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RESEARCH ARTICLE

Effects of chromosome substitution on the utilization efficiency of nitrogen, phosphorus, and potassium in wheat

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Abstract A complete set of chromosome substitution lines with genetic background of Chinese Spring (CS) were used to determine the effects of each chromosome on utilization efficiencies of nitrogen, phosphorus, and potassium in wheat (*Triticum aestivum* L.). In each line, only one pair of chromosomes in CS genome was substituted by the corresponding one of donor Synthetic 6x. Under normal growth conditions supplied with enough inorganic nutrients, the dry mass per plant and the utilization efficiencies of nitrogen (N), phosphorus (P), and potassium (K) in plants varied largely among CS, Synthetic 6x, and the chromosome substitution lines (1A–7A, 1B–7B, and 1D–7D). Of these, 1A substituted by the chromosome 1A of Synthetic 6x (other lines are the same as 1A hereafter) had the highest plant dry mass and the accumulative amount of N and K, and 1B behaved to have the highest plant accumulative P amount. 1D and 4D had the lowest accumulative P amount and plant dry mass, respectively. 4B showed the lowest plant accumulative N and K. Thus, chromosome 1A of Synthetic 6x contains major genes endowing plant capacities of higher dry mass, accumulative N and K, whereas chromosome 1B of Synthetic 6x carries major genes improving plant accumulative P capacities. The lines, together with CS and the donor, could be classified into three groups including high-efficiency, mid-efficiency, and low-efficiency based on plant dry mass. Regression analysis suggested that there are significantly positive correlations between plant dry mass and the accumulated amount of N, P, and K. Further, there are positively significant correlations among the plant accumulative N amount and some plant traits and physiological parameters, as well as positively significant correlations between the accumulative amount of P and K and the photosynthetic rate (P_n).

Keywords wheat (*Triticum aestivum* L.), chromosome substitution line, nitrogen efficiency, phosphorus efficiency, potassium efficiency, plant growth trait, photosynthetic parameter

Introduction

In crop production, the fertilizers of nitrogen (N), phosphorus (P), and potassium (K) applied in the field can be only utilized partly, with a utilization rate of fertilizers of N, P, and K in current growth season to be about 35%–40%, 15%–20%, and 40%–50%, respectively (Wang et al., 1999; Sun et al., 2004; Trehan, 2009). Improvements in fertilizer use efficiency in crop production play a vital role in protection of the environment and promotion of the sustainable agriculture development. Previously, a lot of research results in wheat (*Triticum aestivum* L.) indicate that there are large genetic diversities among the genotypes, varieties, and cultivars in the usage efficiency of inorganic nutrients, such as nitrogen, phosphorus, and potassium (Wang et al., 1999; Sun et al., 2004; Han et al., 2006; Li et al., 2006; Zhang et al., 2007; Guo et al., 2008). The genotypes with higher use efficiencies of the nutrients generally endow plants with an increased nutrient uptake capacity and improved nutrient transportation efficiency at cellular level.

Wheat chromosome substitution line (CSL), where one pair of chromosome in the recipients is substituted by the corresponding one of the donor, has become useful genetic materials for unraveling the genetic effects of the distinct chromosome on controlling of agronomic traits and physiologic and biochemical parameters. A complete set of chromosome substitution lines in wheat consists of a total

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of 21 lines, and each line has only one distinct pair of chromosome in the recipient substituted by the corresponding one of the donor. Therefore, the chromosome lines are valuable in determining the location of major genes on controlling agronomic traits, with a potential as the elite germplasm for plant genetic improvement (Liu et al., 1998).

Chinese Spring (CS), a traditional cultivar cultivated in China, has long been used as an important genetic material worldwide in wheat genetic and molecular studies. Up to date, using Chinese Spring as the recipient, more and more chromosome substitution lines have been generated, in which various wheat genotypes, generally are genetically diverse from CS, and used as the chromosome donor (Law and Wang, 1997; Liu et al., 1998). During the past several years, the wheat chromosome substitution lines (CSLs) have been successfully adopted in mapping the major genes that regulate the biochemical parameters, water use efficiency, and important agronomic traits. Some genetic loci controlling endurance capacities of low-temperature, activities of superoxide dismutase (SOD) and peroxidase (POD), and values of grain weight and yield have been mapped on the distinct chromosomes (Morgan, 1991; Clua et al., 2002; Zhang et al., 2005; Bai et al., 2007).

