219	0.4848	-0.0058	0.6605	0.0717	-0.1593	0.3987	0.1868	0.6399	-0.2672	-0.6884	0.3619	0.0428	0.957	0.1881	0.9535	0.6527	0.6842	0.4807	0.7492	0.6095	-																							
PEA_952	24	0.7503	0.5301	0.7243	0.4748	0.743	0.6079	0.0394	0.7567	0.6102	0.7862	0.2489	-0.6981	-0.1825	0.2311	0.7854	0.7461	0.8115	0.6711	0.8413	0.7766	0.8694	0.8307	0.7718	-																						
PEA_1001	25	0.6626	0.4261	0.7202	0.4768	0.616	0.5198	0.2434	0.5115	0.6383	0.8128	-0.1198	-0.4308	0.1984	-0.0802	0.8871	0.5522	0.7553	0.4472	0.9366	0.7074	0.9725	0.6953	0.8431	0.8464	-																					
PEA_1002	26	0.9632	0.4374	0.8757	0.3882	0.4161	0.4756	0.1817	0.4505	0.5137	0.4642	0.381	-0.6374	-0.3707	0.1309	0.7016	0.6076	0.7498	0.5865	0.761	0.8266	0.6417	0.9805	0.6329	0.802	0.6256	-																			
PRN	27	0.1515	-0.2018	-0.0262	-0.2619	0.095	-0.2001	-0.2282	-0.0682	-0.2621	0.1796	-0.1622	-0.3863	-0.2704	0.1021	0.1654	-0.1324	0.3871	0.2168	-0.0688	-0.0878	0.0215	0.2107	0.3458	0.2794	-0.028	0.3742	-																	
RCH	28	0.6142	0.8155	0.6589	0.8006	0.6675	0.8585	0.3323	0.698	0.8829	0.9211	0.1788	-0.3085	-0.1287	-0.1677	0.6064	0.833	0.4675	0.3412	0.8488	0.6311	0.8848	0.6655	0.5047	0.8319	0.812	0.5526	-0.0573	-																
TLAR	29	0.6868	0.7821	0.6674	0.7535	0.4445	0.8041	0.4166	0.4878	0.7845	0.8447	0.1803	-0.2802	-0.4592	-0.1573	0.4671	0.769	0.429	0.2231	0.7335	0.5796	0.7652	0.7226	0.4367	0.8047	0.6272	0.6917	0.3769	0.8574	-														
TLLR	30	0.3047	0.225	0.2264	0.1303	0.9955	0.2758	-0.4451	0.8337	0.2878	0.7025	0.1027	-0.7637	0.3298	0.1027	0.7403	0.4108	0.7374	0.8071	0.4908	0.3034	0.5778	0.4479	0.6986	0.7386	0.6492	0.3936	0.1045	0.6746	0.4463	-												
TLPR	31	0.6862	0.7875	0.6703	0.7628	0.4056	0.8075	0.4467	0.4577	0.7869	0.8282	0.1792	-0.249	-0.4847	-0.1656	0.4408	0.7651	0.4021	0.1887	0.7249	0.5769	0.7529	0.7159	0.4118	0.7855	0.6086	0.6869	0.3795	0.8425	0.9991	0.4072	-										
WDR	32	0.294	0.2322	0.247	0.2449	0.6957	0.2844	-0.0301	0.3954	0.3563	0.9108	-0.4072	-0.4078	0.314	-0.3152	0.7345	0.2456	0.657	0.3722	0.5667	0.1646	0.7312	0.3852	0.7772	0.6891	0.7326	0.3739	0.3928	0.6994	0.6614	0.7496	0.6387	-								
BYD_Karnal	33	0.713	0.4664	0.5725	0.3445	0.5235	0.4814	-0.0382	0.5762	0.4071	0.5292	0.4406	-0.6778	-0.5354	0.2286	0.4723	0.6209	0.62	0.5904	0.5018	0.564	0.4792	0.7897	0.4755	0.7908	0.4014	0.8362	0.6445	0.5564	0.8033	0.4916	0.7962	0.4714	-						
DTA_Karnal	34	0.5219	0.3823	0.417	0.2644	-0.1352	0.338	0.1504	0.1593	0.2107	-0.1576	0.7395	-0.2264	-0.8906	0.3242	-0.1756	0.4479	0.0064	0.1531	0.0626	0.4111	-0.1022	0.5054	-0.2185	0.2058	-0.2194	0.5628	0.3847	0.0269	0.375	-0.207	0.3929	-0.318	0.6622	-					
DTM_Karnal	35	0.8986	0.1773	0.8107	0.1719	0.2171	0.2201	0.1848	0.1804	0.3046	0.2799	0.1888	-0.555	-0.2398	0.0892	0.6915	0.3421	0.7418	0.4871	0.6634	0.7329	0.5301	0.8853	0.6543	0.6341	0.553	0.9413	0.4069	0.3121	0.4864	0.2081	0.4864	0.2734	0.6722	0.4753	-					
GNS_Karnal	36	-0.2345	0.5535	-0.0735	0.5323	0.0868	0.5407	0.2007	0.3755	0.4525	0.111	0.3588	0.3435	-0.1449	0.0511	-0.3693	0.473	-0.4973	-0.222	0.0244	0.0451	0.0469	-0.2308	-0.4795	-0.057	-0.0349	-0.3929	-0.7071	0.3394	0.04	0.0612	0.0381	-0.1875	-0.2786	-0.1439	-0.6222	-				
GWS_Karnal	37	0.1441	0.7529	0.247	0.6962	0.4171	0.7451	0.183	0.6598	0.6907	0.3805	0.5148	0.0173	-0.1498	-0.0077	0.0004	0.7209	-0.1467	0.1147	0.3474	0.3278	0.3203	0.1756	-0.1827	0.2836	0.2574	-0.003	-0.628	0.6413	0.32	0.384	0.3082	0.0586	0.0518	-0.0074	-0.2868	0.8897	-				
GYD_Karnal	38	0.3012	0.1508	0.1978	0.1731	0.4366	0.1635	0.0763	0.0923	0.2432	0.7668	-0.4738	-0.266	0.1822	-0.5108	0.5877	0.0634	0.5285	0.1859	0.4059	0.008	0.531	0.3587	0.6369	0.4966	0.5041	0.399	0.6152	0.4986	0.6484	0.4916	0.6379	0.8993	0.5136	-0.12	0.3626	-0.4416	-0.207	-			
Germi%Karnal	39	0.5347	0.6267	0.5729	0.5761	0.2393	0.6824	0.2945	0.4964	0.5677	0.4983	0.3869	-0.2859	-0.7	0.4201	0.196	0.777	0.3044	0.2051	0.5492	0.6659	0.5899	0.5649	0.2627	0.7314	0.4413	0.5654	0.341	0.5983	0.7718	0.215	0.7773	0.2898	0.7121	0.5066	0.384	0.1496	0.2505	0.1823	-		
HI%_Karnal	40	-0.5606	-0.3755	-0.5244	-0.2463	-0.096	-0.3775	0.0184	-0.479	-0.2628	0.1995	-0.93	0.4268	0.6951	-0.6482	0.0038	-0.6051	-0.1612	-0.4316	-0.2245	-0.668	-0.0337	-0.5635	0.0935	-0.3418	0.0052	-0.557	0.0292	-0.1196	-0.1961	-0.0101	-0.1998	0.4132	-0.5079	-0.8035	-0.4448	-0.1153	-0.2737	0.4565	-0.4971	-		
Karnal_TGW	41	0.2805	0.7003	0.3066	0.6312	0.5691	0.6753	0.0931	0.6737	0.6753	0.4618	0.4684	-0.1461	0.0076	-0.2123	0.217	0.6446	0.043	0.2843	0.4076	0.3057	0.3441	0.3254	-0.017	0.3328	0.3247	0.157	-0.5281	0.6769	0.3609	0.5412	0.3424	0.2096	0.1628	-0.0024	-0.1059	0.6645	0.913	0.0168	0.0653	-0.2111	-		
PHT_Karnal	42	0.6684	0.5064	0.6178	0.3739	0.6381	0.525	-0.1548	0.8351	0.4913	0.2526	0.7989	-0.6789	-0.2486	0.3839	0.461	0.7336	0.4961	0.7541	0.5349	0.7301	0.3855	0.7297	0.2858	0.63	0.415	0.6496	-0.1989	0.5342	0.364	0.5752	0.3438	0.0634	0.5547	0.4313	0.4581	0.2216	0.5722	-0.1244	0.3516	-0.7614	0.6643	-	
PTM_Karnal	43	0.4183	-0.1857	0.2355	-0.2116	0.0722	-0.1816	-0.084	-0.1363	-0.1593	0.1812	-0.1674	-0.4287	-0.1879	-0.0444	0.384	-0.123	0.5398	0.2767	0.1382	0.1047	0.1405	0.442	0.4931	0.3296	0.1314	0.596	0.9094	-0.0237	0.3807	0.0852	0.3844	0.3828	0.6506	0.4114	0.693	-0.8797	-0.6929	0.6475	0.2265	-0.0308	-0.4893	-0.0758	-	
MWR	44	0.4677	0.6032	0.481	0.6157	0.6658	0.6504	0.2491	0.5292	0.7015	1	-0.1612	-0.2914	0.062	-0.3178	0.6671	0.583	0.5345	0.2843	0.756	0.4034	0.8715	0.5332	0.6399	0.7862	0.8128	0.4642	0.1796	0.9211	0.8447	0.7025	0.8282	0.9108	0.5292	-0.1576	0.2799	0.111	0.3805	0.7668	0.4983	0.1995	0.4618	0.2526	0.1812	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44

S5.4 Table continued.

P values																																													
CHCRX_cm	1	-																																											
CHCRY	2	0.1792	-																																										
CMRX	3	<0.001	0.1163	-																																									
CMRY	4	0.1959	<0.001	0.1024	-																																								
LRN	5	0.475	0.588	0.6014	0.765	-																																						
MDR	6	0.1489	<0.001	0.084	<0.001	0.5171	-																																					
MLAR	7	0.3988	0.1511	0.2173	0.0554	0.2926	0.1581	-																																				
MLLR	8	0.361	0.2533	0.4062	0.4322	0.01	0.2081	0.4775	-																																			
MLPR	9	0.0997	<0.001	0.0439	<0.001	0.5222	<0.001	0.0974	0.2962	-																																		
MWR	10	0.2899	0.1516	0.2745	0.141	0.1026	0.1137	0.5901	0.2219	0.079	-																																	
Mg	11	0.3711	0.2797	0.4284	0.489	0.6757	0.3117	0.8459	0.1693	0.5023	0.7299	-																																
Mn	12	0.2884	0.9251	0.4939	0.6905	0.0335	0.9858	0.1397	0.068	0.9664	0.5261	0.4295	-																															
Mo	13	0.4016	0.2003	0.412	0.2833	0.5595	0.232	0.3969	0.8052	0.4266	0.895	0.115	0.908	-																														
P	14	0.9673	0.7129	0.9864	0.5276	0.7326	0.8079	0.2596	0.3403	0.5621	0.4873	0.2154	0.2442	0.488	-																													
PEA_251	15	0.1072	0.7793	0.1461	0.7619	0.0728	0.6516	0.8705	0.2766	0.445	0.1017	0.7792	0.0922	0.427	0.8935	-																												
PEA_252	16	0.0885	0.0045	0.0569	0.0174	0.3092	0.0018	0.4256	0.0572	0.0101	0.1695	0.1237	0.5201	0.1921	0.6702	0.5011	-																												
PEA_301	17	0.1296	0.9966	0.2213	0.927	0.0647	0.8644	0.5232	0.217	0.7384	0.2165	0.9944	0.0129	0.6357	0.6416	0.0019	0.5553	-																											
PEA_302	18	0.3115	0.9871	0.4966	0.7496	0.0183	0.9281	0.1326	0.0391	0.9565	0.5367	0.3698	<0.001	0.7794	0.273	0.089	0.4768	0.0216	-																										
PEA_501	19	0.0171	0.1214	0.0051	0.0913	0.2782	0.0728	0.3006	0.2616	0.0258	0.0493	0.8205	0.4496	0.8595	0.8247	0.0373	0.0647	0.1193	0.4276	-																									
PEA_502	20	0.0067	0.1579	0.0014	0.1712	0.4651	0.1041	0.4399	0.2041	0.0861	0.3695	0.2531	0.3187	0.3841	0.4957	0.1747	0.0307	0.1882	0.3082	0.0134	-																								
PEA_751	21	0.0855	0.17	0.0465	0.128	0.2026	0.1015	0.3932	0.2485	0.0491	0.0106	0.8842	0.4645	0.9783	0.8162	0.0354	0.1025	0.1095	0.4647	<0.001	0.061	-																						
PEA_752	22	<0.001	0.1899	0.0026	0.2347	0.2854	0.1546	0.5916	0.217	0.1167	0.2178	0.339	0.1572	0.4499	0.8612	0.0685	0.0725	0.07	0.1749	0.0175	0.0085	0.0712	-																					
PEA_951	23	0.2123	0.9629	0.2702	0.9902	0.1063	0.8786	0.733	0.3756	0.6884	0.1217	0.5623	0.0872	0.425	0.9274	<0.001	0.6863	<0.001	0.112	0.09	0.2748	0.0526	0.1462	-																				
PEA_952	24	0.052	0.221	0.0656	0.2816	0.0557	0.1476	0.9332	0.0489	0.1456	0.036	0.5905	0.0811	0.6954	0.6181	0.0364	0.0541	0.0267	0.0988	0.0176	0.04	0.011	0.0206	0.0421	-																			
PEA_1001	25	0.1048	0.3405	0.0679	0.2794	0.1408	0.2318	0.5989	0.2406	0.1229	0.0263	0.7981	0.3345	0.6698	0.8642	0.0077	0.1987	0.0496	0.3143	0.0019	0.0754	<0.001	0.0829	0.0172	0.0163	-																		
PEA_1002	26	<0.001	0.3264	0.0098	0.3895	0.3531	0.2808	0.6967	0.3103	0.2383	0.2941	0.3991	0.1236	0.4131	0.7797	0.0789	0.1479	0.0523	0.1664	0.0469	0.0218	0.1203	<0.001	0.1271	0.03	0.1329	-																	
PRN	27	0.7457	0.6644	0.9555	0.5704	0.8395	0.667	0.6226	0.8844	0.5702	0.7	0.7282	0.392	0.5575	0.8275	0.723	0.7771	0.3909	0.6405	0.8834	0.8514	0.9635	0.6501	0.4474	0.544	0.9526	0.4082	-															
RCH	28	0.1423	0.0254	0.1075	0.0305	0.1014	0.0134	0.4666	0.0812	0.0085	0.0032	0.7013	0.5008	0.7834	0.7193	0.1488	0.02	0.2902	0.4539	0.0157	0.1285	0.0081	0.1028	0.248	0.0203	0.0265	0.1983	0.9029	-														
TLAR	29	0.0883	0.0377	0.1014	0.0505	0.3177	0.0293	0.3525	0.2668	0.0367	0.0168	0.6989	0.5428	0.3	0.7362	0.2906	0.0433	0.3369	0.6306	0.0606	0.1726	0.045	0.0666	0.3272	0.0291	0.1317	0.0852	0.4046	0.0136	-													
TLLR	30	0.5063	0.6277	0.6254	0.7807	<0.001	0.5494	0.3169	0.0198	0.5315	0.0784	0.8266	0.0457	0.4701	0.8266	0.057	0.3599	0.0586	0.0282	0.2635	0.5084	0.1743	0.3135	0.0808	0.058	0.1146	0.3823	0.8236	0.0965	0.3154	-												
TLPR	31	0.0887	0.0355	0.0994	0.0461	0.3667	0.0281	0.3149	0.3018	0.0358	0.0214	0.7006	0.5902	0.2703	0.7228	0.3222	0.0451	0.3712	0.6853	0.0653	0.1751	0.0508	0.0704	0.3587	0.0363	0.147	0.0882	0.4011	0.0173	<0.001	0.3646	-										
WDR	32	0.5222	0.6163	0.5934	0.5966	0.0826	0.5364	0.9489	0.38	0.4328	0.0044	0.3645	0.3638	0.4928	0.491	0.0601	0.5956	0.1089	0.4109	0.1847	0.7243	0.0618	0.3935	0.0398	0.0868	0.0611	0.4087	0.3833	0.0803	0.1057	0.0524	0.1226	-								
BYD_Karnal	33	0.0721	0.2914	0.1792	0.4493	0.2279	0.274	0.9351	0.1757	0.3647	0.222	0.3225	0.0943	0.2155	0.622	0.2845	0.1368	0.1375	0.1629	0.2512	0.1873	0.2766	0.0346	0.2808	0.0342	0.3721	0.0191	0.1182	0.1945	0.0295	0.2625	0.0322	0.2856	-						
DTA_Karnal	34	0.2296	0.3973	0.3519	0.5666	0.7726	0.4585	0.7475	0.733	0.6501	0.7358	0.0575	0.6255	0.0072	0.4781	0.7064	0.3136	0.9892	0.7431	0.894	0.3595	0.8274	0.2472	0.6378	0.6579	0.6364	0.1884	0.3942	0.9543	0.4071	0.6561	0.3832	0.4871	0.1051	-					
DTM_Karnal	35	0.0059	0.7037	0.027	0.7124	0.6401	0.6353	0.6915	0.6987	0.5065	0.5432	0.6851	0.1959	0.6046	0.8491	0.0853	0.4526	0.0563	0.2676	0.1043	0.061	0.221	0.008	0.1108	0.1262	0.1979	0.0016	0.3649	0.4956	0.2683	0.6543	0.2684	0.5529	0.0981	0.2811	-				
GNS_Karnal	36	0.6128	0.1974	0.8756	0.2188	0.8531	0.2101	0.6661	0.4066	0.308	0.8127	0.4293	0.4507	0.7566	0.9134	0.4149	0.2837	0.2562	0.6323	0.9587	0.9235	0.9205	0.6186	0.2763	0.9034	0.9407	0.3832	0.0756	0.4565	0.9321	0.8963	0.9355	0.6872	0.5452	0.7583	0.1357	-			
GWS_Karnal	37	0.7579	0.0508	0.5933	0.0823	0.3518	0.0546	0.6945	0.1068	0.0858	0.3998	0.2371	0.9706	0.7485	0.9869	0.9993	0.0675	0.7537	0.8065	0.4451	0.473	0.4837	0.7065	0.6949	0.5377	0.5773	0.9948	0.131	0.1206	0.4842	0.3951	0.5013	0.9007	0.9121	0.9874	0.5329	0.0073	-		
GYD_Karnal	38	0.5115	0.7469	0.6707	0.7106	0.3274	0.7261	0.8708	0.8439	0.5992	0.0443	0.2828	0.5642	0.6959	0.2414	0.1652	0.8925	0.2227	0.6899	0.3663	0.9865	0.22	0.4295	0.124	0.2569	0.2487	0.3752	0.1415	0.2547	0.1152	0.2625	0.1232	0.0058	0.2384	0.7978	0.4241	0.3212	0.656	-	
Germi%Karnal	39	0.2162	0.132	0.1788	0.1759	0.6052	0.0912	0.5215	0.2571	0.1837	0.255	0.3913	0.5343	0.0799	0.348	0.6736	0.0398	0.5068	0.6592	0.2016	0.1025	0.1633	0.1864	0.5693	0.0617	0.3216	0.1859	0.4541	0.1559	0.0421	0.6434	0.0397	0.5284	0.0726	0.246	0.395	0.7489	0.588	0.6957	-
HI%_Karnal	40	0.1905	0.4065	0.2269	0.5944	0.8379	0.4038	0.9688	0.2768	0.5691	0.668	0.0024	0.3396	0.083	0.1154	0.9936	0.15	0.7299	0.3336	0.6284	0.101	0.9427	0.1877	0.842	0.4531	0.9912	0.194	0.9504	0.7983	0.6735	0.9828	0.6676	0.3568	0.2445	0.0295	0.3173	0.8056	0.5525	0.3032	0.2563	-
Karnal_TGW	41	0.5423	0.0797	0.5036	0.1285	0.1824	0.096	0.8427	0.0971	0.096	0.2969	0.2891	0.7546	0.9871	0.6476	0.6403	0.118	0.927	0.5366	0.3641	0.5049	0.4499	0.4764	0.9711	0.4657	0.4774	0.7368	0.2231	0.0948	0.4265	0.2096	0.4522	0.6519	0.7272	0.9959	0.8213	0.1035	0.0041	0.9714	0.8893	0.6496	-
PHT_Karnal	42	0.1007	0.2461	0.1393	0.4087	0.1231	0.2263	0.7403	0.0194	0.2629	0.5847	0.0312	0.0935	0.5908	0.3952	0.2978	0.0606	0.2575	0.0502	0.2161	0.0625	0.3931	0.0627	0.5344	0.1294	0.3546	0.1143	0.669	0.2167	0.4222	0.1767	0.4502	0.8925	0.1963	0.3339	0.3013	0.633	0.1795	0.7904	0.4393	0.0468	0.1036	-
PTM_Karnal	43	0.3504	0.6901	0.6112	0.6487	0.8777	0.6968	0.8579	0.7708	0.7329	0.6974	0.7197	0.3373	0.6866	0.9247	0.3951	0.7928	0.211	0.5481	0.7676	0.8232	0.7639	0.3207	0.2608	0.4703	0.7789	0.1579	0.0045	0.9598	0.3995	0.8559	0.3946	0.3967	0.1135	0.3592	0.0843	0.009	0.0844	0.1159	0.6252	0.9478	0.2651	0.8717	-	
MWR	44	0.2899	0.1516	0.2745	0.141	0.1026	0.1137	0.5901	0.2219	0.079	<0.001	0.7299	0.5261	0.895	0.4873	0.1017	0.1695	0.2165	0.5367	0.0493	0.3695	0.0106	0.2178	0.1217	0.036	0.0263	0.2941	0.7	0.0032	0.0168	0.0784	0.0214	0.0044	0.222	0.7358	0.5432	0.8127	0.3998	0.0443	0.255	0.668	0.2969	0.5847	0.6974	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44

S5.5 Table. Correlation coefficients between seedling root traits and grain yield and yield components of seven amphidiploids measured at Hisar site. Root traits data are means of ~20 replications and yield and yield components data are means of three replicate plots per amphidiploids at Hisar site over two years, 2014-15 and 2015-16.

r values																																							
CHCRX	1	-																																						
CHCRY	2	0.5725	-																																						
CMRX	3	0.9656	0.6469	-																																					
CMRY	4	0.555	0.9758	0.6661	-																																				
LRN	5	0.3264	0.2504	0.2418	0.1398	-																																		
MDR	6	0.6063	0.9914	0.6935	0.9743	0.2974	-																																	
MLAR	7	0.3812	0.6038	0.5337	0.7435	-0.4654	0.5957	-																																
MLLR	8	0.4099	0.4999	0.3757	0.3567	0.8744	0.5427	-0.3246	-																															
MLPR	9	0.6699	0.9535	0.7677	0.9753	0.294	0.9688	0.6733	0.4624	-																														
MWR	10	0.4677	0.6032	0.481	0.6157	0.6658	0.6504	0.2491	0.5292	0.7015	-																													
PEA_251	11	0.6593	0.1312	0.6096	0.1417	0.7117	0.2098	-0.0765	0.4792	0.3475	0.6671	-																												
PEA_252	12	0.6865	0.9098	0.7406	0.8422	0.4515	0.9381	0.3615	0.7401	0.8739	0.583	0.3083	-																											
PEA_301	13	0.6297	-0.002	0.5298	-0.043	0.726	0.0801	-0.2933	0.5339	0.156	0.5345	0.9359	0.2719	-																										
PEA_302	14	0.4495	-0.0076	0.3114	-0.1491	0.8389	0.0424	-0.6261	0.7786	0.0256	0.2843	0.6858	0.3251	0.8274	-																									
PEA_501	15	0.8432	0.6402	0.9051	0.6822	0.4778	0.7118	0.4587	0.4924	0.8141	0.756	0.783	0.726	0.6429	0.36	-																								
PEA_502	16	0.8936	0.5959	0.9436	0.5812	0.3333	0.6637	0.3512	0.5467	0.6902	0.4034	0.5773	0.8001	0.563	0.4523	0.8584	-																							
PEA_751	17	0.6911	0.5824	0.7619	0.6318	0.5483	0.6673	0.3854	0.5043	0.7565	0.8715	0.7879	0.6659	0.6561	0.3336	0.9572	0.7329	-																						
PEA_752	18	0.985	0.5612	0.9278	0.5171	0.4716	0.5997	0.2481	0.534	0.6464	0.5332	0.7193	0.7124	0.7166	0.5771	0.8418	0.8824	0.7145	-																					
PEA_951	19	0.5386	-0.0219	0.4848	-0.0058	0.6605	0.0717	-0.1593	0.3987	0.1868	0.6399	0.957	0.1881	0.9535	0.6527	0.6842	0.4807	0.7492	0.6095	-																				
PEA_952	20	0.7503	0.5301	0.7243	0.4748	0.743	0.6079	0.0394	0.7567	0.6102	0.7862	0.7854	0.7461	0.8115	0.6711	0.8413	0.7766	0.8694	0.8307	0.7718	-																			
PEA_1001	21	0.6626	0.4261	0.7202	0.4768	0.616	0.5198	0.2434	0.5115	0.6383	0.8128	0.8871	0.5522	0.7553	0.4472	0.9366	0.7074	0.9725	0.6953	0.8431	0.8464	-																		
PEA_1002	22	0.9632	0.4374	0.8757	0.3882	0.4161	0.4756	0.1817	0.4505	0.5137	0.4642	0.7016	0.6076	0.7498	0.5865	0.761	0.8266	0.6417	0.9805	0.6329	0.802	0.6256	-																
PRN	23	0.1515	-0.2018	-0.0262	-0.2619	0.095	-0.2001	-0.2282	-0.0682	-0.2621	0.1796	0.1654	-0.1324	0.3871	0.2168	-0.0688	-0.0878	0.0215	0.2107	0.3458	0.2794	-0.028	0.3742	-															
RCH	24	0.6142	0.8155	0.6589	0.8006	0.6675	0.8585	0.3323	0.698	0.8829	0.9211	0.6064	0.833	0.4675	0.3412	0.8488	0.6311	0.8848	0.6655	0.5047	0.8319	0.812	0.5526	-0.0573	-														
TLAR	25	0.6868	0.7821	0.6674	0.7535	0.4445	0.8041	0.4166	0.4878	0.7845	0.8447	0.4671	0.769	0.429	0.2231	0.7335	0.5796	0.7652	0.7226	0.4367	0.8047	0.6272	0.6917	0.3769	0.8574	-													
TLLR	26	0.3047	0.225	0.2264	0.1303	0.9955	0.2758	-0.4451	0.8337	0.2878	0.7025	0.7403	0.4108	0.7374	0.8071	0.4908	0.3034	0.5778	0.4479	0.6986	0.7386	0.6492	0.3936	0.1045	0.6746	0.4463	-												
TLPR	27	0.6862	0.7875	0.6703	0.7628	0.4056	0.8075	0.4467	0.4577	0.7869	0.8282	0.4408	0.7651	0.4021	0.1887	0.7249	0.5769	0.7529	0.7159	0.4118	0.7855	0.6086	0.6869	0.3795	0.8425	0.9991	0.4072	-										
WDR	28	0.294	0.2322	0.247	0.2449	0.6957	0.2844	-0.0301	0.3954	0.3563	0.9108	0.7345	0.2456	0.657	0.3722	0.5667	0.1646	0.7312	0.3852	0.7772	0.6891	0.7326	0.3739	0.3928	0.6994	0.6614	0.7496	0.6387	-									
BYD_Hisar	29	0.688	0.7916	0.6145	0.6691	0.4922	0.7844	0.1735	0.6795	0.688	0.5736	0.2903	0.8562	0.3474	0.4225	0.5445	0.6068	0.493	0.7454	0.2061	0.7291	0.3654	0.7127	0.3044	0.7215	0.8605	0.4469	0.8568	0.3499	-								
DTA_Hisar	30	0.4991	0.4504	0.3811	0.3835	0.4356	0.3889	0.0676	0.3489	0.4568	0.3504	0.3708	0.3413	0.2396	0.3442	0.342	0.2122	0.1994	0.5218	0.1346	0.2548	0.2122	0.45	-0.0807	0.4429	0.3723	0.4152	0.3601	0.2561	0.5094	-							
DTM_Hisar	31	0.4727	0.7643	0.3776	0.6291	0.4815	0.7143	0.0982	0.619	0.6203	0.4986	0.1252	0.7187	0.1282	0.3199	0.3293	0.3245	0.2733	0.5349	-0.0141	0.4862	0.1548	0.4758	0.1654	0.6378	0.7168	0.4359	0.7108	0.2874	0.9122	0.707	-						
GNS_Hisar	32	-0.3882	0.3831	-0.3416	0.3938	0.1655	0.3297	0.1606	0.0858	0.3106	0.4221	-0.2312	0.095	-0.4213	-0.3547	-0.0999	-0.4402	0.0307	-0.3577	-0.2946	-0.1409	-0.0561	-0.4625	-0.2335	0.3543	0.2131	0.193	0.2083	0.3292	0.0974	0.2777	0.3846	-					
GWS_Hisar	33	-0.4076	0.3357	-0.3931	0.2983	0.2698	0.2713	-0.0403	0.2223	0.2318	0.2968	-0.2493	0.1007	-0.4068	-0.1824	-0.1875	-0.4451	-0.0971	-0.3562	-0.3532	-0.1757	-0.1487	-0.471	-0.3266	0.2911	0.088	0.2767	0.0766	0.2086	0.1148	0.3917	0.4521	0.9529	-				
GYD_Hisar	34	0.0747	0.1657	0.013	0.185	0.1953	0.1774	0.1455	-0.0206	0.1641	0.6535	0.2295	0.0634	0.2481	-0.0757	0.1942	-0.1191	0.3846	0.1242	0.3757	0.3762	0.2766	0.1919	0.7311	0.3754	0.6497	0.2448	0.6512	0.7507	0.3315	-0.0305	0.2598	0.3424	0.1312	-			
Germi%Hisar	35	0.2044	0.6668	0.1968	0.5555	0.2662	0.6632	0.1247	0.5278	0.476	0.4324	-0.1381	0.7005	-0.0235	0.0961	0.1921	0.2756	0.2658	0.2678	-0.098	0.4807	0.0813	0.2512	0.3213	0.5226	0.7	0.229	0.7034	0.2234	0.7944	0.0076	0.7093	0.2934	0.2524	0.4559	-		
HI% _Hisar	36	-0.4282	-0.4984	-0.3802	-0.3397	-0.3628	-0.472	0.1447	-0.6831	-0.3682	0.0525	-0.0179	-0.6497	-0.0883	-0.5082	-0.191	-0.5039	-0.0135	-0.4678	0.1656	-0.2984	0.0024	-0.3907	0.278	-0.2862	-0.1804	-0.2774	-0.1709	0.2894	-0.619	-0.5011	-0.6512	0.1153	-0.1102	0.5061	-0.3735	-	
PHT_Hisar	37	0.4298	0.5359	0.3264	0.3508	0.5686	0.5037	-0.248	0.7886	0.3885	0.1778	0.1326	0.6672	0.2176	0.6144	0.2144	0.4156	0.0972	0.5119	-0.0265	0.4359	0.0672	0.4501	-0.0436	0.4285	0.3738	0.4933	0.3579	-0.0039	0.7686	0.6222	0.8322	0.0585	0.2653	-0.2099	0.5196	-0.9336	-
PTM_Hisar	38	0.6105	0.4381	0.5382	0.3761	0.2522	0.4725	0.1822	0.3413	0.3889	0.5084	0.3236	0.5593	0.4757	0.2929	0.4775	0.5302	0.5112	0.6515	0.4149	0.7228	0.3831	0.7218	0.7189	0.4834	0.8196	0.2383	0.825	0.4392	0.7628	0.0167	0.4933	-0.2228	-0.3389	0.6414	0.7101	-0.1156	0.2741	-
TGW_Hisar	39	0.2196	-0.005	0.1141	-0.1673	0.4267	-0.0208	-0.5574	0.5768	-0.0812	-0.2813	0.1258	0.2309	0.2462	0.701	-0.0381	0.2714	-0.2005	0.2857	-0.0174	0.1324	-0.0977	0.254	-0.2335	-0.0364	-0.2069	0.3529	-0.228	-0.3152	0.2525	0.4224	0.3167	-0.3177	-0.0248	-0.6561	-0.0379	-0.8437	0.7741	-0.1564	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39

S5.5 Table continued.

P values																																								
CHCRX	1	-																																							
CHCRY	2	0.1792	-																																						
CMRX	3	<0.001		0.1163	-																																				
CMRY	4	0.1959	<0.001		0.1024	-																																			
LRN	5	0.475	0.588	0.6014		0.765	-																																		
MDR	6	0.1489	<0.001		0.084	<0.001		0.5171	-																																
MLAR	7	0.3988	0.1511	0.2173		0.0554		0.2926		0.1581	-																															
MLLR	8	0.361	0.2533	0.4062		0.4322		0.01		0.2081		0.4775	-																													
MLPR	9	0.0997	<0.001		0.0439	<0.001		0.5222	<0.001		0.0974		0.2962	-																											
MWR	10	0.2899	0.1516	0.2745		0.141		0.1026		0.1137		0.5901		0.2219		0.079	-																								
PEA_251	11	0.1072	0.7793	0.1461		0.7619		0.0728		0.6516		0.8705		0.2766		0.445		0.1017	-																						
PEA_252	12	0.0885	0.0045	0.0569		0.0174		0.3092		0.0018		0.4256		0.0572		0.0101		0.1695		0.5011	-																				
PEA_301	13	0.1296	0.9966	0.2213		0.927		0.0647		0.8644		0.5232		0.217		0.7384		0.2165		0.0019		0.5553	-																		
PEA_302	14	0.3115	0.9871	0.4966		0.7496		0.0183		0.9281		0.1326		0.0391		0.9565		0.5367		0.089		0.4768		0.0216	-																
PEA_501	15	0.0171	0.1214	0.0051		0.0913		0.2782		0.0728		0.3006		0.2616		0.0258		0.0493		0.0373		0.0647		0.1193		0.4276	-														
PEA_502	16	0.0067	0.1579	0.0014		0.1712		0.4651		0.1041		0.4399		0.2041		0.0861		0.3695		0.1747		0.0307		0.1882		0.3082		0.0134	-												
PEA_751	17	0.0855		0.17		0.0465		0.128		0.2026		0.1015		0.3932		0.2485		0.0491		0.0106		0.0354		0.1025		0.1095		0.4647		<0.001		0.061	-								
PEA_752	18	<0.001		0.1899		0.0026		0.2347		0.2854		0.1546		0.5916		0.217		0.1167		0.2178		0.0685		0.0725		0.07		0.1749		0.0175		0.0085		0.0712							
PEA_951	19		0.2123		0.9629		0.2702		0.9902		0.1063		0.8786		0.733		0.3756		0.6884		0.1217		<0.001		0.6863		<0.001		0.112		0.09		0.2748		0.0526		0.1462	-		
PEA_952	20		0.052		0.221		0.0656		0.2816		0.0557		0.1476		0.9332		0.0489		0.1456		0.036		0.0364		0.0541		0.0267		0.0988		0.0176		0.04		0.011		0.0206		0.0421	-	
PEA_1001	21		0.1048		0.3405		0.0679		0.2794		0.1408		0.2318		0.5989		0.2406		0.1229		0.0263		0.0077		0.1987		0.0496		0.3143		0.0019		0.0754		<0.001		0.0829		0.0172		0.0163	-
PEA_1002	22	<0.001		0.3264		0.0098		0.3895		0.3531		0.2808		0.6967		0.3103		0.2383		0.2941		0.0789		0.1479		0.0523		0.1664		0.0469		0.0218		0.1203		<0.001		0.1271		0.03		0.1329	-
PRN	23		0.7457		0.6644		0.9555		0.5704		0.8395		0.667		0.6226		0.8844		0.5702		0.7		0.723		0.7771		0.3909		0.6405		0.8834		0.8514		0.9635		0.6501		0.4474		0.544		0.9526		0.4082	-
RCH	24		0.1423		0.0254		0.1075		0.0305		0.1014		0.0134		0.4666		0.0812		0.0085		0.0032		0.1488		0.02		0.2902		0.4539		0.0157		0.1285		0.0081		0.1028		0.248		0.0203		0.0265		0.1983		0.9029	-
TLAR	25		0.0883		0.0377		0.1014		0.0505		0.3177		0.0293		0.3525		0.2668		0.0367		0.0168		0.2906		0.0433		0.3369		0.6306		0.0606		0.1726		0.045		0.0666		0.3272		0.0291		0.1317		0.0852		0.4046		0.0136	-
TLLR	26		0.5063		0.6277		0.6254		0.7807		<0.001		0.5494		0.3169		0.0198		0.5315		0.0784		0.057		0.3599		0.0586		0.0282		0.2635		0.5084		0.1743		0.3135		0.0808		0.058		0.1146		0.3823		0.8236		0.0965		0.3154	-
TLPR	27		0.0887		0.0355		0.0994		0.0461		0.3667		0.0281		0.3149		0.3018		0.0358		0.0214		0.3222		0.0451		0.3712		0.6853		0.0653		0.1751		0.0508		0.0704		0.3587		0.0363		0.147		0.0882		0.4011		0.0173		<0.001		0.3646	-
WDR	28		0.5222		0.6163		0.5934		0.5966		0.0826		0.5364		0.9489		0.38		0.4328		0.0044		0.0601		0.5956		0.1089		0.4109		0.1847		0.7243		0.0618		0.3935		0.0398		0.0868		0.0611		0.4087		0.3833		0.0803		0.1057		0.0524		0.1226	-
BYD_Hisar	29		0.0876		0.0339		0.1421		0.1003		0.2618		0.0368		0.7098		0.0932		0.0875		0.1782		0.5276		0.0139		0.4452		0.345		0.2063		0.1485		0.2609		0.0545		0.6576		0.063		0.4203		0.0723		0.5069		0.0672		0.0129		0.3147		0.0138		0.4417	-
DTA_Hisar	30		0.2542		0.3105		0.399		0.3958		0.3286		0.3886		0.8855		0.443		0.3028		0.4409		0.4128		0.4538		0.6048		0.4496		0.4527		0.6478		0.6681		0.2297		0.7736		0.5814		0.6477		0.311		0.8635		0.3196		0.4109		0.3543		0.4276		0.5794		0.2429	-
DTM_Hisar	31		0.284		0.0454		0.4036		0.1302		0.2739		0.0713		0.8341		0.1383		0.1373		0.2548		0.7891		0.0688		0.7841		0.4843		0.4708		0.4777		0.5532		0.216		0.9761		0.2686		0.7404		0.2805		0.723		0.1233		0.0699		0.3282		0.0734		0.5319		0.0042		0.0756	-
GNS_Hisar	32		0.3894		0.3962		0.4534		0.3821		0.7229		0.4702		0.7308		0.8548		0.4978		0.3455		0.618		0.8395		0.3465		0.4351		0.8313		0.3229		0.9478		0.4309		0.5213		0.7632		0.905		0.296		0.6142		0.4356		0.6464		0.6785		0.654		0.471		0.8354		0.5465		0.3943	-
GWS_Hisar	33		0.364		0.4616		0.383		0.5158		0.5585		0.5561		0.9316		0.6319		0.617		0.518		0.5898		0.83		0.365		0.6955		0.6872		0.3169		0.836		0.4329		0.4371		0.7063		0.7503		0.286		0.4746		0.5265		0.8512		0.548		0.8704		0.6536		0.8065		0.3848		0.3085	<0.001	-
GYD_Hisar	34		0.8735		0.7226		0.9779		0.6913		0.6747		0.7036		0.7556		0.9651		0.7251		0.1114		0.6205		0.8927		0.5917		0.8719		0.6765		0.7992		0.3943		0.7907		0.4063		0.4055		0.5482		0.6803		0.0619		0.4066		0.1142		0.5968		0.1131		0.0519		0.4677		0.9482		0.5737		0.4522		0.7791	-
Germi%Hisar	35		0.6602		0.1018		0.6723		0.1955		0.5639		0.1044		0.7899		0.2234		0.2802		0.3325		0.7678		0.0796		0.9602		0.8376		0.6798		0.5497		0.5645		0.5615		0.8345		0.2748		0.8624		0.5869		0.4822		0.2288		0.0799		0.6214		0.0778		0.6302		0.0329		0.987		0.0743		0.5231		0.585		0.304	-
HI%_Hisar	36		0.3378		0.2549		0.4002		0.456		0.4238		0.2849		0.7569		0.0907		0.4164		0.911		0.9695		0.1142		0.8508		0.2442		0.6817		0.2488		0.9771		0.2898		0.7228		0.5157		0.996		0.3862		0.546		0.5338		0.6987		0.547		0.714		0.5291		0.1383		0.252		0.1131		0.8055		0.8141		0.2464		0.4092	-
PHT_Hisar	37		0.3359		0.215		0.475		0.4405		0.1829		0.2491		0.5917		0.0351		0.3891		0.7029		0.7769		0.1016		0.6393		0.1421		0.6443		0.3538		0.8358		0.2402		0.955		0.3282		0.8862		0.3109		0.926		0.3375		0.4087		0.2606		0.4305		0.9934		0.0435		0.1357		0.0202		0.9008		0.5663		0.6515		0.232		0.0021	-
PTM_Hisar	38		0.1454		0.3256		0.2127		0.4057		0.5854		0.2843		0.6958		0.4537		0.3885		0.2439		0.4789		0.1917		0.2807		0.5239		0.2785		0.2209		0.241		0.1129		0.3546		0.0665		0.3963		0.0671		0.0687		0.2718		0.024		0.6069		0.0224		0.3242		0.0461		0.9716		0.2606		0.631		0.4571		0.1205		0.0738		0.805		0.5519	-
TGW_Hisar	39		0.6362		0.9915		0.8076		0.72		0.3398		0.9647		0.1936		0.1752		0.8626		0.5411		0.7882		0.6184		0.5946		0.0783		0.9354		0.556		0.6664		0.5345		0.9705		0.7772		0.8349		0.5825		0.6143		0.9382		0.6562		0.4375		0.6228		0.4911		0.5849		0.3451		0.4889		0.4875		0.9578		0.1095		0.9357		0.017		0.0411		0.7378	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39

S5.6 Table. Correlation coefficients between seedling root traits and grain mineral composition traits of seven amphidiploids measured at Karnal site. Root traits data are means of ~20 replications and grain elemental data are means of three replicate plots per amphidiploids at Karnal site in 2015-16.

r values																																														
CHCRX	1	-																																													
CHCRY	2	0.5725	-																																													
CMRX	3	0.9656	0.6469	-																																												
CMRY	4	0.555	0.9758	0.6661	-																																										
LRN	5	0.3264	0.2504	0.2418	0.1398	-																																									
MDR	6	0.6063	0.9914	0.6935	0.9743	0.2974	-																																								
MLAR	7	0.3812	0.6038	0.5337	0.7435	-0.4654	0.5957	-																																							
MLLR	8	0.4099	0.4999	0.3757	0.3567	0.8744	0.5427	-0.3246	-																																						
MLPR	9	0.6699	0.9535	0.7677	0.9753	0.294	0.9688	0.6733	0.4624	-																																					
MWR	10	0.4677	0.6032	0.481	0.6157	0.6658	0.6504	0.2491	0.5292	0.7015	-																																				
PEA_251	11	0.6593	0.1312	0.6096	0.1417	0.7117	0.2098	-0.0765	0.4792	0.3475	0.6671	-																																			
PEA_252	12	0.6865	0.9098	0.7406	0.8422	0.4515	0.9381	0.3615	0.7401	0.8739	0.583	0.3083	-																																		
PEA_301	13	0.6297	-0.002	0.5298	-0.043	0.726	0.0801	-0.2933	0.5339	0.156	0.5345	0.9359	0.2719	-																																	
PEA_302	14	0.4495	-0.0076	0.3114	-0.1491	0.8389	0.0424	-0.6261	0.7786	0.0256	0.2843	0.6858	0.3251	0.8274	-																																	
PEA_501	15	0.8432	0.6402	0.9051	0.6822	0.4778	0.7118	0.4587	0.4924	0.8141	0.756	0.783	0.726	0.6429	0.36	-																																
PEA_502	16	0.8936	0.5959	0.9436	0.5812	0.3333	0.6637	0.3512	0.5467	0.6902	0.4034	0.5773	0.8001	0.563	0.4523	0.8584	-																																
PEA_751	17	0.6911	0.5824	0.7619	0.6318	0.5483	0.6673	0.3854	0.5043	0.7565	0.8715	0.7879	0.6659	0.6561	0.3336	0.9572	0.7329	-																																
PEA_752	18	0.985	0.5612	0.9278	0.5171	0.4716	0.5997	0.2481	0.534	0.6464	0.5332	0.7193	0.7124	0.7166	0.5771	0.8418	0.8824	0.7145	-																																
PEA_951	19	0.5386	-0.0219	0.4848	-0.0058	0.6605	0.0717	-0.1593	0.3987	0.1868	0.6399	0.957	0.1881	0.9535	0.6527	0.6842	0.4807	0.7492	0.6095	-																															
PEA_952	20	0.7503	0.5301	0.7243	0.4748	0.743	0.6079	0.0394	0.7567	0.6102	0.7862	0.7854	0.7461	0.8115	0.6711	0.8413	0.7766	0.8694	0.8307	0.7718	-																															
PEA_1001	21	0.6626	0.4261	0.7202	0.4768	0.616	0.5198	0.2434	0.5115	0.6383	0.8128	0.8871	0.5522	0.7553	0.4472	0.9366	0.7074	0.9725	0.6953	0.8431	0.8464	-																														
PEA_1002	22	0.9632	0.4374	0.8757	0.3882	0.4161	0.4756	0.1817	0.4505	0.5137	0.4642	0.7016	0.6076	0.7498	0.5865	0.761	0.8266	0.6417	0.9805	0.6329	0.802	0.6256	-																													
PRN	23	0.1515	-0.2018	-0.0262	-0.2619	0.095	-0.2001	-0.2282	-0.0682	-0.2621	0.1796	0.1654	-0.1324	0.3871	0.2168	-0.0688	-0.0878	0.0215	0.2107	0.3458	0.2794	-0.028	0.3742	-																												
RCH	24	0.6142	0.8155	0.6589	0.8006	0.6675	0.8585	0.3323	0.698	0.8829	0.9211	0.6064	0.833	0.4675	0.3412	0.8488	0.6311	0.8848	0.6655	0.5047	0.8319	0.812	0.5526	-0.0573	-																											
TLAR	25	0.6868	0.7821	0.6674	0.7535	0.4445	0.8041	0.4166	0.4878	0.7845	0.8447	0.4671	0.769	0.429	0.2231	0.7335	0.5796	0.7652	0.7226	0.4367	0.8047	0.6272	0.6917	0.3769	0.8574	-																											
TLLR	26	0.3047	0.225	0.2264	0.1303	0.9955	0.2758	-0.4451	0.8337	0.2878	0.7025	0.7403	0.4108	0.7374	0.8071	0.4908	0.3034	0.5778	0.4479	0.6986	0.7386	0.6492	0.3936	0.1045	0.6746	0.4463	-																											
TLPR	27	0.6862	0.7875	0.6703	0.7628	0.4056	0.8075	0.4467	0.4577	0.7869	0.8282	0.4408	0.7651	0.4021	0.1887	0.7249	0.5769	0.7529	0.7159	0.4118	0.7855	0.6086	0.6869	0.3795	0.8425	0.9991	0.4072	-																											
WDR	28	0.294	0.2322	0.247	0.2449	0.6957	0.2844	-0.0301	0.3954	0.3563	0.9108	0.7345	0.2456	0.657	0.3722	0.5667	0.1646	0.7312	0.3852	0.7772	0.6891	0.7326	0.3739	0.3928	0.6994	0.6614	0.7496	0.6387	-																											
As	29	-0.6404	-0.2932	-0.6732	-0.3465	0.4946	-0.2966	-0.648	0.2731	-0.3227	0.1458	-0.0002	-0.2941	-0.0203	0.2062	-0.3559	-0.5835	-0.1736	-0.5222	0.0332	-0.134	-0.0864	-0.5636	-0.1365	0.0046	-0.273	0.5185	-0.3037	0.3226	-																											
Ba	30	0.821	0.3306	0.6649	0.2504	0.584	0.3517	-0.0392	0.4865	0.3806	0.5616	0.7366	0.4704	0.8046	0.6757	0.6261	0.5866	0.5653	0.8835	0.6906	0.7866	0.5628	0.9234	0.5604	0.5479	0.7109	0.5714	0.698	0.5727	-0.2865	-																											
Ca	31	0.1897	0.3567	0.1345	0.2096	-0.115	0.291	-0.0328	0.2757	0.1307	-0.3958	-0.4481	0.4094	-0.3094	0.1147	-0.1922	0.2216	-0.3745	0.1832	-0.5652	-0.0781	-0.4552	0.1666	-0.1065	-0.0927	0.0199	-0.2068	0.0305	-0.6158	-0.3215	0.0656	-																											
Cd	32	0.7727	0.3874	0.6564	0.2776	0.1918	0.3602	0.0586	0.3755	0.3421	-0.0241	0.265	0.5086	0.3417	0.4928	0.3614	0.631	0.1232	0.7676	0.1004	0.3788	0.1143	0.7682	0.1006	0.213	0.3284	0.1246	0.3294	-0.1735	-0.5572	0.6709	0.6809	-																											
Cs	33	0.2897	0.4048	0.1851	0.4041	-0.0399	0.3388	0.406	-0.1583	0.3448	0.4335	0.0303	0.1499	-0.0228	-0.2247	0.1447	-0.0785	0.1512	0.277	0.0058	0.1409	0.0125	0.314	0.5449	0.3007	0.6343	-0.0239	0.6486	0.4	-0.2286	0.4739	0.0175	0.2011	-																											
Cu	34	-0.6779	-0.0319	-0.5966	-0.0185	0.1017	-0.0166	-0.1485	0.0463	-0.1071	0.2532	-0.304	-0.1144	-0.3141	-0.2937	-0.2934	-0.5108	-0.0293	-0.6131	-0.1545	-0.1101	-0.0939	-0.6376	0.0163	0.0898	0.0085	0.139	0.0019	0.3001	0.6646	-0.4821	-0.3683	-0.833	-0.0406	-																											
Fe	35	-0.5274	-0.3504	-0.4287	-0.2272	-0.9504	-0.4036	0.3652	-0.8955	-0.3757	-0.6846	-0.7375	-0.5917	-0.8071	-0.8748	-0.5827	-0.5203	-0.6262	-0.6631	-0.7059	-0.8822	-0.6566	-0.6353	-0.269	-0.7122	-0.6109	-0.9345	-0.5783	-0.6782	-0.2401	-0.7538	-0.0065	-0.3693	-0.0613	0.029	-																											
K	36	-0.4694	-0.9541	-0.5072	-0.9172	-0.1007	-0.908	-0.6034	-0.3455	-0.852	-0.4623	0.0652	-0.7856	0.1851	0.1397	-0.4355	-0.407	-0.357	-0.4463	0.2271	-0.3302	-0.1807	-0.3419	0.1332	-0.6584	-0.7108	-0.0691	-0.7223	-0.1079	0.3045	-0.2797	-0.4782	-0.4213	-0.5648	0.0584	0.1979	-																											
Mg	37	0.4022	0.4765	0.3595	0.3166	0.1947	0.4494	-0.0911	0.5832	0.3075	-0.1612	-0.1312	0.6373	-0.0033	0.4032	0.1064	0.5001	-0.0683	0.4273	-0.2672	0.2489	-0.1198	0.381	-0.1622	0.1788	0.1803	0.1027	0.1792	-0.4072	-0.2785	0.2562	0.9242	0.7642	-0.1175	-0.4028	-0.3218	-0.4935	-																											
Mn	38	-0.469	0.0442	-0.3133	0.1855	-0.7927	-0.0084	0.6173	-0.7201	0.0198	-0.2914	-0.6808	-0.2954	-0.8607	-0.9824	-0.3443	-0.4436	-0.3337	-0.5968	-0.6884	-0.6981	-0.4308	-0.6374	-0.3863	-0.3085	-0.2802	-0.7637	-0.249	-0.4078	-0.1345	-0.7375	-0.0905	-0.4878	0.1387	0.2855	0.869	-0.166	-0.3587	-																											
Mo	39	-0.3791	-0.5506	-0.3714	-0.4734	0.2691	-0.5196	-0.3827	-0.1155	-0.3608	0.062	0.3605	-0.559	0.2199	0.1311	-0.083	-0.3923	0.0128	-0.3441	0.3619	-0.1825	0.1984	-0.3707	-0.2704	-0.1287	-0.4592	0.3298	-0.4847	0.314	0.6485	-0.2223	-0.7279	-0.5133	-0.3548	0.1935	-0.0127	0.6273	-0.6487	-0.0543	-																											
P	40	0.0193	-0.1716	0.008	-0.2904	0.1595	-0.1139	-0.4942	0.4262	-0.2674	-0.3178	-0.0628	0.1981	0.2161	0.4823	-0.1038	0.312	-0.1089	0.082	0.0428	0.2311	-0.0802	0.1309	0.1021	-0.1677	-0.1573	0.1027	-0.1656	-0.3152	-0.0628	0.0126	0.4076	0.1999	-0.6222	-0.0269	-0.2771	0.2832	0.5355	-0.5082	-0.3173	-																											
Rb	41	-0.167	0.0958	-0.1822	0.1598	-0.4878	0.0467	0.4533	-0.5573	0.0137	0.1223	-0.3803	-0.181	-0.3855	-0.6567	-0.2093	-0.3804	-0.1116	-0.2176	-0.2611	-0.2204	-0.2758	-0.1387	0.5374	-0.0862	0.3099	-0.4533	0.3382	0.143	-0.2235	-0.0433	-0.1554	-0.2934	0.7628	0.3173	0.3957	-0.2574	-0.4095	0.5301	-0.3558	-0.4683	-																											
S	42	0.0397	0.5935	0.0644	0.4891	-0.1038	0.5175	0.1903	0.2831	0.3749	-0.1857	-0.5386	0.5038	-0.5409	-0.1391	-0.1348	0.1109	-0.2654	0.0224	-0.7002	-0.1422	-0.3862	-0.0699	-0.3833	0.1193	0.1014	-0.1768	0.1123	-0.4996	-0.1239	-0.1559	0.8694	0.4196	0.0941	-0.0686	0.0725	-0.7094	0.7854	0.2109	-0.6203	0.1113	-0.0539	-																											
Se	43	0.0135	0.1855	-0.076	0.0061	0.2564	0.1826	-0.3943	0.5142	-0.0503	-0.0175	-0.2341	0.3864	0.051	0.3646	-0.177	0.1186	-0.1313	0.1105	-0.1386	0.2964	-0.2263	0.1638	0.4377	0.0731	0.2753	0.194	0.2717	-0.068	0.0397	0.2186	0.5918	0.2568	0.0261	0.2119	-0.407	-0.2065	0.6164	-0.4316	-0.637	0.7012	0.0354	0.4181	-																											
Zn	44	0.0489	0.1295	0.0827	0.165	-0.2574	0.166	0.3191	-0.1823	0.0765	0.2307	-0.1335	0.1313	-0.0078	-0.2991	0.0812	0.0815	0.2206	0.0373	0.0806	0.2345	0.0655	0.1307	0.6219	0.0921	0.4553	-0.2373	0.476	0.2202	-0.3523	0.0947	-0.1572	-0.2516	0.35	0.3622	0.0566	-0.108	-0.2143	0.142	-0.5168	0.1642	0.6996	-0.2038	0.3914	-																											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44			

S5.6 Table conitued.

P values																																														
CHCRX	1	-																																													
CHCRY	2	0.1792	-																																												
CMRX	3	<0.001	0.1163	-																																												
CMRY	4	0.1959	<0.001	0.1024	-																																										
LRN	5	0.475	0.588	0.6014	0.765	-																																									
MDR	6	0.1489	<0.001	0.084	<0.001	0.5171	-																																								
MLAR	7	0.3988	0.1511	0.2173	0.0554	0.2926	0.1581	-																																							
MLLR	8	0.361	0.2533	0.4062	0.4322	0.01	0.2081	0.4775	-																																						
MLPR	9	0.0997	<0.001	0.0439	<0.001	0.5222	<0.001	0.0974	0.2962	-																																					
MWR	10	0.2899	0.1516	0.2745	0.141	0.1026	0.1137	0.5901	0.2219	0.079	-																																				
PEA_251	11	0.1072	0.7793	0.1461	0.7619	0.0728	0.6516	0.8705	0.2766	0.445	0.1017	-																																			
PEA_252	12	0.0885	0.0045	0.0569	0.0174	0.3092	0.0018	0.4256	0.0572	0.0101	0.1695	0.5011	-																																		
PEA_301	13	0.1296	0.9966	0.2213	0.927	0.0647	0.8644	0.5232	0.217	0.7384	0.2165	0.0019	0.5553	-																																		
PEA_302	14	0.3115	0.9871	0.4966	0.7496	0.0183	0.9281	0.1326	0.0391	0.9565	0.5367	0.089	0.4768	0.0216	-																																	
PEA_501	15	0.0171	0.1214	0.0051	0.0913	0.2782	0.0728	0.3006	0.2616	0.0258	0.0493	0.0373	0.0647	0.1193	0.4276	-																																
PEA_502	16	0.0067	0.1579	0.0014	0.1712	0.4651	0.1041	0.4399	0.2041	0.0861	0.3695	0.1747	0.0307	0.1882	0.3082	0.0134	-																																
PEA_751	17	0.0855	0.17	0.0465	0.128	0.2026	0.1015	0.3932	0.2485	0.0491	0.0106	0.0354	0.1025	0.1095	0.4647	<0.001	0.061	-																															
PEA_752	18	<0.001	0.1899	0.0026	0.2347	0.2854	0.1546	0.5916	0.217	0.1167	0.2178	0.0685	0.0725	0.07	0.1749	0.0175	0.0085	0.0712	-																															
PEA_951	19	0.2123	0.9629	0.2702	0.9902	0.1063	0.8786	0.733	0.3756	0.6884	0.1217	<0.001	0.6863	<0.001	0.112	0.09	0.2748	0.0526	0.1462	-																													
PEA_952	20	0.052	0.221	0.0656	0.2816	0.0557	0.1476	0.9332	0.0489	0.1456	0.036	0.0364	0.0541	0.0267	0.0988	0.0176	0.04	0.011	0.0206	0.0421	-																												
PEA_1001	21	0.1048	0.3405	0.0679	0.2794	0.1408	0.2318	0.5989	0.2406	0.1229	0.0263	0.0077	0.1987	0.0496	0.3143	0.0019	0.0754	<0.001	0.0829	0.0172	0.0163	-																									
PEA_1002	22	<0.001	0.3264	0.0098	0.3895	0.3531	0.2808	0.6967	0.3103	0.2383	0.2941	0.0789	0.1479	0.0523	0.1664	0.0469	0.0218	0.1203	<0.001	0.1271	0.03	0.1329	-																							
PRN	23	0.7457	0.6644	0.9555	0.5704	0.8395	0.667	0.6226	0.8844	0.5702	0.7	0.723	0.7771	0.3909	0.6405	0.8834	0.8514	0.9635	0.6501	0.4474	0.544	0.9526	0.4082	-																					
RCH	24	0.1423	0.0254	0.1075	0.0305	0.1014	0.0134	0.4666	0.0812	0.0085	0.0032	0.1488	0.02	0.2902	0.4539	0.0157	0.1285	0.0081	0.1028	0.248	0.0203	0.0265	0.1983	0.9029	-																					
TLAR	25	0.0883	0.0377	0.1014	0.0505	0.3177	0.0293	0.3525	0.2668	0.0367	0.0168	0.2906	0.0433	0.3369	0.6306	0.0606	0.1726	0.045	0.0666	0.3272	0.0291	0.1317	0.0852	0.4046	0.0136	-																				
TLLR	26	0.5063	0.6277	0.6254	0.7807	<0.001	0.5494	0.3169	0.0198	0.5315	0.0784	0.057	0.3599	0.0586	0.0282	0.2635	0.5084	0.1743	0.3135	0.0808	0.058	0.1146	0.3823	0.8236	0.0965	0.3154	-																			
TLPR	27	0.0887	0.0355	0.0994	0.0461	0.3667	0.0281	0.3149	0.3018	0.0358	0.0214	0.3222	0.0451	0.3712	0.6853	0.0653	0.1751	0.0508	0.0704	0.3587	0.0363	0.147	0.0882	0.4011	0.0173	<0.001	0.3646	-																	
WDR	28	0.5222	0.6163	0.5934	0.5966	0.0826	0.5364	0.9489	0.38	0.4328	0.0044	0.0601	0.5956	0.1089	0.4109	0.1847	0.7243	0.0618	0.3935	0.0398	0.0868	0.0611	0.4087	0.3833	0.0803	0.1057	0.0524	0.1226	-																
As	29	0.1213	0.5234	0.0974	0.4465	0.2592	0.5183	0.1155	0.5534	0.4803	0.7552	0.9997	0.5221	0.9655	0.6573	0.4333	0.1691	0.7096	0.2292	0.9437	0.7745	0.8539	0.1876	0.7704	0.9922	0.5536	0.2332	0.5079	0.4804	-																
Ba	30	0.0236	0.469	0.1032	0.5881	0.1686	0.4392	0.9335	0.2682	0.3996	0.1895	0.059	0.2868	0.0291	0.0957	0.1325	0.1663	0.186	0.0084	0.0858	0.0359	0.1884	0.003	0.1907	0.2029	0.0733	0.1802	0.0812	0.179	0.5334	-														
Ca	31	0.6837	0.4322	0.7738	0.652	0.806	0.5267	0.9444	0.5495	0.7801	0.3794	0.3133	0.3617	0.4996	0.8065	0.6798	0.633	0.4079	0.6941	0.1861	0.8678	0.3047	0.7211	0.8203	0.8434	0.9663	0.6564	0.9483	0.141	0.482	0.8889	-												
Cd	32	0.0417	0.3906	0.1093	0.5467	0.6803	0.4274	0.9008	0.4065	0.4526	0.9591	0.5658	0.2438	0.4532	0.2612	0.4258	0.1286	0.7924	0.0439	0.8305	0.402	0.8073	0.0436	0.8301	0.6465	0.472	0.7901	0.4707	0.7099	0.1938	0.099	0.0922	-											
Cs	33	0.5286	0.3677	0.6911	0.3686	0.9322	0.4573	0.3661	0.7346	0.4489	0.3312	0.9486	0.7484	0.9613	0.6281	0.7569	0.8671	0.7463	0.5475	0.9901	0.7632	0.9788	0.4929	0.2059	0.5123	0.126	0.9594	0.115	0.3739	0.622	0.2827	0.9703	0.6654	-									
Cu	34	0.0942	0.946	0.1574	0.9686	0.8282	0.9718	0.7506	0.9215	0.8193	0.5838	0.5075	0.8071	0.4926	0.5227	0.5231	0.2414	0.9502	0.1432	0.7409	0.8142	0.8414	0.1235	0.9723	0.8482	0.9855	0.7662	0.9968	0.5132	0.1034	0.2732	0.4163	0.02	0.9311	-							
Fe	35	0.2238	0.441	0.3372	0.6241	0.001	0.3692	0.4205	0.0064	0.4063	0.0898	0.0585	0.1617	0.0282	0.01	0.1697	0.2313	0.1325	0.1044	0.0763	0.0086	0.1091	0.1253	0.5597	0.0726	0.1451	0.002	0.1738	0.094	0.6041	0.0504	0.989	0.415	0.8961	0.9508	-						
K	36	0.2879	<0.001	0.2453	0.0036	0.8299	0.0047	0.1514	0.4478	0.0149	0.2963	0.8896	0.0363	0.691	0.7651	0.3287	0.3649	0.4318	0.3154	0.6243	0.4695	0.6981	0.4529	0.7759	0.1078	0.0734	0.8829	0.0668	0.8178	0.5066	0.5435	0.2777	0.3465	0.1864	0.901	0.6706	-					
Mg	37	0.3711	0.2797	0.4284	0.489	0.6757	0.3117	0.8459	0.1693	0.5023	0.7299	0.7792	0.1237	0.9944	0.3698	0.8205	0.2531	0.8842	0.339	0.5623	0.5905	0.7981	0.3991	0.7282	0.7013	0.6989	0.8266	0.7006	0.3645	0.5454	0.5791	0.0029	0.0455	0.8019	0.3703	0.4815	0.2604	-				
Mn	38	0.2884	0.9251	0.4939	0.6905	0.0335	0.9858	0.1397	0.068	0.9664	0.5261	0.0922	0.5201	0.0129	<0.001	0.4496	0.3187	0.4645	0.1572	0.0872	0.0811	0.3345	0.1236	0.392	0.5008	0.5428	0.0457	0.5902	0.3638	0.7738	0.0585	0.847	0.2668	0.7668	0.5348	0.0111	0.7221	0.4295	-			
Mo	39	0.4016	0.2003	0.412	0.2833	0.5595	0.232	0.3969	0.8052	0.4266	0.895	0.427	0.1921	0.6357	0.7794	0.8595	0.3841	0.9783	0.4499	0.425	0.6954	0.6698	0.4131	0.5575	0.7834	0.3	0.4701	0.2703	0.4928	0.1151	0.6319	0.0637	0.2388	0.4348	0.6776	0.9785	0.1316	0.115	0.908	-		
P	40	0.9673	0.7129	0.9864	0.5276	0.7326	0.8079	0.2596	0.3403	0.5621	0.4873	0.8935	0.6702	0.6416	0.273	0.8247	0.4957	0.8162	0.8612	0.9274	0.6181	0.8642	0.7797	0.8275	0.7193	0.7362	0.8266	0.7228	0.491	0.8936	0.9786	0.3641	0.6673	0.1357	0.9544	0.5474	0.5383	0.2154	0.2442	0.488	-	
Rb	41	0.7205	0.838	0.6958	0.7321	0.2668	0.9207	0.307	0.1936	0.9767	0.7939	0.4	0.6978	0.3931	0.1091	0.6524	0.3998	0.8117	0.6393	0.5717	0.6348	0.5493	0.7668	0.2135	0.8542	0.4988	0.307	0.4581	0.7598	0.63	0.9266	0.7393	0.523	0.0461	0.488	0.3795	0.5774	0.3616	0.221	0.4335	0.2892	-	
S	42	0.9327	0.1601	0.8909	0.2653	0.8247	0.2342	0.6828	0.5384	0.4073	0.6901	0.2123	0.249	0.2099	0.7661	0.7733	0.813	0.5652	0.962	0.0798	0.7611	0.3921	0.8816	0.396	0.799	0.8288	0.7046	0.8106	0.2536	0.7912	0.7385	0.011	0.3486	0.841	0.8838	0.8772	0.0742	0.0363	0.6499	0.1372	0.8122	0.9087	-	
Se	43	0.9771	0.6905	0.8713	0.9896	0.579	0.6952	0.3814	0.2377	0.9147	0.9703	0.6134	0.3919	0.9135	0.4213	0.7041	0.8	0.7789	0.8136	0.767	0.5187	0.6255	0.7256	0.326	0.8762	0.5501	0.6769	0.5556	0.8847	0.9327	0.6377	0.1616	0.5783	0.9557	0.6482	0.3648	0.6568	0.1404	0.3336	0.1239	0.0792	0.94	0.3506	-	
Zn	44	0.9171	0.782	0.8601	0.7237	0.5774	0.7221	0.4855	0.6957	0.8705	0.6187	0.7754	0.779	0.9868	0.5147	0.8626	0.8621	0.6346	0.9367	0.8636	0.6128	0.889	0.7799	0.1359	0.8443	0.3046	0.6084	0.2802	0.6352	0.4384	0.8399	0.7364	0.5862	0.4416	0.4246	0.904	0.8177	0.6444	0.7613	0.2349	0.725	0.0802	0.6611	0.3852	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44

S5.7 Table. Correlation coefficients between seedling root traits and grain mineral composition traits of seven amphidiploids measured at Hisar site. Root traits data are means of ~20 replications and grain elemental data are means of two replicate plots in 2014-15 and three replicates plots per amphidiploid at Hisar site in 2015-16.

r values																																													
CHCRX	1	-																																											
CHCRY	2	0.5725	-																																										
CMRX	3	0.9656	0.6469	-																																									
CMRY	4	0.555	0.9758	0.6661	-																																								
LRN	5	0.3264	0.2504	0.2418	0.1398	-																																							
MDR	6	0.6063	0.9914	0.6935	0.9743	0.2974	-																																						
MLAR	7	0.3812	0.6038	0.5337	0.7435	-0.4654	0.5957	-																																					
MLLR	8	0.4099	0.4999	0.3757	0.3567	0.8744	0.5427	-0.3246	-																																				
MLPR	9	0.6699	0.9535	0.7677	0.9753	0.294	0.9688	0.6733	0.4624	-																																			
MWR	10	0.4677	0.6032	0.481	0.6157	0.6658	0.6504	0.2491	0.5292	0.7015	-																																		
PEA_251	11	0.6593	0.1312	0.6096	0.1417	0.7117	0.2098	-0.0765	0.4792	0.3475	0.6671	-																																	
PEA_252	12	0.6865	0.9098	0.7406	0.8422	0.4515	0.9381	0.3615	0.7401	0.8739	0.583	0.3083	-																																
PEA_301	13	0.6297	-0.002	0.5298	-0.043	0.726	0.0801	-0.2933	0.5339	0.156	0.5345	0.9359	0.2719	-																															
PEA_302	14	0.4495	-0.0076	0.3114	-0.1491	0.8389	0.0424	-0.6261	0.7786	0.0256	0.2843	0.6858	0.3251	0.8274	-																														
PEA_501	15	0.8432	0.6402	0.9051	0.6822	0.4778	0.7118	0.4587	0.4924	0.8141	0.756	0.783	0.726	0.6429	0.36	-																													
PEA_502	16	0.8936	0.5959	0.9436	0.5812	0.3333	0.6637	0.3512	0.5467	0.6902	0.4034	0.5773	0.8001	0.563	0.4523	0.8584	-																												
PEA_751	17	0.6911	0.5824	0.7619	0.6318	0.5483	0.6673	0.3854	0.5043	0.7565	0.8715	0.7879	0.6659	0.6561	0.3336	0.9572	0.7329	-																											
PEA_752	18	0.985	0.5612	0.9278	0.5171	0.4716	0.5997	0.2481	0.534	0.6464	0.5332	0.7193	0.7124	0.7166	0.5771	0.8418	0.8824	0.7145	-																										
PEA_951	19	0.5386	-0.0219	0.4848	-0.0058	0.6605	0.0717	-0.1593	0.3987	0.1868	0.6399	0.957	0.1881	0.9535	0.6527	0.6842	0.4807	0.7492	0.6095	-																									
PEA_952	20	0.7503	0.5301	0.7243	0.4748	0.743	0.6079	0.0394	0.7567	0.6102	0.7862	0.7854	0.7461	0.8115	0.6711	0.8413	0.7766	0.8694	0.8307	0.7718	-																								
PEA_1001	21	0.6626	0.4261	0.7202	0.4768	0.616	0.5198	0.2434	0.5115	0.6383	0.8128	0.8871	0.5522	0.7553	0.4472	0.9366	0.7074	0.9725	0.6953	0.8431	0.8464	-																							
PEA_1002	22	0.9632	0.4374	0.8757	0.3882	0.4161	0.4756	0.1817	0.4505	0.5137	0.4642	0.7016	0.6076	0.7498	0.5865	0.761	0.8266	0.6417	0.9805	0.6329	0.802	0.6256	-																						
PRN	23	0.1515	-0.2018	-0.0262	-0.2619	0.095	-0.2001	-0.2282	-0.0682	-0.2621	0.1796	0.1654	-0.1324	0.3871	0.2168	-0.0688	-0.0878	0.0215	0.2107	0.3458	0.2794	-0.028	0.3742	-																					
RCH	24	0.6142	0.8155	0.6589	0.8006	0.6675	0.8585	0.3323	0.698	0.8829	0.9211	0.6064	0.833	0.4675	0.3412	0.8488	0.6311	0.8848	0.6655	0.5047	0.8319	0.812	0.5526	-0.0573	-																				
TLAR	25	0.6868	0.7821	0.6674	0.7535	0.4445	0.8041	0.4166	0.4878	0.7845	0.8447	0.4671	0.769	0.429	0.2231	0.7335	0.5796	0.7652	0.7226	0.4367	0.8047	0.6272	0.6917	0.3769	0.8574	-																			
TLLR	26	0.3047	0.225	0.2264	0.1303	0.9955	0.2758	-0.4451	0.8337	0.2878	0.7025	0.7403	0.4108	0.7374	0.8071	0.4908	0.3034	0.5778	0.4479	0.6986	0.7386	0.6492	0.3936	0.1045	0.6746	0.4463	-																		
TLPR	27	0.6862	0.7875	0.6703	0.7628	0.4056	0.8075	0.4467	0.4577	0.7869	0.8282	0.4408	0.7651	0.4021	0.1887	0.7249	0.5769	0.7529	0.7159	0.4118	0.7855	0.6086	0.6869	0.3795	0.8425	0.9991	0.4072	-																	
WDR	28	0.294	0.2322	0.247	0.2449	0.6957	0.2844	-0.0301	0.3954	0.3563	0.9108	0.7345	0.2456	0.657	0.3722	0.5667	0.1646	0.7312	0.3852	0.7772	0.6891	0.7326	0.3739	0.3928	0.6994	0.6614	0.7496	0.6387	-																
As	29	-0.2728	0.0169	-0.0999	0.0408	-0.5108	0.0222	0.1787	-0.1301	-0.0524	-0.6018	-0.596	0.0615	-0.5868	-0.3685	-0.2567	0.0777	-0.3402	-0.3513	-0.6204	-0.4156	-0.3634	-0.4113	-0.6492	-0.343	-0.4874	-0.5509	-0.4708	-0.8038	-															
Ba	30	0.3805	0.5925	0.2798	0.4736	0.3739	0.5753	0.0687	0.4778	0.4366	0.5477	0.0938	0.6034	0.2129	0.2416	0.2625	0.2574	0.3171	0.4558	0.1235	0.5742	0.1569	0.4804	0.6012	0.5468	0.8237	0.3471	0.824	0.4351	-0.4379	-														
Ca	31	0.1965	0.3597	0.1647	0.2031	-0.0043	0.3229	-0.1108	0.4225	0.1423	-0.3404	-0.3771	0.4985	-0.206	0.2286	-0.1195	0.3264	-0.2698	0.2106	-0.462	0.056	-0.3431	0.1892	-0.1196	-0.0215	0.0447	-0.0979	0.0506	-0.5659	0.4955	0.3411	-													
Cd	32	0.7251	0.2256	0.6148	0.1431	0.036	0.1985	0.0698	0.196	0.2082	-0.1863	0.2249	0.3423	0.3001	0.4142	0.2823	0.5765	0.0219	0.6947	0.0699	0.2391	0.0389	0.7135	0.0723	0.0359	0.1624	-0.0263	0.1671	-0.2959	-0.0119	0.1464	0.5593	-												
Cs	33	0.2629	-0.0941	0.0399	-0.238	0.7471	-0.1078	-0.6446	0.5221	-0.1077	0.2803	0.5358	0.0481	0.6387	0.8067	0.0928	0.0296	0.0822	0.3906	0.4856	0.4038	0.178	0.427	0.411	0.21	0.2075	0.7303	0.1765	0.4585	-0.7158	0.3431	0.0415	0.3464	-											
Cu	34	0.1561	0.7057	0.1787	0.567	0.404	0.6796	-0.0199	0.7348	0.5302	0.2166	-0.1566	0.7491	-0.1468	0.2504	0.1562	0.3098	0.112	0.2154	-0.2948	0.2969	0.0182	0.0955	-0.3303	0.4981	0.3497	0.3394	0.3408	-0.08	0.2708	0.4881	0.7364	0.1756	0.1246	-										
Fe	35	0.4413	0.3818	0.3237	0.1981	0.3981	0.3444	-0.2766	0.647	0.2337	-0.0682	0.0574	0.5433	0.184	0.5991	0.1097	0.4194	-0.0629	0.499	-0.0988	0.3059	-0.0704	0.4665	-0.0358	0.2074	0.2014	0.3126	0.1906	-0.2233	0.0595	0.4024	0.8377	0.7411	0.5232	0.7125	-									
K	36	0.4239	0.5145	0.3541	0.3651	0.2828	0.4611	-0.0667	0.561	0.378	-0.0691	-0.0331	0.5791	-0.0003	0.4045	0.1389	0.4038	-0.062	0.4472	-0.2483	0.19	-0.087	0.3709	-0.2638	0.2494	0.1814	0.201	0.1757	-0.3023	0.168	0.304	0.8157	0.7178	0.3642	0.7704	0.9526	-								
Mg	37	0.2942	0.4133	0.2204	0.2247	0.434	0.3876	-0.32	0.7378	0.2422	-0.0548	-0.0363	0.595	0.0933	0.5657	0.0644	0.3832	-0.062	0.3661	-0.1708	0.2979	-0.0806	0.3101	-0.1503	0.2414	0.1644	0.3474	0.1512	-0.2402	0.2102	0.3932	0.8832	0.5533	0.4112	0.843	0.9594	0.9171	-							
Mn	38	0.2976	0.44	0.2497	0.2699	0.182	0.4295	-0.1396	0.577	0.2259	-0.077	-0.2067	0.6326	0.0092	0.3587	0.0363	0.4284	-0.0438	0.3475	-0.2281	0.3338	-0.1447	0.3476	0.1369	0.1791	0.3108	0.0975	0.3127	-0.2806	0.2979	0.6022	0.9281	0.4621	0.1334	0.7416	0.7893	0.6957	0.8506	-						
Mo	39	0.211	0.6983	0.214	0.5849	0.6226	0.6728	-0.0433	0.7774	0.6075	0.4443	0.124	0.6899	0.0309	0.3522	0.3068	0.2684	0.2756	0.2852	-0.0665	0.3731	0.2326	0.1368	-0.3927	0.659	0.3994	0.5825	0.3797	0.2009	-0.0192	0.399	0.4384	0.1235	0.3391	0.8985	0.6268	0.7168	0.7157	0.4372	-					
P	40	0.4308	0.6138	0.4243	0.4723	0.3635	0.5954	-0.0323	0.7157	0.4914	0.0378	0.01	0.7453	0.0442	0.4361	0.2714	0.5536	0.1119	0.4641	-0.1772	0.3411	0.0743	0.3623	-0.3633	0.3927	0.2506	0.2827	0.2423	-0.2509	0.3236	0.3165	0.8468	0.5796	0.2164	0.8804	0.8993	0.9382	0.9426	0.7821	0.7768	-				
Rb	41	0.3334	0.0338	0.1463	-0.1171	0.8368	0.0306	-0.6187	0.6834	0.0297	0.3139	0.5807	0.2114	0.6549	0.8809	0.2084	0.1795	0.1736	0.4626	0.4858	0.4836	0.2764	0.4568	0.208	0.3276	0.2194	0.8101	0.1849	0.4186	-0.5763	0.298	0.1526	0.3937	0.9659	0.2947	0.6339	0.5037	0.5561	0.2206	0.5083	0.4087	-			
S	42	0.3251	0.4232	0.2576	0.2357	0.4087	0.4055	-0.2952	0.7382	0.2494	-0.054	-0.0388	0.6269	0.1125	0.5631	0.0886	0.4343	-0.0334	0.3946	-0.1528	0.3382	-0.0631	0.3484	-0.102	0.2447	0.1988	0.3207	0.1876	-0.2465	0.2385	0.4295	0.9083	0.5592	0.3662	0.8324	0.9476	0.8891	0.9934	0.8997	0.6676	0.9362	0.5084	-		
Se	43	0.1799	0.6922	0.2662	0.729	0.0029	0.6998	0.6061	0.1105	0.6383	0.6403	-0.0547	0.5345	-0.128	-0.3573	0.3742	0.1883	0.4953	0.1716	-0.0047	0.3731	0.2916	0.1347	0.2256	0.6032	0.7662	0.0233	0.7809	0.4315	-0.1464	0.6731	-0.0609	-0.3311	-0.331	0.2815	-0.219	-0.1608	-0.1449	0.1654	0.2121	-0.0313	-0.3507	-0.1	-	
Zn	44	0.3437	0.5599	0.3792	0.4371	0.1549	0.5483	0.0408	0.5893	0.4209	-0.1249	-0.1638	0.7026	-0.1014	0.2826	0.1799	0.5455	0.0207	0.3513	-0.3129	0.2286	-0.0358	0.2614	-0.4022	0.2529	0.1452	0.0704	0.145	-0.4361	0.5489	0.2374	0.9143	0.5298	-0.0211	0.8388	0.8128	0.8549	0.8878	0.8336	0.6297	0.9591	0.1725	0.903	-0.0082	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44

S5.7 table continued.

P values																																													
CHCRX	1	-																																											
CHCRY	2	0.1792	-																																										
CMRX	3	<0.001	0.1163	-																																									
CMRY	4	0.1959	<0.001	0.1024	-																																								
LRN	5	0.475	0.588	0.6014	0.765	-																																							
MDR	6	0.1489	<0.001	0.084	<0.001	0.5171	-																																						
MLAR	7	0.3988	0.1511	0.2173	0.0554	0.2926	0.1581	-																																					
MLLR	8	0.361	0.2533	0.4062	0.4322	0.01	0.2081	0.4775	-																																				
MLPR	9	0.0997	<0.001	0.0439	<0.001	0.5222	<0.001	0.0974	0.2962	-																																			
MWR	10	0.2899	0.1516	0.2745	0.141	0.1026	0.1137	0.5901	0.2219	0.079	-																																		
PEA_251	11	0.1072	0.7793	0.1461	0.7619	0.0728	0.6516	0.8705	0.2766	0.445	0.1017	-																																	
PEA_252	12	0.0885	0.0045	0.0569	0.0174	0.3092	0.0018	0.4256	0.0572	0.0101	0.1695	0.5011	-																																
PEA_301	13	0.1296	0.9966	0.2213	0.927	0.0647	0.8644	0.5232	0.217	0.7384	0.2165	0.0019	0.5553	-																															
PEA_302	14	0.3115	0.9871	0.4966	0.7496	0.0183	0.9281	0.1326	0.0391	0.9565	0.5367	0.089	0.4768	0.0216	-																														
PEA_501	15	0.0171	0.1214	0.0051	0.0913	0.2782	0.0728	0.3006	0.2616	0.0258	0.0493	0.0373	0.0647	0.1193	0.4276	-																													
PEA_502	16	0.0067	0.1579	0.0014	0.1712	0.4651	0.1041	0.4399	0.2041	0.0861	0.3695	0.1747	0.0307	0.1882	0.3082	0.0134	-																												
PEA_751	17	0.0855	0.17	0.0465	0.128	0.2026	0.1015	0.3932	0.2485	0.0491	0.0106	0.0354	0.1025	0.1095	0.4647	<0.001	0.061	-																											
PEA_752	18	<0.001	0.1899	0.0026	0.2347	0.2854	0.1546	0.5916	0.217	0.1167	0.2178	0.0685	0.0725	0.07	0.1749	0.0175	0.0085	0.0712	-																										
PEA_951	19	0.2123	0.9629	0.2702	0.9902	0.1063	0.8786	0.733	0.3756	0.6884	0.1217	<0.001	0.6863	<0.001	0.112	0.09	0.2748	0.0526	0.1462	-																									
PEA_952	20	0.052	0.221	0.0656	0.2816	0.0557	0.1476	0.9332	0.0489	0.1456	0.036	0.0364	0.0541	0.0267	0.0988	0.0176	0.04	0.011	0.0206	0.0421	-																								
PEA_1001	21	0.1048	0.3405	0.0679	0.2794	0.1408	0.2318	0.5989	0.2406	0.1229	0.0263	0.0077	0.1987	0.0496	0.3143	0.0019	0.0754	<0.001	0.0829	0.0172	0.0163	-																							
PEA_1002	22	<0.001	0.3264	0.0098	0.3895	0.3531	0.2808	0.6967	0.3103	0.2383	0.2941	0.0789	0.1479	0.0523	0.1664	0.0469	0.0218	0.1203	<0.001	0.1271	0.03	0.1329	-																						
PRN	23	0.7457	0.6644	0.9555	0.5704	0.8395	0.667	0.6226	0.8844	0.5702	0.7	0.723	0.7771	0.3909	0.6405	0.8834	0.8514	0.9635	0.6501	0.4474	0.544	0.9526	0.4082	-																					
RCH	24	0.1423	0.0254	0.1075	0.0305	0.1014	0.0134	0.4666	0.0812	0.0085	0.0032	0.1488	0.02	0.2902	0.4539	0.0157	0.1285	0.0081	0.1028	0.248	0.0203	0.0265	0.1983	0.9029	-																				
TLAR	25	0.0883	0.0377	0.1014	0.0505	0.3177	0.0293	0.3525	0.2668	0.0367	0.0168	0.2906	0.0433	0.3369	0.6306	0.0606	0.1726	0.045	0.0666	0.3272	0.0291	0.1317	0.0852	0.4046	0.0136	-																			
TLLR	26	0.5063	0.6277	0.6254	0.7807	<0.001	0.5494	0.3169	0.0198	0.5315	0.0784	0.057	0.3599	0.0586	0.0282	0.2635	0.5084	0.1743	0.3135	0.0808	0.058	0.1146	0.3823	0.8236	0.0965	0.3154	-																		
TLPR	27	0.0887	0.0355	0.0994	0.0461	0.3667	0.0281	0.3149	0.3018	0.0358	0.0214	0.3222	0.0451	0.3712	0.6853	0.0653	0.1751	0.0508	0.0704	0.3587	0.0363	0.147	0.0882	0.4011	0.0173	<0.001	0.3646	-																	
WDR	28	0.5222	0.6163	0.5934	0.5966	0.0826	0.5364	0.9489	0.38	0.4328	0.0044	0.0601	0.5956	0.1089	0.4109	0.1847	0.7243	0.0618	0.3935	0.0398	0.0868	0.0611	0.4087	0.3833	0.0803	0.1057	0.0524	0.1226	-																
As	29	0.554	0.9713	0.8312	0.9308	0.2414	0.9623	0.7014	0.7809	0.9112	0.1528	0.1578	0.8958	0.166	0.4161	0.5785	0.8685	0.4553	0.4397	0.1372	0.3537	0.423	0.3593	0.1146	0.4514	0.2672	0.1999	0.2863	0.0294	-															
Ba	30	0.3998	0.161	0.5434	0.283	0.4087	0.1766	0.8837	0.2782	0.3274	0.2031	0.8415	0.1514	0.6467	0.6017	0.5696	0.5773	0.4884	0.304	0.792	0.1776	0.737	0.2752	0.1533	0.204	0.0227	0.4456	0.0227	0.3293	0.3257	-														
Ca	31	0.6728	0.4281	0.7241	0.6623	0.9928	0.4799	0.813	0.3449	0.7609	0.455	0.4043	0.2549	0.6577	0.622	0.7986	0.475	0.5584	0.6503	0.2967	0.9051	0.4513	0.6845	0.7985	0.9635	0.9242	0.8346	0.9142	0.1854	0.2582	0.4541	-													
Cd	32	0.0652	0.6267	0.1418	0.7595	0.9389	0.6696	0.8818	0.6735	0.6541	0.6892	0.6278	0.4523	0.5132	0.3555	0.5396	0.1755	0.9628	0.0832	0.8817	0.6055	0.934	0.0718	0.8775	0.939	0.7279	0.9554	0.7202	0.5194	0.9797	0.7541	0.1918	-												
Cs	33	0.569	0.8409	0.9323	0.6074	0.0536	0.8181	0.1181	0.2293	0.8182	0.5426	0.2151	0.9184	0.1226	0.0283	0.8432	0.9497	0.8609	0.3862	0.2693	0.369	0.7026	0.3393	0.3597	0.6512	0.6553	0.0623	0.705	0.3008	0.0705	0.4512	0.9295	0.4465	-											
Cu	34	0.7383	0.0765	0.7014	0.1844	0.3688	0.093	0.9662	0.0599	0.2209	0.6409	0.7374	0.0526	0.7535	0.5881	0.738	0.4989	0.8111	0.6427	0.521	0.5179	0.969	0.8386	0.4694	0.2553	0.4419	0.4565	0.4545	0.8646	0.557	0.2664	0.0591	0.7065	0.7902	-										
Fe	35	0.3215	0.398	0.4788	0.6703	0.3764	0.4494	0.5482	0.1163	0.614	0.8845	0.9027	0.2075	0.6929	0.1552	0.8149	0.3489	0.8934	0.2542	0.833	0.5047	0.8807	0.2913	0.9392	0.6554	0.665	0.4949	0.6822	0.6302	0.8991	0.3708	0.0186	0.0567	0.2281	0.0724	-									
K	36	0.3433	0.2374	0.4358	0.4207	0.5388	0.2977	0.887	0.1902	0.4032	0.8829	0.9439	0.173	0.9996	0.368	0.7664	0.369	0.8949	0.3144	0.5913	0.6832	0.8528	0.4127	0.5675	0.5897	0.6971	0.6657	0.7064	0.5099	0.7188	0.5074	0.0253	0.0693	0.4219	0.0427	<0.001	-								
Mg	37	0.5219	0.3568	0.6349	0.6281	0.3306	0.3903	0.4841	0.0583	0.6008	0.9071	0.9385	0.1587	0.8422	0.1856	0.8908	0.3962	0.8949	0.4193	0.7142	0.5164	0.8636	0.4985	0.7477	0.602	0.7247	0.4451	0.7462	0.6038	0.6509	0.3829	0.0084	0.1976	0.3595	0.0172	<0.001	0.0036	-							
Mn	38	0.5169	0.3232	0.5891	0.5584	0.6961	0.3362	0.7654	0.175	0.6262	0.8697	0.6565	0.1273	0.9844	0.4295	0.9385	0.3376	0.9257	0.445	0.6227	0.4643	0.7569	0.4449	0.7697	0.7008	0.4974	0.8353	0.4948	0.5421	0.5164	0.1525	0.0026	0.2966	0.7755	0.0564	0.0348	0.0826	0.0153	-						
Mo	39	0.6497	0.081	0.6449	0.1678	0.1354	0.0977	0.9265	0.0397	0.1479	0.3179	0.7911	0.0863	0.9476	0.4384	0.5034	0.5606	0.5496	0.5353	0.8873	0.4098	0.6157	0.7699	0.3835	0.1074	0.3747	0.17	0.4008	0.6657	0.9674	0.3752	0.3251	0.7919	0.4569	0.006	0.132	0.0699	0.0705	0.3266	-					
P	40	0.3345	0.1426	0.3427	0.2845	0.4228	0.1584	0.9451	0.0705	0.2628	0.9359	0.9831	0.0545	0.925	0.328	0.5561	0.1973	0.8113	0.2942	0.7038	0.4541	0.8743	0.4245	0.4231	0.3836	0.5878	0.5391	0.6006	0.5874	0.479	0.4892	0.0162	0.1726	0.6411	0.0089	0.0058	0.0018	0.0015	0.0377	0.0399	-				
Rb	41	0.4649	0.9426	0.7543	0.8026	0.0189	0.9481	0.1385	0.0906	0.9496	0.493	0.1716	0.649	0.1104	0.0088	0.6538	0.7001	0.7097	0.2959	0.2691	0.2716	0.5484	0.3028	0.6544	0.4731	0.6364	0.0272	0.6915	0.35	0.1757	0.5162	0.7439	0.3823	<0.001	0.5212	0.1263	0.2491	0.1949	0.6346	0.2441	0.3627	-			
S	42	0.4768	0.3441	0.577	0.611	0.3626	0.3668	0.5204	0.0582	0.5897	0.9084	0.9343	0.1319	0.8103	0.1881	0.8502	0.3302	0.9434	0.381	0.7436	0.4581	0.8931	0.4438	0.8278	0.597	0.6691	0.4831	0.687	0.5941	0.6066	0.3362	0.0046	0.1919	0.4191	0.0201	0.0012	0.0074	<0.001	0.0058	0.1013	0.0019	0.2439	-		
Se	43	0.6995	0.0848	0.564	0.063	0.9952	0.08	0.1492	0.8136	0.1229	0.1213	0.9074	0.2165	0.7845	0.4313	0.4083	0.6859	0.2584	0.713	0.9921	0.4097	0.5257	0.7733	0.6267	0.1516	0.0445	0.9604	0.0382	0.3338	0.7541	0.0975	0.8968	0.4682	0.4683	0.5408	0.637	0.7305	0.7567	0.7231	0.648	0.9468	0.4406	0.831	-	
Zn	44	0.4503	0.1912	0.4016	0.3268	0.7402	0.2025	0.9307	0.1638	0.3471	0.7896	0.7257	0.0783	0.8287	0.5392	0.6995	0.2053	0.9648	0.4397	0.4945	0.622	0.9393	0.5712	0.371	0.5843	0.7561	0.8808	0.7565	0.328	0.2019	0.6083	0.0039	0.2213	0.9642	0.0183	0.0262	0.0142	0.0076	0.0198	0.1296	<0.001	0.7114	0.0053	0.9861	-
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44

CHAPTER 6. EVALUATION OF 40 WILD WHEAT SPECIES FROM *AGROPYRON*, *AEGILOPS*, *SECALE*, *THINOPYRUM*, *TRITICUM*, *ELYMUS*, GENERA, AND DERIVATIVES, FOR GRAIN ZN CONCENTRATION AND THE GRAIN IONOME

6.1 Abstract

Background: Micronutrient deficiencies, particularly, zinc (Zn), are widespread globally and affect human health. Wheat is an important source of dietary Zn in many developing countries. Domestication of wheat has narrowed the grain Zn concentration in modern wheat. Therefore, the aim of this study was to evaluate 225 wild accessions, representing 40 wild wheat species and 17 amphidiploids derived from different wild species, for grain Zn concentration and the grain ionome.

Methods: Grain of 225 wild accessions from Wheat Research Centre (WRC) at University of Nottingham, UK were analysed for grain mineral composition using inductively coupled plasma-mass spectrometry (ICP-MS). Glasshouse experiments were conducted to test grain and leaf mineral composition of 17 amphidiploids, five wheat cultivars and 13 wild wheat species in 2014-15 and 2015-16.

Results: The mean grain Zn concentration of 225 wild accessions varied from 47.4 to 178.4 mg kg^{-1}. The mean grain Zn concentration of 17 amphidiploids varied from 67 to 223 mg kg^{-1}, averaged across years. Amphidiploids showed up to 2.5-fold greater grain Zn concentration than wheat parents. There were no

relationships between flag leaf Zn and grain Zn concentrations. However, grain Zn and iron (Fe) concentration were positively correlated.

Conclusion: Wild wheat species, for example, *Amblyopyrum muticum*, *Aegilops speltoides*, *Aegilops umbellulata* and *Aegilops comosa* and their derived amphidiploids could be useful sources of variation to increase the grain Zn concentration in breeding programmes. Further work is needed to look at relative size of endosperm and grain Zn concentration in different fraction of grain.

6.2 Introduction

Micronutrient deficiencies (e.g. Zn) are widespread globally, particularly in developing countries (Stein, 2010; Muthayya *et al*., 2013; Joy *et al*., 2014; Kumssa *et al*., 2015). Wheat (*Triticum aestivum* L.) is the third most widely consumed cereal crop after rice and maize, providing up to 60% of the energy in many developing countries, including India (www.dwr.in; Chatzav *et al*., 2010). It is an important source of Zn and supply ~50% Zn of daily needs in India (Stein *et al*., 2007; Black *et al*., 2013; Kumssa *et al*., 2015). The Green Revolution has increased the wheat production to ensure the food security but overlooked the nutrition value of wheat cultivars which are not able to provide sufficient nutrients in human diet (Zhao *et al*., 2009).

Modern wheat varieties typically show grain Zn concentration from 20-31 mg kg^{-1} under field condition at global scale, which is 10 to 20 mg kg^{-1} less than the ideal target of 40 mg kg^{-1} for human diet (Chen *et al*., 2017). A grain Zn concentration range of 25-35 mg kg^{-1} has been reported in a panel of 36 diverse Indian wheat genotypes under field conditions, on Zn-deficient soils (Khokhar *et al*., submitted). Khokhar *et al*., submitted, reported a relatively small contribution of genotype was associated with total variation in grain Zn concentration. However, some genotypes showed consistent ranking across site for grain Zn concentration, despite a significant effect of different environments on grain Zn concentration. Grain Zn concertation in wheat can be increased through opting biofortification approaches, agronomic and genetic biofortification. Biofortification is a process of increasing the nutritional value in edible part of food crops (Saltzman *et al*., 2013). Agronomic Zn biofortification involves the use of Zn fertilisers in granular and foliar forms to

increase the crop yield and grain Zn concentration in wheat (Joy *et al*., 2015; Cakmak and Kutman, 2017; Chen *et al*., 2017). Genetic Zn biofortification in wheat is likely to be more cost-effective approach in longer term provided enough genetic variation present in wheat germplasm. Cultivated wheat have limited genetic variation (Khokhar *et al*., submitted; Chen et al., 2017), wild relatives have shown considerable variations for grain Zn concentration in wheat and can be used to achieve the breeding target of ~40 mg kg^{-1} grain Zn in wheat (White and Broadley, 2009; Bouis and Saltzman, 2017; Cakmak and Kutman, 2017; Chen *et al*., 2017).

The 'HarvestPlus' programme has been the primary driver of genetic biofortification in wheat. It has developed and deployed high-Zn wheat varieties in South Asia using the synthetic wheat lines which were developed by using the wild wheat relatives, *Aegilops tauschii*, D genome donor of wheat, *Triticum spelta* and wild *T. dicoccon*. The *T. durum* based synthetic hexaploid wheat was developed by crossing of *T. durum* wheat cultivar with *Ae. squarrosa* and further selections have developed a high-Zn variety, the Zinc Shakti (CROC1_/AE.SQUARROSA (210)//INQALAB91*2/KUKUNA/3/PBW343*2/KUKUNA) for North-Eastern Plain Zones of India, showed 14 mg kg^{-1} greater grain Zn concentration than the notional baseline grain Zn concentration of 25 mg kg^{-1}. The *T. dicoccon* based synthetic hexaploid wheat was developed by crossing of a high Zn containing accession of wild *T. dicoccon* with *Ae. squarrosa* and further selections have developed the WB02 and HPBW-01 (T.DICOCCON, CI9309/AE.SQUARROSA (409)//MUTUS/3/2*MUTUS) wheat varieties for North-Western Plain Zones of India and showed 7 mg kg^{-1} greater grain Zn

concentration than the notional baseline grain Zn concentration. Similarly, Zincol-2016 has been released for the Pakistan and developed by crossing of a well-adapted NARC2011 wheat variety with a high Zn containing accession of *T. spelta* and showed 9 mg kg $^{-1}$ greater grain Zn concentration than the notional baseline grain Zn concentration of 25 mg kg^{-1} (Singh and Velu, 2017). Therefore, there is scope to explore the progenitors and non-progenitors of modern wheat to identify the greater source of Zn variation and use them in breeding programmes to help to alleviate the grain quality of modern wheat varieties.

Wheat wild relatives and landraces from primary gene pool (*Triticum turgidum*; *T. urartu*; *Ae. tauschii* and landraces) and secondary gene pool (include B genome species i.e. *Ae. speltoides* and D genome polyploid *Aegilops* species) and their derivatives have shown reservoir for greater variation in grain Zn concentration (Rodriguez *et al*., 2011; Guzman *et al*., 2014; Manickavelu *et al*., 2017). For example, grain Zn concentration from 37-90 mg kg^{-1} in six accessions of *Ae. tauschii* and from 56-80 mg kg^{-1} in five accessions of *Ae. kotschyi* have been reported under field conditions (Chhuneja *et al*., 2006). Cakmak *et al*., 2004, reported grain Zn concentration form 30-98 mg kg^{-1} in field grown 518 accessions of *T. dicoccoides*. Kumar *et al*., 2016, screened 16 accessions of *Triticum* and *Aegilops* wild species which includes progenitor and non-progenitor of wheat, under field condition and reported grain Zn concentration from 32-112 mg kg^{-1}. Guzman *et al*., 2014, screened 141 advance lines, which were developed by crossing of Mexican landraces, wild *spelt* wheat, *Triticum dicoccoides* and *Ae. tauschii* with durum and wheat genotypes, under field condition in Mexico and reported grain Zn concentration from 27-53 mg kg^{-1}.

Similarly, Srinivasa *et al*., 2014, reported grain Zn concentration from 25-60 mg kg^{-1} in 185 recombinant inbred lines derived from crossing between *T. spelta* and *T. aestivum* under field condition. Non-wheat progenitor wild species, *T. boeticum* (Am), *T. araraticum* (AG), *Ae. longissima* (S), *Ae. Kotschyi*, *Ae. peregrine* (US), *Ae. cylindrica* (CD), *Ae. ventricosa* (DN) and *Ae. geniculata* (MU) have been screened under field condition and showed greater grain Zn concentration (19-67 mg kg^{-1}) than modern wheat cultivars (Rawat *et al*., 2008). Neelam *et al*., 2011, grew derivatives of *Ae. peregrina* (US) under field condition and reported grain Zn concentration from 23-67 mg kg^{-1}. Similarly, derivatives of *Ae. longissima* under field condition showed greater grain Zn concentration (60-95 mg kg^{-1}) than their wheat parents (Neelam *et al*., 2013). Schlegel *et al*., 1998, have reported that *Secale cereal* and *Agropyron* derivatives had greater Zn efficiency than wheat and oat under greenhouse controlled conditions.

The aim of this study was to screen the grains of 225 wild wheat accessions representing 40 wild wheat species and 17 amphidiploids derived from different wild species, for grain Zn concentration and the grain ionome. Most research to date has explored the *Aegilops* and *Triticum* genera, less information is available for grain Zn concentration in wild wheat species belongs to *Agropyron*, *Thinopyrum*, *Secale* and *Elymus* genus.

6.3 Materials and Methods

6.3.1 Wild wheat germplasms

The seed materials of 225 accessions (S6.1 Table) of wild wheat species were obtained from Wheat Research Centre' (WRC) at University of Nottingham, which further obtained from United States Department of Agriculture (USDA), National Centre for Genetic Resources Preservation (Fort Collins, Colorado); the John Innes Centre (Colney, Norwich, UK); and The Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, (Gogerddan, Aberystwyth, UK). All 225 accessions were further categorised into 40 species of six genus of tribe, *Triticeae* (**Table 6.1**). The spikes of all the 225 wild accession were de-husked by hand to get the grains.

Table 6.1 List of 40 wild wheat species used for grain mineral analysis.

Genus	Species name	Accessions	Genome
Aegilops	*Ae bicornis*	5	S^b
Aegilops	*Ae biuncialis*	8	UM
Aegilops	*Ae columnaris*	8	UM
Aegilops	*Ae comosa*	10	M
Aegilops	*Ae crassa*	7	D^cM
Aegilops	*Ae cylindrica*	7	DC
Aegilops	*Ae geniculata*	9	MU
Aegilops	*Ae juvenalis*	5	DMU
Aegilops	*Ae kotschyi*	7	SU
Aegilops	*Ae longissima*	8	S^l
Aegilops	*Ae markgrafii*	7	CC
Aegilops	*Ae neglecta*	11	UMN
Aegilops	*Ae peregrina*	14	SU
Aegilops	*Ae searsii*	8	S^S
Aegilops	*Ae sharonensis*	8	S^l
Aegilops	*Ae speltoides*	7	BB
Aegilops	*Ae tauschii*	2	D
Aegilops	*Ae triuncialis*	13	UC
Aegilops	*Ae umbellulata*	3	UU
Aegilops	*Ae uniaristata*	6	N
Aegilops	*Ae vavilovii*	5	DMS
Aegilops	*Ae ventricosa*	7	DN
Agropyron	*Agropyron fragile*	1	P
Aegilops	*Amblyopyrum muticum*	2	TT
Elymus	*Elymus breviaristatus*	1	StYH
Elymus	*Elymus caninus*	1	StH
Secale	*S anatolicum*	2	RR
Secale	*S cereale*	2	RR
Secale	*S iranicum*	3	RR
Secale	*S segetale*	1	RR
Secale	*S strictum*	1	RR
Secale	*S vavilovi*	4	RR
Triticum	*T monococcum*	3	A^m A^m
Triticum	*T timopheevii*	7	GA^u
Triticum	*T Urartu*	22	A^uA^u
Triticum	*Triticum turgidum*	4	BA^u
Thinopyrum	*Thinopyrum elongatum*	1	$E^eE^eE^bE^bE^xE^xS^tS^t$
Thinopyrum	*Thinopyrum intermedium*	1	EStV/St
Thinopyrum	*Thinopyrum ponticum*	2	$E^bE^bE^bJJ$
Thinopyrum	*Thinopyrum turcicum*	2	EEEEE

6.3.2 Planting materials used in glasshouse experiment

The seeds of twenty amphidiploids, thirteen accessions of seven wild species (wild parents) and five wheat parents were collected from WRC, University of Nottingham, UK (**Table 6.2**). The seeds of 51 *Amblyopyrum muticum* [(Boiss.) Eig. (*Aegilops mutica* Boiss.)], derived double haploid lines which were grown in soil filled pots in glasshouse in 2015-16 and threshed mechanically were received from WRC, University of Nottingham.

Table 6.2 List of amphidiploids with their wild and wheat parents grown in glasshouse in 2014-15 and 2015-16.

Lines	**Pedigree**	**Parent**	**Wild species accessions**
Amphi 1	*Amblyopyrum muticum* 2130004 x CS Eup 94	**WT 1**	*Amblyopyrum muticum* 2130004
Amphi 2	*Amblyopyrum muticum* 2130008 x CS Eup 94	**WT 2**	*Am muticum* 2130008
Amphi 3	*Amblyopyrum muticum* 2130012 x Paragon	**WT 3**	*Am. muticum* 2130012
Amphi 4	*Amblyopyrum muticum* 2130012 x Highbury	**WT 4**	*Aegilops speltoides* 2140008
Amphi 5	*Amblyopyrum muticum* 2130012 x CS Eup 94	**WT 5**	*Aegilops speltoides* 449340
Amphi 6	*Aegilops speltoides* 2140008 x CS Eup 94	**WT 6**	*Aegilops umbellulata* 542377
Amphi 7	*Aegilops speltoides* 2140008 x Pavon 76	**WT 7**	*Aegilops umbellulata* 554410
Amphi 8	*Aegilops speltoides* 449340 x Pavon 76	**WT 8**	*Aegilops comosa* var. comosa 276970
Amphi 9	*Aegilops umbellulata* 542377 x Pavon 76	**WT 9**	*Thinopyrum turcicum* P208/201
Amphi 10	*Aegilops umbellulata* 554410 x CS Eup 94	**WT 10**	*Secale anatolicum* P208/142
Amphi 11	*Aegilops umbellulata* 554410 x CS Eup 94	**WT 11**	*Secale anatolicum* P208/141
Amphi 12	*Aegilops comosa* var. comosa 276970 x Paragon	**WT 12**	*Thinopyrum bessarabicum* 531712
Amphi 13	*Thinopyrum turcicum* P208/201 x CS Eup 94	**WT 13**	*Thinopyrum bessarabicum* Abers
Amphi 14	*Secale anatolicum* P208/142 x Highbury		
Amphi 15	*Secale anatolicum* P208/142 x CS Eup 94		**Wheat Parents**
Amphi 16	*Secale anatolicum* P208/141 x CS Eup 94	**1**	CS Eup 94
Amphi 17	*Secale anatolicum* P208/142 x CS Eup 94	**2**	Paragon
Amphi 18	*Secale anatolicum* P208/142 x CS Eup 94	**3**	Highbury
Amphi 19	*Thinopyrum bessarabicum* 531712 x CS Mut P208/535	**4**	Pavon 76
Amphi 20	*Thinopyrum bessarabicum* Abers. X Chinese spring	**5**	CS Mutant 84

6.3.3 Seed sowing, vernalisation and transplanting seedlings into soil pots in glasshouse

The study was carried out under controlled conditions in glasshouse at Sutton Bonington Campus, University of Nottingham (58.8202°N 1.2512°), UK in 2014-15 and 2015-16. The twenty amphidiploids, thirteen wild parents and five wheat parents were grown in soil pots in glasshouse.

Ten seeds of each amphidiploid, wild wheat species and wheat parents were sown into professional soil growing media; Levington Seed and Modular Plus Sand - F2+S (Everris Ltd., Ipswich, UK) in modular propagation trays (84 cells; 524 plants m^{-2}; Desch Plantpak, Essex, UK) for six days in glasshouse at 15 degree. Plants were watered every day manually. At two leaves stage, wild parents were vernalised for six weeks and amphidiploids and wheat parents were vernalised for four weeks in phytotron at 7 degree.

The Irish peat compost (Klasmann Medium Peat 818; Dejex Supplies Ltd. UK) were used as a soil medium to prepare a mixture of 250 L soil by adding of 375 g of normal super phosphate, 188 g of sulphate of potash, 556 g of ground chalk, 556 g of ground magnesium and limestone and 100 g of fitted trace elements. Approximately 2 L soil were filled in 190 pots of size 2.5 L. After vernalisation, wheat seedlings were transplanted into 2.5 L soil pots. The pots were arranged into randomised block design with five replications.

Fertilisers were applied at rate of 200 kg N, 36 kg P_2O_5 and 36 kg K_2O per hectare. Nitrogen doses were split into three doses; 1st dose of 80 kg ha^{-1} was applied at the time of transplanting seedlings into soil pots; 2nd dose of 60 kg ha^{-1} was applied at growth stage, GS31 and 3rd dose of 60 kg ha^{-1} was applied at

the time of anthesis (GS 69). The stock solution of P and K fertilisers were prepared into water and pumped to the plants in pots through drippers.

6.3.4 Leaf and grain sampling

Leaves were sampled from amphidiploids, wild and wheat parents from 2014-15 experiment only. Two leaves, flag leaves of 1st and 2nd tillers, from amphidiploids and wheat parents and 2-10 flag leaves from wild relatives were removed by scissor from five replications of each plant in a pot, collected and stored at -20 degree for further analysis. Grain of wild wheat parents were not analysed due to non-availability of enough seeds after threshing. After threshing of 20 amphidiploids, grains from 17 amphidiploids were used for digestion, seed of three amphidiploids were not available.

6.3.5 Leaf and grain digestion and multi-elemental analysis

The leaf samples stored in paper bags were freeze dried at -80 °C (CHRIST Alpha 2-4 LD freeze dryer; Martin Christ Gefriertrock-nungsanlagen Gmbh, Osterode, Germany) for 60-72 h, hand crushed to powder and weighed for digestion. The weight of leaf samples varied from 0.04 to 0.21 g. Approximately 2-10 seeds, from one to five replication, of 17 amphidiploids and five wheat parents and five grains of each 225 wild wheat accessions were weighed and used in microwave digestion.

The grains of 225 wild wheat accessions were digested in 6 runs, 171 leaf samples of amphidiploids, wild parents and five wheat parents from 2014-15 experiments were digested in 4 runs and 114 grain samples from amphidiploids and wheat parent from 2014-15 and 2015-16 experiments were digested in 3 runs, excluding blanks, LRM and CRM. The further details of microwave

digestion and analysis for 31 mineral elemental and data validation are described in Khokhar *et al*., submitted (Chapter 3).

6.3.6 Statistical analysis

Variance components were calculated for grain concentration of Zn and a further 15 elements (As, Ba, Ca, Cd, Cs, Cu, Fe, K, Mg, Mn, P, Rb, S, Se, and Sr). An unbalanced Analyses of Variance (ANOVA) and Least Significant Difference (LSD) tests were used to test for differences in mean grain elemental concentration of genus, wild species and amphidiploids. Difference between amphidiploids for grain mineral composition traits were considered significant at $P<0.001$. Pearson correlation coefficients were calculated between leaf and grain concentration 16 grain mineral elements. All analyses were conducted using GenStat 17th Edition (VSN International Ltd, Hemel Hempstead, UK).

6.4 Results

In present study, 225 wild wheat accessions representing 40 wild wheat species, 17 amphidiploids derived from *Amblyopyrum muticum*, *Aegilops speltoides*, *Ae. umbellulata*, *Ae. comosa*, *Thinopyrum turcicum*, *Secale anatolicum* and *Thinopyrum bessarabicum*, 51 double haploid lines derived from *Amblyopyrum muticum* and five wheat parents were characterised for grain Zn concentration.

6.4.1 Differences in grain Zn concentration and the grain ionome between *Aegilops, Secale, Triticum* and *Thinopyrum* genera

Grain Zn concentration differed between genus (P<0.001). The mean grain Zn concentration varied from 62.7 (*Secale*) to 111.4 (*Triticum*) mg kg^{-1} (LSD=45.8) (**Figure 6.1**).

Among the macronutrients, grain Ca, Mg and S differed between genus. The mean grain calcium (Ca) concentration varied from 520 (*Secale*) to 1030 (*Thinopyrum*) mg kg^{-1}, averaged across 167 accessions of *Aegilops*, 13 accessions of *Secale*, 36 accessions of *Triticum* and 6 accessions of *Thinopyrum* genus (LSD=451.5). The mean grain magnesium (Mg) concentration varied from 1652 (*Secale*) to 2641 (*Triticum*) mg kg^{-1} (LSD=533.7). The mean grain sulphur (S) concentration varied from 2350 (*Secale*) to 3472 (*Triticum*) mg kg^{-1} (LSD=958.5).

Among the micronutrients, the mean grain copper (Cu) concentration varied from 7.01 (*Triticum*) to 9.1 (*Thinopyrum*) mg kg^{-1}, averaged across 167 accessions of *Aegilops*, 13 accessions of *Secale*, 36 accessions of *Triticum* and 6 accessions of *Thinopyrum* genus (LSD=3.5). The mean grain iron (Fe) concentration varied from 37 (*Secale*) to 81.7 (*Thinopyrum*) mg kg^{-1} (LSD=34.9). The mean grain manganese (Mn) concentration varied from 31.4 (*Secale*) to 68.7 (*Thinopyrum*) mg kg^{-1} (LSD=29.3). Among the non-essential trace elements, the mean grain selenium (Se) concentration varied from 0.007 (*Secale*) to 0.03 (*Aegilops*) mg kg^{-1} (LSD=0.02).

Among the four genus, *Triticum* showed greatest mean grain concentration of As, Cd, Cs, K, Mg, P, S and Zn while *Thinopyrum* showed greatest mean grain concentration of Ba, Ca, Cu, Fe, Mn and Sr (**Figure 6.1**).

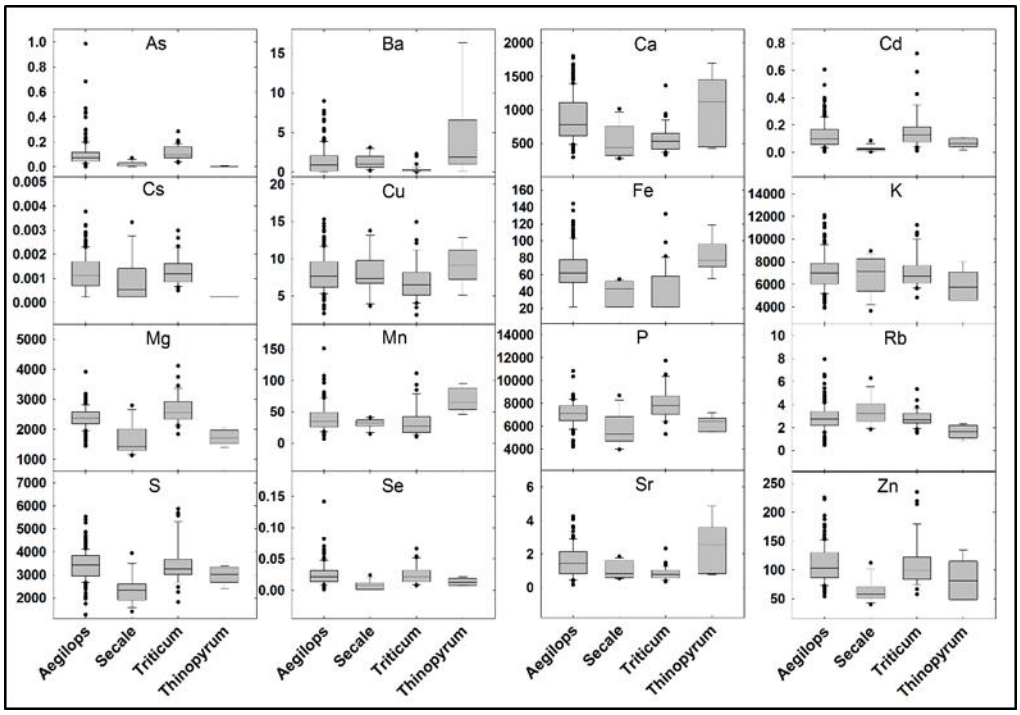


Figure 6.1 Grain element concentrations of *Aegilops*, *Secale*, *Triticum* and *Thinopyrum* genus of wheat. Data represent 167 accessions of *Aegilops*, 13 accessions of *Secale*, 36 accessions of *Triticum* and 6 accessions of *Thinopyrum* genus. Boxes represent the two mid-quartiles with the median drawn; whiskers are the 95% confidence limits; circles are the outliers.

6.4.2 Differences in grain Zn concentration and the grain ionome between 40 wild wheat species

Grain Zn concentration differed between 40 wild wheat species ($P<0.001$). The mean grain Zn concentration of 40 wild species varied from 47.4 to 178.4 mg

kg^{-1} (**Table 6.3**). The *Amblyopyrum muticum* and *Elymus breviaristatus* had the largest and smallest grain Zn concentration, respectively.

Among the macronutrients and micronutrients, the variations in grain concentrations of Ca, Mg, S, Fe, Mn and Zn were greater between 40 wild species as compared to grain Cu concentration. The mean grain Ca concentration of 40 wild wheat species varied from 322.9 to 2717.9 mg kg^{-1}. The *Agropyron fragile* and *Secale iranicum* had the greatest and smallest grain Ca concentration, respectively. The mean grain Mg concentration varied from 1134 to 2707 mg kg^{-1}. The *Triticum monococcum* and *Secale strictum* had the greatest and smallest grain Mg concentration, respectively. The grain S concentration varied from 2019 to 4341 mg kg^{-1}. The *Ae. umbellulata* and *S. anatolicum* had the largest and smallest grain S concentration, respectively.

Among the micronutrients, the mean grain Cu concentration of 40 wild wheat species varied from 5.9 to 10.8 mg kg^{-1}. The *Th. turcicum* and *S. cereal*e had the greatest and smallest grain Cu concentration, respectively. The mean grain Fe concentration of 40 wild species varied from 21.7 to 96.7 mg kg^{-1}. The *Th. turcicum* and *S. vavilovi* had the greatest and smallest grain Fe concentration, respectively. The mean grain Mn concentration of 40 wild species varied from 19.9 to 126.6 mg kg^{-1}. The *Am. muticum* and *Ae. searsii* had the greatest and smallest grain Mn concentration, respectively. Among the non-essential trace elements, the mean grain Se concentration of 40 wild species varied from 0.001 to 0.04 mg kg^{-1}. The *Am. muticum* and *Elymus caninus* had the greatest and smallest grain Se concentration, respectively (**Table 6.3**).

Table 6.3 The mean and range of grain Ca, Mg, S, Cu, Fe, Mn, Zn and Se concentrations in 40 wild wheat species. N represents no of accessions.

Species	N	Ca (Mg kg^{-1})		Mg (mg kg^{-1})		S (mg kg^{-1})		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Zn (mg kg^{-1})		Se (mg kg^{-1})	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Ae bicornis	5	1210	776-1380	2260	1800-2670	2410	1270-2860	7.57	4.56-12.6	89.2	62.6-114	43.8	15.0-78.9	88.5	63.9-130	0.0270	0.0199-0.0315
Ae biuncialis	8	651	376-849	2310	1510-2870	3370	1750-4090	9.88	5.62-13.0	94.5	52.6-119	45.5	24.8-68.7	125	64.7-177	0.0370	0.0181-0.0824
Ae columnaris	8	629	463-894	2360	2150-2930	3650	2940-4590	8.98	6.34-12.7	76.8	51.0-109	34.9	23.4-47.8	116	76.2-188	0.0213	0.0132-0.0288
Ae comosa	10	668	414-853	2480	1910-2920	3790	2470-4490	9.49	6.13-13.8	75.0	21.7-112	53.1	21.6-96.7	109	54.2-194	0.0424	0.0123-0.142
Ae crassa	7	846	611-1290	2390	1700-3050	3150	2080-3990	6.79	5.23-10.2	71.8	63.6-80.8	32.9	17.0-66.2	93.7	72.7-109	0.0260	0.0122-0.0645
Ae cylindrica	7	1090	652-1590	2380	1860-2810	3000	2010-3970	6.91	5.05-12.7	76.2	53.3-136	33.4	17.4-53.5	79.8	63.4-96.6	0.0278	0.0131-0.0580
Ae geniculata	9	639	292-1020	2560	1950-3910	3660	2530-4450	9.77	5.46-15.3	62.1	43.4-95.0	29.9	14.9-51.9	109	59.6-161	0.0281	0.0174-0.0476
Ae juvenalis	5	698	597-859	2490	2310-2600	3420	2950-3830	6.74	5.58-7.8	59.1	52.4-69.3	33.9	26.5-41.5	107	91.5-125	0.0196	0.0147-0.0242
Ae kotschyii	7	1170	788-1620	2690	2310-2920	3580	2680-3930	8.05	4.85-12.1	56.1	21.7-121	41.7	17.4-51.1	118	85.8-179	0.0374	0.0245-0.0516
Ae longissima	8	1250	742-1560	2540	1840-3190	3600	2830-4700	8.644	3.22-11.2	56.8	21.7-103	56.6	24.8-78.4	133	107-168	0.0437	0.00658-0.0631
Ae markgrafii	7	903	569-1220	2430	2160-3130	3980	3140-5530	8.16	3.54-14.7	89.4	62.9-144	68.6	20.0-108	132	66.9-175	0.0423	0.0147-0.0705
Ae neglecta	11	521	367-697	2150	1450-2440	3600	2380-4480	8.16	4.97-12.0	57.8	46.1-79.1	42.6	26.8-75.5	105	73.1-140	0.0216	0.0109-0.0373
Ae peregrina	14	856	482-1360	2410	2150-2760	3310	2880-4110	8.70	5.81-13.9	56.6	21.7-98.2	31.3	12.5-53.6	122	96.4-151	0.0161	0.00544-0.0391
Ae searsii	8	1620	1339-1810	2300	1960-2540	3470	3020-3680	8.10	4.39-11.5	73.0	52.2-123	19.9	6.5-46.0	95.2	77.4-134	0.00869	0.00141-0.0183
Ae sharonensis	8	1190	965-1480	2230	1680-2440	2990	2210-4000	8.49	6.80-10.0	58.5	44.9-81.9	50.9	30.4-81.1	101	70.7-156	0.00726	0.00141-0.0153
Ae speltoides	7	945	777-1160	2180	1940-2560	3340	2630-3920	6.50	4.88-9.10	59.7	21.7-109	41.3	32.0-65.0	117	84.2-153	0.0193	0.00141-0.0583
Ae tauschii	2	1180	1166-1190	2600	2510-2690	3480	3400-3570	8.63	6.43-10.8	50.2	48.0-52.3	40.8	36.3-45.3	64.9	63.2-66.6	0.0303	0.0253-0.0353
Ae triuncialis	13	664	382-1180	2510	2020-3100	3710	3270-5260	6.93	3.75-11.7	39.5	21.7-73.6	35.2	11.9-63.9	113	88.3-156	0.0195	0.00839-0.0351
Ae umbellulata	3	626	445-864	2560	1950-2870	4340	2800-5390	7.72	5.32-10.4	56.4	21.7-103	32.1	23.2-48.6	138	89.7-225	0.0244	0.0230-0.0267
Ae uniaristata	6	582	493-682	1800	1450-2030	3160	1960-3960	6.12	5.46-6.76	60.1	53.2-69.3	39.3	26.3-49.4	87.6	70.1-104	0.0193	0.0113-0.0307
Ae vavilovii	5	933	763-1090	2520	2380-2870	3430	2720-4510	6.10	2.62-9.47	47.9	21.7-75.4	23.9	11.9-33.8	108	92.8-125	0.0258	0.0947-0.0444
Ae ventricosa	7	721	550-823	2150	2030-2240	2970	2590-3330	7.24	5.09-8.63	57.1	21.7-83.5	32.3	19.3-59.5	79.6	67.4-113	0.0190	0.0111-0.0335
Agropyron fragile	1	2720	2718-2720	1360	1360-1360	2550	2550-2550	7.17	7.17-7.17	70.4	70.4-70-4	68.8	68.8-68.8	79.4	79.4-79.4	0.00566	0.00566-0.00566
Amblyopyrum muticum	2	1540	1520-1560	2670	2410-2930	3800	3500-4110	9.33	7.26-11.4	96.7	70.7-123	127	102-151	178	134-223	0.0437	0.0422-0.0452
Elymus breviaristatus	1	874	874-874	1550	1550-1550	3180	3180-3180	6.25	6.25-6.25	45.3	45.3-45.3	26.1	26.1-26.1	47.4	47.4-47.4	0.00572	0.00572-0.00572
Elymus caninus	1	1160	1156-1160	1680	1680-1680	3530	3530-3530	7.94	7.94-7.94	76.8	76.8-76.8	22.4	22.4-22.4	52.7	52.7-52.7	0.00141	0.00141-0.00141
S anatolicum	2	562	432-691	1520	1490-1550	2020	1910-2130	10.6	9.00-12.2	53.3	51.9-54.6	33.4	32.5-34.3	55.0	50.2-59.8	0.00141	0.00141-0.00141
S cereale	2	330	276-384	1440	1270-1600	2070	1810-2330	5.86	4.42-7.31	32.9	21.7-44.1	31.5	28.7-34.2	54.9	51.3-58.4	0.00767	0.00684-0.00850
S iranicum	3	323	277-380	1380	1330-1420	2190	1890-2590	9.08	6.70-13.8	42.3	21.7-52.7	21.2	14.8-27.0	57.3	40.4-85.0	0.00501	0.00141-0.0122
S segetale	1	498	498-498	1410	1410-1410	2610	2610-2610	10.49	10.5-10.5	51.8	51.8-51.8	41.0	41.0-41.0	112	112-112	0.00330	0.00330-0.00330
S strictum	1	458	458-458	1130	1130-1130	2440	2440-2440	6.84	6.84-6.84	43.5	43.5-43.5	39.7	39.7-39.7	55.6	55.6-55.6	0.0126	0.0126-0.0126
S vavilovi	4	764	332-1020	2210	1180-2800	2690	1410-3940	6.56	3.61-8.03	21.7	21.7-21.7	32.8	28.3-41.1	63.8	55.4-70.9	0.0118	0.00141-0.0240
T monococcum	3	632	367-907	2710	2170-3750	3870	2820-5690	7.57	5.00-12.1	44.6	21.7-64.4	51.5	23.9-76.4	1201	87.5-165	0.0297	0.0199-0.0437
T timopheevii	7	466	373-699	2590	2140-3030	2970	2250-3680	6.41	4.00-8.47	49.8	21.7-76.5	24.3	10.2-39.1	97.5	57.8-156	0.0296	0.0114-0.0542
T urartu	22	578	330-1360	2700	1840-4110	3640	1820-5870	7.33	2.41-14.9	35.4	21.7-132	36.6	10.4-112	118	58.2-235	0.0232	0.00763-0.0664
Thinopyrum elongatum	1	1076	1076-1080	1550	1550-1550	3320	3320-3320	9.37	9.37-9.37	78.6	78.6-78.6	94.7	94.7-94.7	101	101-101	0.00771	0.00771-0.00771
Thinopyrum intermedium	1	1690	1690-1690	1800	1800-1800	2770	2770-2770	10.59	10.6-10.6	88.5	88.5-88.5	86.3	86.3-86.3	61.3	61.3-61.3	0.0132	0.0132-0.0132
Thinopyrum ponticum	2	1260	1155-1370	1530	1410-1640	2690	2390-3000	6.51	5.06-7.96	64.8	55.7-73.8	64.4	63.7-65.1	48.6	48.2-49.0	0.0148	0.00806-0.0215
Thinopyrum turcicum	2	442	429-429	2000	1950-2040	3210	3020-3400	10.79	8.75-12.8	96.7	74.4-119	51.1	46.0-56.1	122	109-135	0.0153	0.0130-0.0177
Triticum turgidum	4	587	453-739	2390	2140-2620	3180	2770-3680	5.90	4.59-7.64	55.5	21.7-81.9	33.6	13.6-63.0	92.6	76.8-123	0.0247	0.0131-0.0416

6.4.3 Differences in grain Zn concentration and the grain ionome between 17 amphidiploids

Grain Zn concentration differed between 17 amphidiploids ($P<0.001$). The mean grain Zn concentration of 17 amphidiploids varied from 67.4 to 223.1 mg kg^{-1}, averaged across years (**Table 6.4**). The amphi 8 and amphi 13 lines had the greatest and smallest grain Zn concentration, respectively.

Among the macronutrients, the mean grain Ca concentration of 17 amphidiploids varied from 283.1 to 689.9 mg kg^{-1}, averaged across years. The amphi 7 and amphi 13 lines had the greatest and smallest grain Ca concentration, respectively. The mean grain Mg concentration of 17 amphidiploids varied from 1736 to 2666 mg kg^{-1}. The amphi 6 and amphi 13 lines had the greatest and smallest grain Mg concentration, respectively. The grain S concentration of 17 amphidiploids varied from 1963 to 3560 mg kg^{-1}. The amphi 12 and amphi 13 lines had the greatest and smallest grain S concentration, respectively.

Among the micronutrients, the mean grain Cu concentration of 17 amphidiploids varied from 7.3 to 20.3 mg kg^{-1}, averaged across years. The amphi 3 and amphi 20 lines had the greatest and smallest grain Cu concentration, respectively. The mean grain Fe concentration varied from 35.3 to 100 mg kg^{-1}. The amphi 12 and amphi 13 lines had the greatest and smallest grain Fe concentration, respectively. The mean grain Mn concentration of 17 amphidiploids varied from 77.9 to 139.5 mg kg^{-1}. The amphi 1 and amphi 16 lines had the greatest and smallest grain Mn concentration, respectively. Among the non-essential trace elements, the mean grain Se concentration of 17 amphidiploids varied from 0.001 to 0.06 mg kg^{-1}.

The amphi 6 and amphi 18 lines had the greatest and smallest grain Se concentration, respectively.

Most of the wheat parents (*T. aestivum* L.) had lower grain Zn concentration than the amphidiploids, except amphi 13. (**Table 6.4**).

Table 6.4 The grain Zn concentration and the grain ionome of the 17 amphidiploids and five wheat parents grown in glasshouse. The amphidiploids data are the mean of one to five replications per amphidiploids grown in 2014-15 and 2015-16 and wheat parent data are means of five replicates per genotypes in 2014-15.

Amphidiploids	n	Ca (mg kg^{-1})	Mg (mg kg^{-1})	S (mg kg^{-1})	Cu (mgkg^{-1})	Fe (mg kg^{-1})	Mn (mgkg^{-1})	Zn (mg kg^{-1})	Se (mg kg^{-1})
		Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD
Amphi 1	3	590±162	2430±203	3020±150	17.1±4.59	88.8±16.0	140±30.8	173.3±34.3	0.0287±0.0249
Amphi 2	3	535±49.0	2590±203	3130±192	18.1±4.54	68.6±30.7	115±9.79	172±26.3	0.0171±0.0280
Amphi 3	2	445±79.9	2110±49.2	3300±439	20.3±5.90	92.1±4.10	104±12.9	181±10.8	0.0394±0.0215
Amphi 5	5	473±260	2130±1120	2630±1400	13.7±5.47	69.9±30.1	122±65.9	179±98.6	0.0118±0.0152
Amphi 6	1	472	2670	3380	17.7	55.1	82.6	114.5	0.0589
Amphi 7	3	690±95.7	2320±49.8	2990±386	15.8±3.41	60.2±8.08	113±11.7	204±8.15	0.0149±0.0199
Amphi 8	5	668±142	2610±249	3540±476	12.9±9.24	65.8±17.95	120±28.9	223±40.4	0.0289±0.0353
Amphi 9	4	485±62.6	2430±192	3160±300	17.9±3.18	58.4±5.29	94.7±10.2	120±15.5	0.0308±0.00578
Amphi 11	5	373±154	2420±234	3320±423	17.5±4.46	62.8±15.8	103±14.6	162±32.4	0.0195±0.00977
Amphi 12	4	461±70.7	2180±40.7	3560±389	10.4±6.27	100±11.2	102±22.4	193±61.7	0.0169±0.0190
Amphi 13	9	283±37.2	1740±188	1960±243	8.88±4.75	35.3±8.73	84.4±7.5	67.4±6.05	0.0118±0.0137
Amphi 14	9	396±68.8	1940±157	2470±278	10.9±5.73	40.5±11.3	82.0±21.1	107±22.4	0.0144±0.0113
Amphi 15	9	428±152	2110±157	2420±133	11.4±5.81	54.1±13.5	117±16.3	118±14.7	0.0119±0.0134
Amphi 16	8	310±125	2050±126	2440±191	9.3±5.13	51.8±8.69	77.9±11.7	119±17.7	0.0134±0.0131
Amphi 17	8	487±93.1	2210±236	2840±201	10.4±6.06	50.6±5.66	128±46.7	117±14.6	0.00598±0.00779
Amphi 18	4	435±235.7	1970±155	2510±101	9.8±5.66	40.2±9.39	128±12.3	115±24.5	0.00119±0.000600
Amphi 20	8	595±66.8	2100±122	2590±146	7.3±3.32	49.9±7.06	124±33.8	112±12.3	0.00426±0.00156
CSE Mutant 84	5	379±29.4	1890±153.5	2370±301	7.2±3.05	42.4±8.36	78.4±9.3	81±12.7	0.00775±0.00495
CSEup 94	5	300±48.3	1950±156.6	2470±374	9.12±4.98	50.8±11.9	90.1±20.9	102±35.7	0.00598±0.00194
Highbury	5	391±37.3	2200±227.8	2760±217	7.24±3.15	36.8±5.48	51.7±8.6	70.4±5.26	0.0126±0.00399
Paragon	4	364±31.9	1840±378.1	2560±559	6.39±2.88	46.1±4.48	55.1±14.6	73.4±7.10	0.0110±0.00318
Pavon 76	5	386±16.5	2330±195.1	2810±352	12.4±1.88	39.5±5.31	68.4±2.84	92.8±12.4	0.0110±0.00204

Amphidiploids developed by using of wild wheat species for example, *Am. muticum*, *Ae. speltoides*, *Ae. umbellulata* and *Ae. comosa* had up to 2.5 fold greater grain Zn concentration than their wild and wheat parents (**Table 6.5**).

Table 6.5 Grain Zn concentrations in eleven amphidiploids and their wild and wheat parents.

Amphidiploids		Wild parent species			Wheat parents	
Amphi. no.	Mean grain Zn (mg kg^{-1})	Wild species	Accession number	Grain Zn (mg kg^{-1})	Wheat parents	Grain Zn (mg kg^{-1})
Amphi 1	173.3	*Am. muticum*	2130004	222.5	CS Eup94	101.9
Amphi 6	114.5	*Ae. speltoides*	2140008	94.1	CS Eup94	101.9
Amphi 7	204.1	*Ae. speltoides*	2140008	94.1	Pavon 76	92.8
Amphi 11	161.5	*Ae. umbellulata*	554410	89.7	CS Eup94	101.9
Amphi 12	192.8	*Ae. comosa*	276970	194	Paragon	73.4
Amphi 13	67.4	*Th. turcicum*	P208/201	108.6	CS Eup94	101.9
Amphi 14	106.6	*S. anatolicum*	P208/142	50.2	Highbury	70.4
Amphi 15	117.7	*S. anatolicum*	P208/142	50.2	CS Eup94	101.9
Amphi 16	118.7	*S. anatolicum*	P208/141	59.8	CS Eup94	101.9
Amphi 17	116.9	*S. anatolicum*	P208/142	50.2	CS Eup94	101.9
Amphi 18	114.5	*S. anatolicum*	P208/142	50.2	CS Eup94	101.9

6.4.4 Correlations between flag leaf ionome and the grain ionome

There was no relationship between flag leaf Zn concentration and grain Zn concentration of 17 amphidiploids (r=0.32; P=0.22) (**Figure 6.2**).

There were no relationships between mean flag leaf concentration of Ba, Cs, Cu, Fe, K, Mn, P, Rb, S, Se, Sr and mean grain concentration of Ba, Cs, Cu, Fe, K, Mn, P, Rb, S, Se, Sr of 17 amphidiploids. There were positive relationships between flag leaf As and grain As concentrations(r=0.51), flag leaf Ca and grain Ca concentration (r=052), flag leaf Cd and grain Cd concentration (r=0.49) and between flag leaf Mg and grain Mg (r=0.67) concentrations (**Figure 6.2**).

There was positive relationship between grain Fe and grain Zn concentration of 17 amphidiploids (r=0.75).

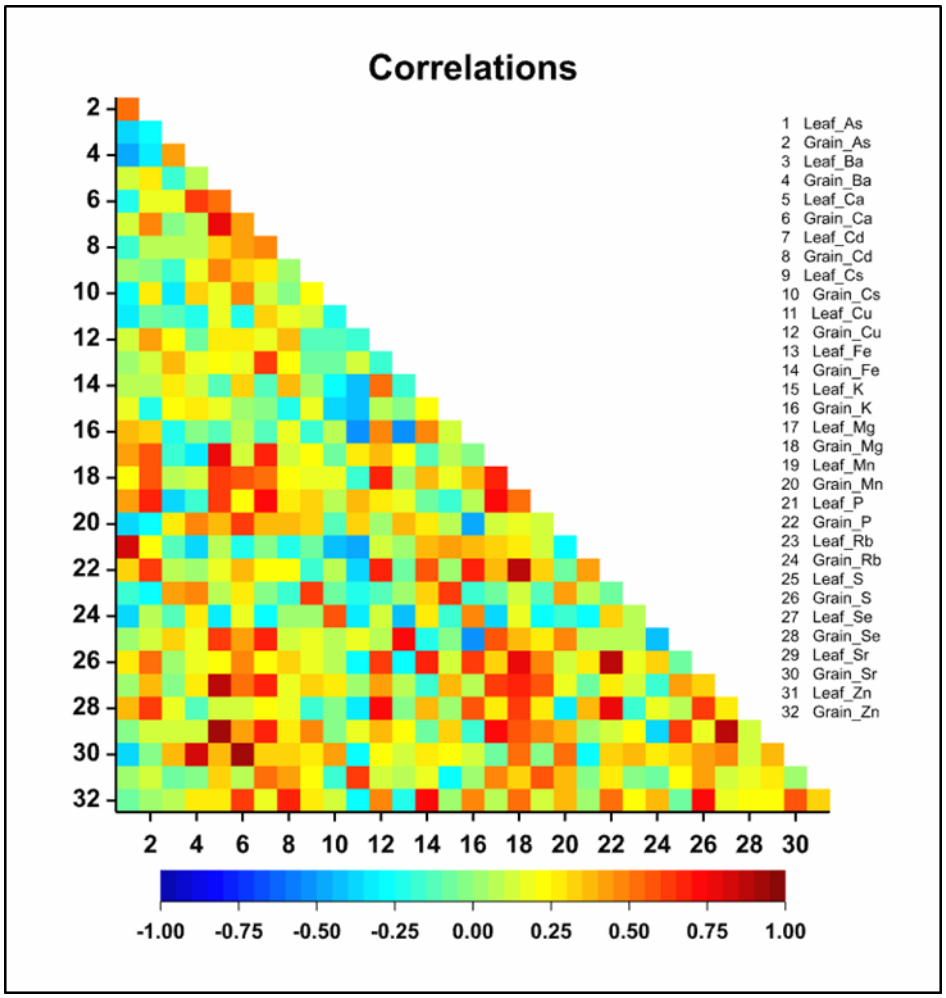


Figure 6.2 The correlation coefficients between the flag leaf ionome and grain ionome of 17 amphidiploids. The leaf mineral data represent the mean of five replicates per amphidiploid grown in glasshouse in 2014-15 and grain mineral data represent the mean of one to five replicates per amphidiploid grown in glasshouse in 2014-15 and 2015-16. Colours represent strength of correlation from strongly negative (dark blue) to strongly positive (dark red).

6.4.5 Differences in grain Zn concentration between 51 double haploid (DH) lines derived from *Amblyopyrum muticum*

Grain Zn concentration differed between DH lines significantly (P<0.001) (S6.2 Table). The grain Zn concentration of 51 double haploid lines varied from 50.6 to 148.2 mg kg^{-1} (**Figure 6.3**). The DHF 348 and DHF 253 lines had the greatest and smallest grain Zn concentration, respectively. Visual observations showed that grain size was relatively smaller than bread wheat grain. In addition, grain colour of double haploid lines was similar to wheat grain.

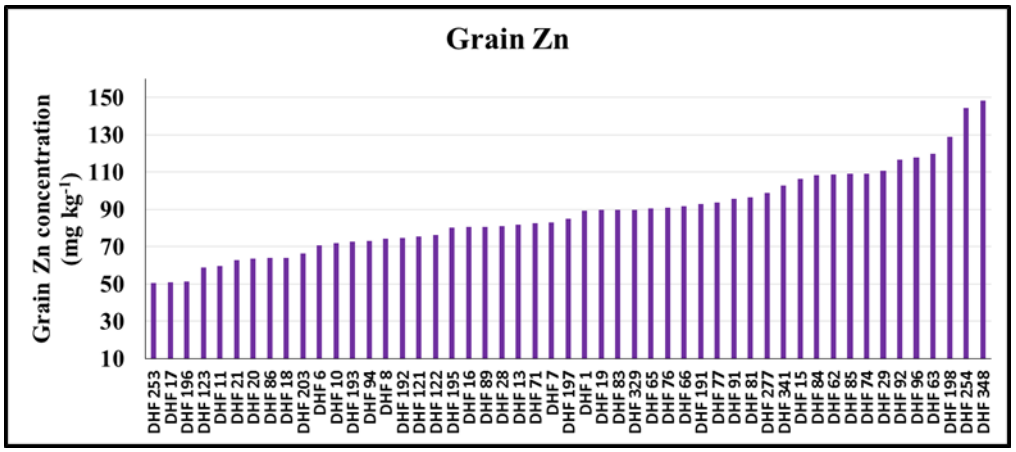


Figure 6.3 Grain Zn concentration of 51 double haploid lines derives from *Amblyopyrum muticum* wild species.

6.5 Discussion

Wheat is an important dietary source of Zn for the population in developing countries. Modern wheat varieties in India and at global scale have shown less variation in grain Zn concentration in field conditions and reported a difference of 10 to 20 mg kg^{-1} from the notional biofortification target of 40 mg kg^{-1} for

human diet (Khokhar *et al*., submitted; Chen *et al*., 2017). Wild relative of wheat have shown many fold greater grain Zn concentration than modern wheat genotypes (Cakmak, 2004; Rawat *et al*., 2008; Neelam *et al*., 2013). Therefore, present study explored 225 wild wheat accession representing 40 wild wheat species, 17 amphidiploids derived from different wild wheat species and 51 double haploid line derived from *Am. muticum* for grain Zn concentration.

This study showed grain Zn varied from 47.4 to 178.4 mg kg^{-1} in 225 accession of 40 wild wheat species. The mean grain Zn concentration were greater in species belonging to genus *Aegilops* followed by species in genus *Triticum*, *Thinopyrum*, *Secale*, *Agropyron* and *Elymus*. Mean grain Zn concentration in non-progenitor, for example, *Ae. biuncialis* (UM), *Ae. longissima* (S^l), *Ae. kotschyii* (SU), *Ae. markgrafii* (C), *Ae. peregrina* (SU), *Ae. umbellulata* (U), *Am. muticum* (TT), *S. segetale* (RR) and *Th. turcicum* (EEEEE) was greater (118-178 mg kg^{-1}) than wheat progenitors (65-93 mg kg^{-1}), *Ae. tauschii* (DD) and *T. turgidum* (AB). Our results are in agreement to some extent with Rawat *et al*., 2008 who reported grain Zn concentration from 19-67 mg kg^{-1} in field grown wild wheat species, for example, *Ae. longissima*, *Ae. kotschyii*, *Ae. geniculata*, *Ae. peregrina*, *Ae. cylindrica* and *Ae. ventricosa*. The wild wheat species in *Triticum* genus, for example, *T. monococcum*, *T. timopheevii* and *T. urartu* showed mean grain Zn concentration from 98-121 mg kg^{-1}. Cakmak *et al*., 2004, also reported greater grain Zn concentration from 14 to 190 mg kg^{-1} in grains of 825 accessions of *Triticum turgidum* (Syn. *Triticum dicoccoides*) collected from Fertile Crescent (e.g., Iran, Iraq, Lebanon, Syria, Israel and Jordan).

Amphidiploids derived from crossing of wheat parents with *Amblyopyrum muticum* (TT), *Ae. speltoides* (B), *Ae. umbellulata* (U), *Ae. comosa* (M) and *Secale anatolicum* (R) wild species showed up to 2.5 fold greater grain Zn concentration than both wheat and wild parents, except wild species, *Am. muticum*. It indicates transgressive segregation in grain Zn concentration and greater grain Zn accumulation in transgressive derivatives might be due to the additive gene action from both the parents (Neelam *et al*., 2013). Wang *et al*., 2011, also reported greater grain Zn concentration in derivatives of Chinese spring wheat and *Ae. umbellulata* than wheat parents. Rawat *et al*., 2008; Rawat *et al*., 2011; Neelam *et al*., 2011; Neelam *et al*., 2013 and Kumar *et al*., 2016, reported greater grain Zn concentration in derivatives of *Ae. kotschyii*, *Ae. geniculata*, *Ae. peregrina*, *Ae. cylindrica*, *Ae. ventricosa* and *Ae. longissima* than modern wheat cultivars. *Thinopyrum bessarabicum* derivatives had shown higher grain Zn concentration under field condition in India (Chapter 5). Flag leaf Zn concentration not correlated with grain Zn concentration of 17 amphidiploids. Contrastingly, Rawat *et al*., 2008, reported positive relationships between flag leaf Zn and grain Zn concentrations in derivatives of wild species.

Grain Zn concentration was consistently higher in wild species *Am. muticum* (TT), its derived amphidiploids and 51 double haploid lines, indicates that T genome may be potential source for transferring genes responsible for higher grain Zn in modern wheat genotypes. In general, transferring of genes from wild wheat species into wheat is difficult due to presence of Ph1 locus on long arm of 5B chromosome of wheat, which restrict the homoeologous recombination between interspecific crosses (Al-Kaff *et al*., 2008). However, *Am. muticum* has some genes which supress the action of Ph1 locus and permitting the

recombination between homoeologus chromosomes in crossing of *Am. muticum* and wheat (Dover and Riley, 1972). This trait makes it potential donor of high-Zn into modern wheat genotypes.

Visual observation showed that grain size of amphidiploids and 51 DH lines derived from *Am. muticum* was smaller than their wheat parents. It is evident that Zn mainly accumulate in aleurone layer, embryo and very less concentration in endosperm of wheat grain (Cakmak *et al*., 2010; Ajiboye *et al*., 2015). Wheat grain aleurone layer and embryo can accumulate more than ten times Zn than endosperm (Ozturk *et al*., 2006). Wheat grain milling remove bran and embryo and left over white flour (endosperm) which contain ~10 mg kg^{-1} Zn which are not sufficient for human diet (Cakmak *et al*., 2010). In addition, Zn bioavailability is affected by presence of phytic acid, a major storage form of phosphorous in cereals. Phytate form insoluble complexes with Zn and inhibit its absorption in monogastric animals, including human because they lack the digestive enzyme phtytase in their intestine (Gupta *et al*., 2015). The diets with phytic acid: zinc molar ratio greater than 15 is likely to be considered as insufficient in bioavailable Zn (Kumssa *et al*., 2015). Phytate is dominant in aleurone layer and embryo, very less concentration in endosperm (Gibson *et al*., 2010), indicates that either decrease the phytate level or increase the Zn concentration in endosperm can improve the intake bioavailability from diet. Further research is required to study the concentration of Zn in different grain fractions of *Am. muticum* derivatives. In addition, 51 DH lines have been screened and identified with introgressions from *Am. muticum* using SNPs (Single nucleotide polymorphisms) array. A SNP array is composed of large number of markers and, 25487 markers have shown polymorphism between *Am.*

muticum and paragon. However, it is still not known in which wheat chromosomes introgression from *Am. muticum* has occurred (King *et al*., 2017). Therefore, our future aim is development of homozygous line of each introgressed segment and identify the genes responsible for high grain Zn concentration and further transfer into modern wheat genotypes.

6.6 References

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6.7 Supplementary table

S6.1 Table List of 225 wild accession of 40 wild wheat species.

Sr. No.	Species	Accessions	New species name	Genome	Genus
1	*Ae bicornis*	2190001	*Ae bicornis*	S	*Aegilops*
2	*Ae bicornis*	2190002	*Ae bicornis*	S	*Aegilops*
3	*Ae bicornis*	2190003	*Ae bicornis*	S	*Aegilops*
4	*Ae bicornis*	Clae 47	*Ae bicornis*	S	*Aegilops*
5	*T bicornis*	P95-88.1-1	*Ae bicornis*	S	*Aegilops*
6	*Ae biuncialis*	2060002	*Ae biuncialis*	UM	*Aegilops*
7	*Ae biuncialis*	2060003	*Ae biuncialis*	UM	*Aegilops*
8	*Ae biuncialis*	550945	*Ae biuncialis*	UM	*Aegilops*
9	*Ae biuncialis*	550935	*Ae biuncialis*	UM	*Aegilops*
10	*Ae biuncialis*	550957	*Ae biuncialis*	UM	*Aegilops*

Sr. No.	Species	Accessions	New species name	Genome	Genus
11	*Ae caudata*	2090002	*Ae markgrafii*	C	*Aegilops*
12	*T caudata*	P95-87.1-1	*Ae markgrafii*	C	*Aegilops*
13	*Ae columnaris*	2050001	*Ae columnaris*	UM	*Aegilops*
14	*Ae columnaris*	2050002	*Ae columnaris*	UM	*Aegilops*
15	*Ae columnaris*	276968	*Ae columnaris*	UM	*Aegilops*
16	*Ae columnaris*	468281	*Ae columnaris*	UM	*Aegilops*
17	*Ae columnaris*	428558	*Ae columnaris*	UM	*Aegilops*
18	*Ae columnaris*	564179	*Ae columnaris*	UM	*Aegilops*
19	*T columnaris*	P95-93.1-1	*Ae columnaris*	UM	*Aegilops*
20	*Ae biuncialis*	550940	*Ae biuncialis*	UM	*Aegilops*
21	*Ae comosa*	2110002	*Ae comosa*	M	*Aegilops*
22	*Ae comosa*	2110005	*Ae comosa*	M	*Aegilops*
23	*Ae comosa*	2110007	*Ae comosa*	M	*Aegilops*
24	*Ae comosa*	2110008	*Ae comosa*	M	*Aegilops*
25	*Ae comosa*	Bulgaria 46	*Ae comosa*	M	*Aegilops*
26	*Ae comosa*	551038	*Ae comosa*	M	*Aegilops*
27	*Ae comosa*	551023	*Ae comosa*	M	*Aegilops*
28	*Ae crassa* (4x)	2240001	*Ae crassa*	DM	*Aegilops*
29	*Ae crassa* (4x)	2240002	*Ae crassa*	DM	*Aegilops*
30	*Ae crassa* (6x)	2250002	*Ae crassa*	DDM	*Aegilops*
31	*Ae crassa*	392330	*Ae crassa*	DM	*Aegilops*
32	*Ae crassa*	298892	*Ae crassa*	DM	*Aegilops*
33	*Ae crassa*	487286	*Ae crassa*	DM	*Aegilops*
34	*Ae crassa*	317400	*Ae crassa*	DM	*Aegilops*
35	*Ae cylindrica*	2100001	*Ae cylindrica*	DC	*Aegilops*
36	*Ae cylindrica*	2100006	*Ae cylindrica*	DC	*Aegilops*
37	*Ae cylindrica*	639301	*Ae cylindrica*	DC	*Aegilops*
38	*Ae cylindrica*	560515	*Ae cylindrica*	DC	*Aegilops*
39	*Ae cylindrica*	378188	*Ae cylindrica*	DC	*Aegilops*
40	*Ae cylindrica*	344778	*Ae cylindrica*	DC	*Aegilops*
41	*T cylindrica*	P95-90.1-1	*Ae cylindrica*	DC	*Aegilops*
42	*T dicocchoides*	Daryl	*Triticum turgidum*	BA	*Triticum*
43	*T dicocchoides*	P95-98.3-2	*Triticum turgidum*	BA	*Triticum*
44	*T dicocchoides*	P95-98.4-2	*Triticum turgidum*	BA	*Triticum*
45	*Ae geniculata*	287737	*Ae geniculata*	MU	*Aegilops*
46	*Ae geniculata*	369576	*Ae geniculata*	MU	*Aegilops*
47	*Ae geniculata*	341797	*Ae geniculata*	MU	*Aegilops*
48	*Ae juvenalis*	2280001	*Ae juvenalis*	DMU	*Aegilops*
49	*Ae juvenalis*	574463	*Ae juvenalis*	DMU	*Aegilops*
50	*Ae juvenalis*	266815	*Ae juvenalis*	DMU	*Aegilops*
51	*Ae juvenalis*	276993	*Ae juvenalis*	DMU	*Aegilops*
52	*Ae juvenalis*	289577	*Ae juvenalis*	DMU	*Aegilops*
53	*Ae kotschyii*	TKK03	*Ae kotschyii*	SU	*Aegilops*
54	*Ae kotschyii*	TKK39	*Ae kotschyii*	SU	*Aegilops*
55	*Ae kotschyii*	227435	*Ae kotschyii*	SU	*Aegilops*
56	*Ae kotschyii*	227290	*Ae kotschyii*	SU	*Aegilops*
57	*Ae kotschyii*	226617	*Ae kotschyii*	SU	*Aegilops*
58	*Ae kotschyii*	276997	*Ae kotschyii*	SU	*Aegilops*
59	*Ae longissima*	2150002	*Ae longissima*	S	*Aegilops*
60	*Ae longissima*	2150006	*Ae longissima*	S	*Aegilops*
61	*Ae longissima*	2150011	*Ae longissima*	S	*Aegilops*
62	*Ae longissima*	2150015	*Ae longissima*	S	*Aegilops*
63	*Ae longissima*	TL01	*Ae longissima*	S	*Aegilops*
64	*Ae longissima*	TL14	*Ae longissima*	S	*Aegilops*
65	*T monococcum*	TM01	*T monococcum*	A	*Triticum*
66	*T monococcum*	P95-91.1-1	*T monococcum*	A	*Triticum*
67	*T monococcum*	227340	*T monococcum*	A	*Triticum*
68	*T monococcum subsp aegilopoides*	219865	*T urartu*	A	*Triticum*

Sr. No.	Species	Accessions	New species name	Genome	Genus
69	*T monococcum subsp aegilopoides*	317395	*T urartu*	A	*Triticum*
70	*T monococcum subsp aegilopoides*	560557	*T urartu*	A	*Triticum*
71	*T monococcum subsp aegilopoides*	554401	*T urartu*	A	*Triticum*
72	*T monococcum subsp aegilopoides*	554410	*T urartu*	A	*Triticum*
73	*Ae neglecta*	2120001	*Ae neglecta*	UMX	*Aegilops*
74	*Ae neglecta*	2120002	*Ae neglecta*	UMX	*Aegilops*
75	*Ae neglecta*	298895	*Ae neglecta*	UMX	*Aegilops*
76	*Ae neglecta*	298890	*Ae neglecta*	UMX	*Aegilops*
77	*Ae neglecta*	491435	*Ae neglecta*	UMX	*Aegilops*
78	*Ae ovata*	2020001	*Ae geniculata*	MU	*Aegilops*
79	*Ae ovata*	2020003	*Ae geniculata*	MU	*Aegilops*
80	*Ae ovata*	2020006	*Ae geniculata*	MU	*Aegilops*
81	*Ae ovata*	2020009	*Ae geniculata*	MU	*Aegilops*
82	*Ae ovata*	2020013	*Ae geniculata*	MU	*Aegilops*
83	*T ovata*	P95-95.1-1	*Ae geniculata*	MU	*Aegilops*
84	*Ae peregrina*	604152	*Ae peregrina*	SU	*Aegilops*
85	*Ae peregrina*	487202	*Ae peregrina*	SU	*Aegilops*
86	*Ae peregrina*	487277	*Ae peregrina*	SU	*Aegilops*
87	*Ae peregrina*	604183	*Ae peregrina*	SU	*Aegilops*
88	*Ae peregrina*	604173	*Ae peregrina*	SU	*Aegilops*
89	*Ae geniculata*	170191	*Ae peregrina*	SU	*Aegilops*
90	*Ae geniculata*	Clae 63	*Ae peregrina*	SU	*Aegilops*
91	*Ae peregrina var brachyathera*	603247	*Ae peregrina*	SU	*Aegilops*
92	*Ae peregrina var brachyathera*	542236	*Ae peregrina*	SU	*Aegilops*
93	*T tauschii*	P99-131.1-1	*Ae tauschii*	D	*Aegilops*
94	*T tauschii*	P95-81.1-1	*Ae tauschii*	D	*Aegilops*
95	*T timopheevii*	P95-99.1-1	*T timopheevii*	GA	*Triticum*
96	*T timopheevii subsp armeniacum*	538429	*T timopheevii*	GA	*Triticum*
97	*T timopheevii subsp armeniacum*	427998	*T timopheevii*	GA	*Triticum*
98	*T timopheevii subsp armeniacum*	355452	*T timopheevii*	GA	*Triticum*
99	*T timopheevii subsp armeniacum*	427414	*T timopheevii*	GA	*Triticum*
100	*T timopheevii subsp armeniacum*	538512	*T timopheevii*	GA	*Triticum*
101	*T timopheevii subsp timopheevii*	289752	*T timopheevii*	GA	*Triticum*
102	*Ae triaristata (4x)*	2030001	*Ae neglecta*	UM	*Aegilops*
103	*Ae triaristata (4x)*	2030003	*Ae neglecta*	UM	*Aegilops*
104	*Ae triaristata (4x)*	2030004	*Ae neglecta*	UM	*Aegilops*
105	*Ae triaristata (4x)*	2030006	*Ae neglecta*	UM	*Aegilops*
106	*Ae triaristata (6x)*	2040002	*Ae neglecta*	UMX	*Aegilops*
107	*Ae triaristata (6x)*	2040003	*Ae neglecta*	UMX	*Aegilops*
108	*Ae triuncialis*	2080001	*Ae triuncialis*	UC	*Aegilops*
109	*Ae triuncialis*	2080006	*Ae triuncialis*	UC	*Aegilops*
110	*Ae triuncialis*	2080013	*Ae triuncialis*	UC	*Aegilops*
111	*Ae triuncialis*	227292	*Ae triuncialis*	UC	*Aegilops*
112	*Ae triuncialis*	487201	*Ae triuncialis*	UC	*Aegilops*
113	*Ae triuncialis*	486284	*Ae triuncialis*	UC	*Aegilops*
114	*Ae triuncialis*	486278	*Ae triuncialis*	UC	*Aegilops*
115	*Ae triuncialis*	486251	*Ae triuncialis*	UC	*Aegilops*
116	*Ae triuncialis*	428559	*Ae triuncialis*	UC	*Aegilops*
117	*T triuncialis*	P95-91.1-1	*Ae triuncialis*	UC	*Aegilops*
118	*Ae triuncialis var persica*	227340	*Ae triuncialis*	UC	*Aegilops*
119	*Ae triuncialis var persica*	219865	*Ae triuncialis*	UC	*Aegilops*
120	*Ae triuncialis var persica*	317395	*Ae triuncialis*	UC	*Aegilops*
121	*Ae umbellulata*	560557	*Ae umbellulata*	U	*Aegilops*
122	*Ae umbellulata*	554401	*Ae umbellulata*	U	*Aegilops*
123	*Ae umbellulata*	554410	*Ae umbellulata*	U	*Aegilops*
124	*Ae uniaristata*	2120001	*Ae uniaristata*	N	*Aegilops*
125	*Ae uniaristata*	2120002	*Ae uniaristata*	N	*Aegilops*
126	*Ae uniaristata*	554420	*Ae uniaristata*	N	*Aegilops*

Sr. No.	Species	Accessions	New species name	Genome	Genus
127	*Ae uniaristata*	276996	*Ae uniaristata*	N	*Aegilops*
128	*Ae uniaristata*	554418	*Ae uniaristata*	N	*Aegilops*
129	*T uniaristata*	P95-86.1-2	*Ae uniaristata*	N	*Aegilops*
130	*Ae columnaris*	554186	*Ae columnaris*	UM	*Aegilops*
131	*T macrochaetum*	P95-94.1-3	*Ae biuncialis*	UM	*Aegilops*
132	*Ae biuncialis*	2060001	*Ae biuncialis*	UM	*Aegilops*
133	*T urartu A*	1010001	*T urartu*	A	*Triticum*
134	*T urartu B*	1010002	*T urartu*	A	*Triticum*
135	*T urartu G*	1010006	*T urartu*	A	*Triticum*
136	*T urartu K*	1010009	*T urartu*	A	*Triticum*
137	*T urartu W*	1010020	*T urartu*	A	*Triticum*
138	*T urartu*	TM14	*T urartu*	A	*Triticum*
139	*T urartu*	TM17	*T urartu*	A	*Triticum*
140	*T urartu*	428234	*T urartu*	A	*Triticum*
141	*T urartu*	428336	*T urartu*	A	*Triticum*
142	*T urartu*	428335	*T urartu*	A	*Triticum*
143	*T urartu*	428333	*T urartu*	A	*Triticum*
144	*T urartu*	428191	*T urartu*	A	*Triticum*
145	*T urartu*	427328	*T urartu*	A	*Triticum*
146	*T urartu*	428255	*T urartu*	A	*Triticum*
147	*T urartu*	428244	*T urartu*	A	*Triticum*
148	*T urartu*	428239	*T urartu*	A	*Triticum*
149	*T urartu*	428235	*T urartu*	A	*Triticum*
150	*Ae variablis*	2070001	*Ae peregrina*	SU	*Aegilops*
151	*Ae variablis*	2070002	*Ae peregrina*	SU	*Aegilops*
152	*Ae variablis*	2070007	*Ae peregrina*	SU	*Aegilops*
153	*T variablis*	P95-96.1-1	*Ae peregrina*	SU	*Aegilops*
154	*T variablis*	P95-96.2-1	*Ae peregrina*	SU	*Aegilops*
155	*Ae vavilovii*	2260001	*Ae vavilovii*	DMS	*Aegilops*
156	*Ae vavilovii*	2260002	*Ae vavilovii*	DMS	*Aegilops*
157	*Ae vavilovii*	TZ01	*Ae vavilovii*	DMS	*Aegilops*
158	*Ae vavilovii*	TZ02	*Ae vavilovii*	DMS	*Aegilops*
159	*Ae vavilovii*	TZ07	*Ae vavilovii*	DMS	*Aegilops*
160	*Ae ventricosa*	2270001	*Ae ventricosa*	DN	*Aegilops*
161	*Ae ventricosa*	2270004	*Ae ventricosa*	DN	*Aegilops*
162	*Ae ventricosa*	388753	*Ae ventricosa*	DN	*Aegilops*
163	*Ae ventricosa*	Clae 40	*Ae ventricosa*	DN	*Aegilops*
164	*Ae ventricosa*	Clae 58	*Ae ventricosa*	DN	*Aegilops*
165	*Ae ventricosa*	330493	*Ae ventricosa*	DN	*Aegilops*
166	*T ventricosa*	P95-89.1-1	*Ae ventricosa*	DN	*Aegilops*
167	*S vavilovi*	P208/370	*S vavilovi*	RR	*Secale*
168	*S vavilovi*	P208/144	*S vavilovi*	RR	*Secale*
169	*S vavilovi*	P208/145	*S vavilovi*	RR	*Secale*
170	*T turgidum subsp carthlicuni*	94748	*Triticum turgidum*	BA	*Triticum*
171	*Ae comosa var ventricosa*	551044	*Ae comosa*	M	*Aegilops*
172	*Ae comosa var ventricosa*	551060	*Ae comosa*	M	*Aegilops*
173	*Ae comosa var comosa*	276970	*Ae comosa*	M	*Aegilops*
174	*Ae kotschyii*	TKK19	*Ae kotschyii*	SU	*Aegilops*
175	*Ae markgrafii*	551121	*Ae markgrafii*	C	*Aegilops*
176	*Ae markgrafii*	551124	*Ae markgrafii*	C	*Aegilops*
177	*Ae markgrafii*	551144	*Ae markgrafii*	C	*Aegilops*
178	*Ae markgrafii*	554194	*Ae markgrafii*	C	*Aegilops*
179	*Ae markgrafii*	542204	*Ae markgrafii*	C	*Aegilops*
180	*Ae longissima*	TL07	*Ae longissima*	S	*Aegilops*
181	*Ae longissima*	TL22	*Ae longissima*	S	*Aegilops*
182	*Ae searsii*	599149	*Ae searsii*	S	*Aegilops*
183	*Ae searsii*	566127	*Ae searsii*	S	*Aegilops*
184	*Ae mutica*	2130004	*Amblyopyrum muticum*	T	*Aegilops*

Sr. No.	Species	Accessions	New species name	Genome	Genus
185	*Ae mutica*	2130001	*Amblyopyrum muticum*	T	*Aegilops*
186	*Ae searsii*	599146	*Ae searsii*	S	*Aegilops*
187	*Ae searsii*	599134	*Ae searsii*	S	*Aegilops*
188	*Ae searsii*	599145	*Ae searsii*	S	*Aegilops*
189	*Ae searsii*	599140	*Ae searsii*	S	*Aegilops*
190	*T searsii*	P95-85 1.1	*Ae searsii*	S	*Aegilops*
191	*T searsii*	TL33	*Ae searsii*	S	*Aegilops*
192	*Ae sharonensis*	2170005	*Ae sharonensis*	S	*Aegilops*
193	*Ae sharonensis*	2170004	*Ae sharonensis*	S	*Aegilops*
194	*Ae sharonensis*	2170007	*Ae sharonensis*	S	*Aegilops*
195	*Ae sharonensis*	584392	*Ae sharonensis*	S	*Aegilops*
196	*Ae sharonensis*	584379	*Ae sharonensis*	S	*Aegilops*
197	*Ae sharonensis*	584409	*Ae sharonensis*	S	*Aegilops*
198	*Ae sharonensis*	584411	*Ae sharonensis*	S	*Aegilops*
199	*Ae sharonensis*	584414	*Ae sharonensis*	S	*Aegilops*
200	*Ae speltoides*	2140008	*Ae speltoides*	B	*Aegilops*
201	*Ae speltoides*	2140018	*Ae speltoides*	B	*Aegilops*
202	*Ae speltoides*	2140020	*Ae speltoides*	B	*Aegilops*
203	*Ae speltoides*	2140007	*Ae speltoides*	B	*Aegilops*
204	*Ae speltoides*	369626	*Ae speltoides*	B	*Aegilops*
205	*Ae speltoides*	487238	*Ae speltoides*	B	*Aegilops*
206	*Ae speltoides var ligustica*	542241	*Ae speltoides*	B	*Aegilops*
207	*Agropyron fragile*	440094	*Agropyron fragile*	P	*Agropyron*
208	*Elymus breviaristatus*	499411	*Elymus breviaristatus*	StYH	*Elymus*
209	*Elymus caninus*	439908	*Elymus caninus*	StH	*Elymus*
210	*S cereale subsp segetale*	326284	*S cereale*	RR	*Secale*
211	*S cereale*	578092	*S cereale*	RR	*Secale*
212	*S anatolicum*	P208/142	*S anatolicum*	RR	*Secale*
213	*S anatolicum*	P208/141	*S anatolicum*	RR	*Secale*
214	*S iranicum*	P208/151	*S iranicum*	RR	*Secale*
215	*S iranicum*	P208/152	*S iranicum*	RR	*Secale*
216	*S iranicum*	P208/11	*S iranicum*	RR	*Secale*
217	*A segetale*	P208/143	*S segetale*	RR	*Secale*
218	*S strictum*	205222	*S strictum*	RR	*Secale*
219	*S vavilovi*	573649	*S vavilovi*	RR	*Secale*
220	*Thinopyrum elongatum*	401107	*Thinopyrum elongatum*	ES	*Thinopyrum*
221	*Thinopyrum intermedium*	401141	*Thinopyrum intermedium*	EStV/St	*Thinopyrum*
222	*Thinopyrum ponticum*	547312	*Thinopyrum ponticum*	EJ	*Thinopyrum*
223	*Thinopyrum ponticum*	636523	*Thinopyrum ponticum*	EJ	*Thinopyrum*
224	*Thinopyrum turcicum*-5	P208/202	*Thinopyrum turcicum*	EEEEE	*Thinopyrum*
225	*Thinopyrum turcicum*-13	P208/201	*Thinopyrum turcicum*	EEEEE	*Thinopyrum*

S6.2 Table Grain zinc (Zn) concentration (mg kg^{-1}) of 51 double haploid lines derived from *Amblyopyrum muticum*.

Rank	DHF Lines	Grain Zn ($mgkg^{-1}$)	Rank	DHF Lines	Grain Zn ($mgkg^{-1}$)
1	DHF 348	148.2	27	DHF 7	83.0
2	DHF 254	144.4	28	DHF 71	82.7
3	DHF 198	128.8	29	DHF 13	82.0
4	DHF 63	119.8	30	DHF 28	80.9
5	DHF 96	117.8	31	DHF 89	80.7
6	DHF 92	116.6	32	DHF 16	80.6
7	DHF 29	110.6	33	DHF 195	80.1
8	DHF 74	109.1	34	DHF 122	76.3
9	DHF 85	109.0	35	DHF 121	75.4
10	DHF 62	108.7	36	DHF 192	74.9
11	DHF 84	108.2	37	DHF 8	74.2
12	DHF 15	106.3	38	DHF 94	73.2
13	DHF 341	102.8	39	DHF 193	72.7
14	DHF 277	98.9	40	DHF 10	72.0
15	DHF 81	96.5	41	DHF 6	70.9
16	DHF 91	95.6	42	DHF 203	66.5
17	DHF 77	93.7	43	DHF 18	64.1
18	DHF 191	93.0	44	DHF 86	64.0
19	DHF 66	91.8	45	DHF 20	63.5
20	DHF 76	90.9	46	DHF 21	62.8
21	DHF 65	90.7	47	DHF 11	59.6
22	DHF 329	89.9	48	DHF 123	58.9
23	DHF 83	89.7	49	DHF 196	51.5
24	DHF 19	89.7	50	DHF 17	50.8
25	DHF 1	89.4	51	DHF 253	50.6
26	DHF 197	85.1			

CHAPTER 7. GENERAL DISCUSSION

7.1 Wheat improvement for hostile soil environments

Intensive crop breeding has increased wheat yield and production in India. Wheat improvement in India typically involves selecting yield and component traits under non-hostile soil conditions at regional scales. Hostile soil conditions, for example, saline/alkaline and acidic soils, constraints wheat production. Therefore, we studied the contribution of genotype (G), environment/site (E) and G*E interaction on grain yield and component traits of a diverse panel of 36 Indian wheat genotypes, to identify traits which could help in crop improvement under hostile soils, based upon site specific trait selection. Detailed discussion of the effect of G, E and G*E interaction on grain yield and component traits under a wide range of soil environment (pH 4.5 to 9.5) conditions are described in Chapter 2. Briefly, the mean grain yield varied from 1.0 to 5.5 t ha^{-1} at hostile and non-hostile soils, respectively. Given the diverse selection of hostile and non-hostile soils from within three agro-climatic regions, it is unsurprising that site accounted most of the variation in all the traits. Grain yield reduction was greater under sodic soils (Kumarganj-sodic site, 52%) followed by saline soils (Hisar, 33%) and smallest in acidic soils (Pundibari, 4%) compare to their respective normal soil sites. Reduction in grain yield under saline/sodic soils is consistent with many studies, including those of Wright and Rajper, 2000; Munns and Tester, 2008; Ashraf *et al*., 2008; James *et al.*, 2008; Zhang *et al.*, 2016, who reported yield reduction in wheat genotypes under sodic soils due to fewer grains per plant and reduced grain weight. In the present study reduction in wheat grain yield under acidic soils was lesser than reduction under salt affected soils (Khokhar *et al*., 2017). Acidic soils increase the aluminium

concentration in the soil which reduces the root length, and consequently water and nutrient uptake which can reduce grain yield. The grain weight and number of productive tillers also reduced under acidic soils which are the important yield components (Tank *et al*., 2002; Tang *et al*., 2003).

Hostile soils can be reclaimed by using chemical and mechanical soil management practices, however these practices increase input costs and in India where farmers have small land holdings is likely to require subsidies. There is therefore a need to develop varieties tolerant to hostile soils. A panel of 36 genotypes with diverse genetic diversity showed significant differences in yield and yield components under a wide range of soil environments. However, genotypes did not perform identically on hostile and non-hostile soils, indicating the scope for site-specific trait selection. The genotype by site interaction (G*E) was associated with more of the variation in 1000 weight (TGW), grain weight per spike (GWS), harvest index (HI) and grain yield (GYD) than plant height at maturity (PHT), days to anthesis (DTA) and days to maturity (DTM). Under saline and sodic soils GYD correlated positively with TGW, GWS, biological yield (BYD), grain number per spike (GNS) and productive tillers per meter (PTM), therefore routine selection based on these traits could improve the grain yield under saline and sodic soils (Khokhar *et al*., 2017; Chapter 2). In addition, early flowering and maturity might favour the increase in grain yield under saline/sodic soils or a way to escape salt stresses (McDonald *et al*., 2013). However, selection for PTM, TGW and BYD traits could help to increase the grain yield under acidic soils.

Some genotypes performed better for grain yield and component traits under acidic and salt affected soils. For example, genotypes KRL 210, HD 2967 performed well on acidic soils by maintaining greater TGW and BYD and could be used in breeding programmes for the development of acidic tolerant varieties. Similarly, genotypes Kharchia 65, KRL 210 and KRL 3-4 showed higher grain yield under saline soils by maintaining greater TGW, GWS and BYD under salt affected soils and can be a potential source for these traits in the development of salt tolerant varieties. Genotypes, KRL 3-4 and KRL 210 have Kharchia 65 background, which has been selected from salt affected areas of Rajasthan, India (Munns *et al*., 2006; Setter *et al*., 2016). Beneficial salt tolerance mechanism which might have been transferred into these genotypes from Kharchia 65 include high K^+ and K^+:Na^+ concentrations and water content (Sairam *et al*., 2002).

Some variation for salt tolerance in modern Indian wheat genotypes have been reported in Chapter 2, however, greater salt tolerance have been shown in a salt tolerant wild wheatgrass, *Thinopyrum bessarabicum,* and their derivatives in solution culture (Gorham *et al*., 1985; King *et al*., 1997a). A panel of 36 diverse Indian wheat genotypes showed a reduction in grain yield up to 59% under saline soil (Hisar) than in normal soil (Karnal) (Khokhar *et al*., 2017). Contrastingly, eight amphidiploids derived from *Th. bessarabicum*, showed a reduction in grain yield up to 26% under saline soil (Hisar) than in normal soil (Karnal) (Chapter 5). Four of the amphidiploids showed up to 28% greater grain yield under saline soil than in normal soil which makes them potential candidates to include in breeding programmes in the development of salt tolerant wheat varieties. Some amphidiploids for example, EC 787014 had greater grain yield in comparison to

other amphidiploids through maintaining the higher GWS, TGW under saline soils (Chapter 5). Our results are consistent with Qi *et al*., 2010, who reported that translocation line T2JS-2BS.2BL derived from crossing between *Th. bessarabicum* and Chinese spring wheat, showed greater grain yield per plant than wheat parent under normal soil field conditions in China. Since the same *Th. bessarabicum* accession was used to develop all the amphidiploids, it would indicate that the better performance of EC 787014 (*Th. bessarabicum* x Chinese spring) might be result of genetic variation within wheat parents or different gene recombinations (King *et al*., 1997b). Thus, it may be possible to develop greater salt tolerant amphidiploids by selecting specific wheat genotypes which combine more efficiently with *Th. bessarabicum* for salt tolerance. This could be assessed by crossing different high yielding genotypes with *Th. bessarabicum* and their testing under saline field conditions. Furthermore, the better performance of these amphidiploids for GYD and component traits under saline soil possibly due to introgressed segment from *Th. bessarabicum* into amphidiploids which further confers salt tolerance by limiting the leaf Na^+ and Cl^- concentration, maintain high K^+, K^+/Na^+ concentrations and synthesize glycinebetaine for osmotic adjustment and protecting the plant from toxic effect of excessive salt in the soil (Colmer *et al*., 2006).

All of the amphidiploids in present study had brittle spikes at maturity which is consistent with King *et al*., 1997b and Hassani *et al*., 2000, who screened these amphidiploids in glass house and normal soil conditions, respectively. King *et al*., 1997b, reported that brittle spikes amphidiploids might be due to presence of genes present on *Th. bessarabicum* chromosomes because brittle spikes is not shown by wheat parents. Similarly, Miller *et al*., 1997, reported that an addition

line which replaces the 3A, 3B or 3D chromosomes from wheat with 3N chromosomes of *Aegilops uniaristata* showed brittle rachis. However, this problem could be overcome by mutation or deletion using ionizing radiation (King *et al*., 1997b).

Overall, it appears that *Th. bessarabicum* derived amphidiploids presents considerable potential for the development of salt tolerant wheat genotypes and further backcrossing and selection for wheat components can give salt tolerant wheat genotypes. In addition amphidiploids used in present study showed greater variation in grain Zn concentration than grain Zn concentration in a panel of 36 widely adapted Indian wheat genotypes.

7.2 Quantification of grain Zn concentration and the grain ionome of Indian wheat under a wide range of soil conditions in India

Wheat is an important dietary source of Zn for the Indian population and there is scope to increase grain Zn concentration in wheat through breeding to help to alleviate dietary Zn deficiency. The 'HarvestPlus' programme is developing and deploying new wheat varieties with higher grain Zn concentrations in South Asia (Singh and Velu, 2017). The HarvestPlus target is to enhance the grain Zn concentration in locally-adapted wheat varieties by 8-12 mg kg^{-1}, from a baseline of ~25 mg kg^{-1}, without compromising grain yield or other grain quality attributes (Velu *et al*., 2012; Velu *et al*., 2014). In present study, a panel of 36 genotypes showed grain Zn concentration from 26-32 mg kg^{-1}. Similarly, grain Zn concentration from 20-31 mg kg^{-1} in field grown wheats were reported at global scale, showed a difference of 10 to 20 mg kg^{-1} from the biofortification

notional target of 40 mg kg^{-1} for human diet (Chen *et al*., 2017). Genotype accounted for a relatively small proportion of the total variation in grain Zn concentration, indicating this is a very complex traits that is affected by many sources of variations. However, some genotypes, for example, Kharchia 65 and BH 1146 genotypes showed consistent ranking across sites and years for grain Zn concentration. Genotype, Kharchia 65 is a salt tolerant genotype (Munns *et al*., 2006) and BH 1146 is an aluminium tolerant genotype (De Sousa *et al*., 1998) and might be potential new sources for development of Zn-biofortified wheat varieties, including under saline/sodic and acidic soils.

Given that some of the genotypes used in present study already have implicitly good grain yield and other quality attributes for India, such lines could also be useful for crossing with high-Zn lines derived from the HarvestPlus, to support site-specific approaches as adopted previously for yield and yield component traits (Khokhar *et al*., 2017). There was no evidence of a yield dilution effect on grain Zn concentration in this study which are in line with Welch and Graham, 2004 and Joshi *et al*., 2010, who reported no trade- off between grain Zn and grain yield concentration in wheat. But, it will be important to continue to monitor grain Zn concentration in the wider context of yield and yield component traits in breeding programmes, especially given that grain yields in the region are relatively low.

Most of the soils in present study were probably Zn deficient, based on the use of a $Ca(NO_3)_2$ soil extraction to assess Zn-availability. Variation in plant-available Zn in soils is likely to represent a large proportion of environmental sources of variation in grain Zn concentration (Cakmak, 2008; White and

Greenwood, 2013; Rengel, 2015). Application of Zn fertilizers in granular or foliar application have shown increase in wheat grain Zn concentration and grain yield, provided optimum nitrogen supply (Joy *et al*., 2015; Joy *et al*., 2017; Wang *et al*., 2016). Approaches to increase the grain Zn by genetic biofortification can clearly be complemented with the use of Zn fertilizers. In addition, greater grain Zn variation in modern wheat genotypes can be created through use of wild wheat relatives and their derivatives which have shown a big reservoir for grain Zn concentration.

7.3 Approaches to alleviate the grain Zn concentration of modern wheat through the use of wild wheat species and their derivatives

Modern wheat varieties have shown less variation in grain Zn concentration under field condition in India and at global scale (Khokhar *et al*., submitted; Chen *et al*., 2017). Wild wheat relatives are a potential new reservoir for grain Zn concentration (Rodriguez *et al*., 2011; Guzman *et al*., 2014; Manickavelu *et al*., 2017) and are being used for the development of high-Zn wheat varieties. The 'HarvestPlus' programme has developed and deployed high-Zn wheat varieties in South Asia. They used synthetic wheat lines which were developed by using the wild wheat relatives, e.g., *Aegilops tauschii* - D genome donor of wheat, *Triticum spelta* and wild *T. dicoccon* and released Zink Shakti, WB 02, HPBW-01 in India and Zincol-2016 in Pakistan with 7 to 14 mg kg^{-1} greater grain Zn than the notional baseline of 25 mg kg^{-1} (Singh and Velu, 2017). However, they have not explored other progenitors and non-progenitors species of wheat for development of high-Zn wheat. Therefore, there is scope to explore

the wild wheat species and their derivatives for greater variation in grain Zn concentration.

The eight amphidiploids derived from *Th. bessarabicum* showed grain Zn concentration from 36-43 mg kg^{-1} under field conditions in India (Chapter 5). Ardalani *et al*., 2016, also reported greater grain Zn concentration in *Th. bessarabicum* derived amphidiploids than wheat parent under field condition in Kurdistan. Most of the amphidiploids in present study showed greater grain Zn concentration in saline soil (Hisar) than in normal soil (Karnal). Khokhar *et al*., submitted, reported that Kharchia 65, a salt tolerant genotypes, had greater grain Zn concentration under saline soil. Therefore there is potential that amphidiploids derived from *Th. Bessarabicum*, for example, EC 7870007, EC 787013 and EC 787014 might be a new source for greater variation in grain Zn concentration and can be used in wheat Zn-biofortification breeding programmes for development of high-Zn wheat varieties even under saline soils.

Grain Zn concentration and the grain ionome of these 40 wild species and their derivatives, grown under glasshouse condition, were described in Chapter 6. However many fold greater grain Zn concentration have been reported in grain of 225 wild accessions representing 40 wild wheat species belongs to six different genus of tribe, *Triticeae* namely, *Agropyron, Aegilops, Elymus, Secale, Triticum* and *Thinopyrum* and their derivatives than the Indian wheat genotypes and eight amphidiploids derived from *Th. bessarabicum*.

Mean grain Zn concentration of 225 wild accessions representing 40 wild species varied from 47.1 to 178.4 mg kg^{-1}. The mean grain Zn concentration were greater in species belonging to genus *Aegilops* followed by species in

genus *Triticum*, *Thinopyrum*, *Secale*, *Agropyron* and *Elymus*. Mean grain Zn concentration was greater in wheat non-progenitor than progenitor's wild wheat species. Our results are in agreement with Rawat *et al*., 2008, who reported greater grain Zn concentration in *Ae. longissima*, *Ae. kotschyii*, *Ae. geniculata*, *Ae. peregrina*, *Ae. cylindrica* and *Ae. ventricosa* wild wheat species than *Triticum* wild species and modern wheats under field conditions. Amphidiploids derived from crossing of wheat parents with *Amblyopyrum muticum* (TT), *Aegilops speltoides* (B), *Ae. umbellulata* (U), *Ae. comosa* (M) and *Secale anatolicum* (R) wild species showed up to 2.5 fold greater grain Zn concentration than both wheat and wild parents, except wild species, *Am. muticum*. It indicates transgressive segregation in grain Zn concentration and greater grain Zn accumulation in transgressive derivatives might be due to the additive gene action from both the parents (Neelam *et al*., 2013). Therefore, *Amblyopyrum muticum*, *Ae. speltoides*, *Ae. umbellulata* and *Ae. comosa* and their derivatives might be potential new sources for the development of high-Zn wheat varieties. Grain Zn concentration was consistently higher in wild species *Am. muticum* (TT), its derived amphidiploids and 51 double haploid lines, indicates that the T genome may be potential source for transferring genes responsible for higher grain Zn in modern wheat genotypes. Visual observation showed that grain size of amphidiploids and 51 DH lines derived from *Am. muticum* was smaller than their wheat parents. It is evident that Zn mainly accumulate in aleurone layer, embryo and less concentration in endosperm of wheat grain. Wheat grain aleurone layer and embryo can accumulate more than ten times Zn than endosperm (Ozturk *et al*., 2006). In aleurone cells Zn chelate with phytic acid (inositol hexakisphophate-6) which inhibit its absorption in

human intestine (Gibbson *et al*., 2010; Gupta *et al*., 2015). Wheat grain milling removes bran and embryo and left over white flour (endosperm) which contain ~10 mg kg^{-1} Zn which is not sufficient for human diet (Cakmak *et al*., 2010a), therefore there is need to increase Zn concentration in endosperm to improve the bioavailable intake in diet. Cakmak *et al*., 2010b, reported that application of Zn fertiliser at grain filling stage can increase the endosperm Zn concentration and also showed that Zn mobilise into endosperm through crease phloem during grain filling period. Persson *et al*., 2016, reported that application of both Zn and nitrogen (N) fertilisers increases the endosperm Zn concentration in wheat grain, however role of association between Zn and N in terms of storage in endosperm is still unknown. Wang *et al*., 2011, reported that Zn accumulate in crease vascular tissues of grain and suggested two barriers of Zn transfer into endosperm, one is translocation from transfer cells to endosperm cavity and second is translocation from maternal to filial tissues, unlocking mechanism behind these barriers would be of great importance to increase the endosperm Zn concentration in wheat. Further research is required to study the concentration of Zn in different grain fractions of *Am. muticum* derivatives and to develop the homozygous line of each introgressed segment and identify the genes responsible for high grain Zn concentration and further transfer into modern wheat genotypes.

7.4 Juvenile root phenotyping as a strategy to screen germplasm for yield, yield components, grain Zn concentration and the grain ionome

The panel of 36 diverse Indian wheat genotypes and eight amphidiploids derived from *Th. bessarabicum*, showed differences in grain yield, yield components and grain mineral composition traits under a wide range of soil field conditions in India. These differences in field traits are affected by different soil properties, weather conditions and might be root traits in the soil which have been overlooked during the development of high yielding modern wheat verities. This is supported by Waines and Ehdai, 2007, who reported that modern wheat cultivars have root biomass less than two-third of the mean of wheat landraces. Many researchers for example, Bai *et al*., 2013, Atkinson *et al*., 2015 and Xie *et al*., 2017, have studied the root traits using germination paper based system and showed correlation between early seedling root traits with grain yield and yield components under normal soil field condition. Present study tested that seedling root traits associated with grain yield, yield components and mineral composition traits under a wide range of hostile soil environments (Chapter 4 and Chapter 5). The hypothesis being tested are that GYD, BYD and HI not correlated with length related root traits at all sites except Kumarganj-sodic. Narrow root angle traits correlated with GYD at most of the sites except Hisar (saline) and Kumarganj-sodic sites. Wider root angle traits correlated with PHT at all the sites. Lateral root length correlated with grain Zn concentration at Pundibari. Length related root traits associated with grain magnesium (Mg) and sulphur (S) concentration under hostile and non-hostile soils. The wider root angle and lateral root length related traits associated with grain iron (Fe) concentration under hostile and non-hostile soil types.

In brief, narrow root angle which potentially represent the steeper root system associated with grain yield of 36 genotypes measured in saline soil (Hisar), normal/saline soil (Kumarganj-reclaimed site) and acidic soil (Pundibari site). It indicates that narrow root angle could help to increase the grain yield through better adaptation under saline/acidic soil conditions. Richard *et al*., 2015, also reported that narrow root angle could result into the development of compact and deeper root system which is highly desirable trait in wheat particularly when grown in water deficient soils conditions. Among length related root traits, total length of lateral roots associated with grain yield and biological yield of 36 Indian genotypes under sodic soil (Kumarganj-sodic).

Wider and deeper root system correlated with grain yield of amphidiploids measured in normal soil (Karnal), contrastingly, narrow root angle traits showed association with GYD at Karnal as studied in Chapter 4. This could be due to the less variation for wider and deeper root traits in spring Indian wheat genotypes as compared to *Th. bessarabicum* derived amphidiploids. However, Xie *et al*., 2017, reported positive correlation between maximum widths of root with grain yield of 226 lines of wheat under normal soil field conditions. TLAR and TLPR and MDR associated with BYD and PTM of seven amphidiploids measured at Hisar (saline soil) site which are contradictory with association between juvenile root traits and field traits of 36 Indian wheat genotypes under saline soil (Hisar) studied in Chapter4. However, Xie *et al*., 2017 also reported correlation between seedling total roots length with biomass m^{-2} of wheat genotypes measured in normal soil field conditions. Therefore, longer, wider and deeper root traits of amphidiploids can be explored in breeding programmes

to develop the salt tolerant genotypes for salt affected soil condition to improve the grain yield.

There was little evidence of association between length related juvenile root traits and grain Zn concentration of Indian genotypes. Grain Zn concentration of Indian wheat genotypes correlated with total length of lateral roots (TLLR) only at Pundibari (acidic) site. It indicates that increased length of lateral roots potentially increase the surface area which may help the roots to explore more Zn in the soil. Accordingly, Rose *et al*., 2013, who reported that longer lateral roots and longer root hairs increases the acquisition of soil Zn by rice genotypes. However, wider root angle which potentially represent the shallow root system showed association with grain Zn concentration of amphidiploids.

It has been seen that association of juvenile root traits of 36 India genotypes with GYD, yield components and mineral composition traits are contradictory with the association of juvenile root traits of seven *Th. bessarabicum* derived amphidiploids with GYD, yield components and mineral composition traits under normal and saline field conditions. These differences might be due to the presence of extra wild chromosomes from *Th. bessarabicum* which affect the root architectural traits of amphidiploids.

Thus, it is not possible to measure these traits under field condition, therefore, these traits need further study with following objectives; 1) to study the effect on lateral root length, lateral root number and root angle traits under nutrient limited and nutrient adequate condition 2) to quantify the wider group of Indian wheat genotypes with diverse genetic background and amphidiploids derived

from wild wheat species for these traits to identify the valuable root traits for breeding.

7.5 Conclusion and future work

A panel of 36 Indian diverse wheat genotypes showed significant variation in GYD and component traits under hostile and non-hostile soils in India. Site had the largest effect on yield and component traits, however, G*E interaction affected most traits. Some genotypes performed better under hostile soils, with site-specific relationships between yield and component traits, which support the value of ongoing site-specific traits selection activities. Despite a relatively small contribution of 36 Indian wheat genotypes to the overall variation in grain Zn concentration (25-35 mg kg^{-1}), biofortifying wheat through is likely to be effective at scale given that some genotypes performed consistently across wide range of soil types. Juvenile root traits of 36 Indian wheat genotypes, for example, narrow root angle traits correlated with GYD at most of the sites. Wider root angle and lateral root length correlated with grain Zn and Fe concentrations. Amphidiploids derived from *Th. bessarabicum* (EC787011 to EC 787014) showed greater GYD and grain Zn concertation under saline soils than other amphidiploids which make them potential candidates to develop the salt tolerant wheat varieties. Grain Zn was greater in wild wheat species and their derivatives. Wild wheat species, for example, *Amblyopyrum muticum*, *Aegilops speltoides*, *Aegilops umbellulata* and *Aegilops comosa* and their derivatives present themselves as a new reservoirs for grain Zn concentration.

Amphidiploid derived from *Th. bessarabicum* showed less reduction in GYD under saline soils than Indian wheat genotypes, it is necessary now to cross these amphidiploids with high yielding Indian wheat varieties and test them under different hostile soil conditions for yield, yield components, grain Zn concentration and to include best performing lines in advance breeding programmes for the development of salt tolerant wheat varieties with high grain Zn. Amphidiploids derived from *Th. bessarabicum* showed wider and longer root system than Indian wheat genotypes, further research is required to optimize the root architectural traits under acidic, saline/alkaline solutions and under nutrient limited and nutrient adequate conditions.

Among wild wheat derivatives, 51 double haploid lines derives from *Amblyopyrum muticum* had great potential to increase the grain Zn concentration in wheat varieties. Therefore, further step is to screen these lines for grain Zn concentration in different part of grains (embryo, aleurone layer, endosperm) and content of phytates. Best performing lines will be selected for further development of homozygous line of each introgressed segment from *Am. muticum*, then genes responsible for high grain Zn concentration will be identified to further transfer into modern wheat genotypes.

7.6 References

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