In the past two decades, more attention has been paid to understanding the biologic and genetic mechanism on how plants efficiently utilize inorganic nutrients. For this purpose, the cultivars and lines are used as the experimental materials in most cases (Glass et al., 1981; Muurinen et al., 2006). So far, although a lot of studies have been conducted in this area, the delicate chromosome effects on controlling utilization efficiencies of inorganic nutrients have still been elusive. In the present study, a complete set of CSLs of Chinese Spring (CS) is used for dissection of chromosome effects on controlling of utilization efficiencies of N, P, and K. The CSLs had almost whole CS genetic background, with only a single pair of chromosome substituted by the corresponding one of donor Synthetic 6x, a wheat genotype with a strong capacity of utilization of inorganic nutrients. It is revealed that several CSLs showed significant variations in plant growth and nutrient uptake compared with CS, suggesting that the corresponding chromosomes in the donor carry major genes for improving the uptake capacity of N, P, and K. Therefore, these CSLs could be further used as the potential resources for the genetic improvement of nutrient use efficiency in wheat.

Materials and methods

Experimental materials

A complete set of wheat single chromosome substitution lines (CSL) deduced from Chinese Spring (CS) in which Synthetic 6x acted as the chromosome donor has been used in this study. Synthetic 6x is unraveled to be a genotype with a strong endurance ability of abiotic stresses, such as drought, salt, and inorganic nutrient deficiencies (unpublished data). Each CSL had CS genetic background, with only one pair of chromosome derived from the donor. Therefore, the complete set of CSLs included 1A–7A, 1B–7B, and 1D–7D derived from genomes A, B, and D of the donor, respectively. The seeds of CSLs, recipient CS, and donor Synthetic 6x were all kindly provided by Dr. Cundong Li (College of Agronomy, Agricultural University of Hebei, China).

The experiment was conducted by three replicates in a growth room. The seeds of CSLs, CS, and Synthetic 6x were germinated at 25ºC and then transferred onto a stainless steel net, which was propped onto the surface of MS nutrient solution in a plastic tray (20 cm × 12 cm × 12 cm). The primary roots of young seedlings entered the solution via the net meshes. The solution provided all macro- and micronutrients suitable for wheat seedling growth under air circulation through plastic tubes connected to a minipump during experimental stage. The concentrations of nitrogen (N), phosphorus (P_i), and potassium (K) in the solution were 10 mmol/L, 3 mmol/L, and 8 mmol/L, respectively. The seedlings were grown at a thermal cycle of 20ºC/15ºC (day/night), with a photoperiod of 12 h/12 h (day/night) and a light intensity of 300 μME/($m^2 \cdot s$). During the growth of seedlings, the nutrient solution was renewed every three days. When the fourth leaves were fully expanded, the representative seedlings of CSLs, CS, and Synthetic 6x were collected for the analysis of plant growth traits, leaf photosynthetic parameters, and plant nutrient traits.

Measurement of plant growth traits

Ten representative seedlings derived from CSLs, CS, and Synthetic 6x were used for measurement of plant height, leaf age, primary root number, and leaf area per plant, according to the conventional methods. For measurement of plant dry mass, the seedlings after measurement of the above traits were dried at 85ºC for 24 h before being weighed.

Measurement of leaf photosynthetic parameters

The seedling second leaves of CSLs, CS, and Synthetic 6x were used for the measurement of leaf photosynthetic parameters. The soluble protein content was measured according to the descriptions by Read and Northcote (1981). Chlorophyll a, chlorophyll b, and carotenoid were determined based on spectrophotometric analysis after extraction using 95% ethanol for 48 h in the darkness. The chlorophyll fluorescence parameter of Fv/Fm (ratio of variable fluorescence to maximum fluorescence) was measured by Chlorophyll Fluorescence Analyzer (Hanson, English). The photosynthetic rate (P_n) was assayed by a portable Photosynthesis System (LI-6400, USA). Each parameter was performed with three replicates in each CSL, CS, and Synthetic 6x.

Measurements of nutrient concentrations

The concentrations of total N, P, and K in CSLs, CS, and Synthetic 6x were measured based on the conventional methods. The N concentration was determined based on Kjeldahl method, while the P concentration is determined by Vanadium molybdate method and the K content assayed via flame atomization measurement method. The accumulative amounts of total N, P, and K were achieved by plant dry weight and the corresponding concentrations of N, P, and K, respectively. The subgroups of nutrient utilization efficiencies were classified based on the accumulative N, P, and K in CSLs, CS, and Synthetic 6x, according to the descriptions of Li et al. (2006).

Data analysis

All analysis of data, covering the average value, standard errors, regression analysis, and significant tests, were performed by using the statistical product and service solutions (SPSS) software.

Results

The plant dry mass and accumulated N, P, and K

The plant dry mass and accumulated N, P, and K in CSLs, CS, and Synthetic 6x were listed in Fig. 1. Of CSLs, 1A showed the highest plant dry mass, whereas 4D showed the lowest plant dry mass. The former had 55.56% plant dry mass over the latter. Similarly, 1A had higher accumulative N and K than 4B with the former 69.61% and the latter 75.00% of accumulative N and K, respectively. In addition, the accumulative P behaved the highest in 1B and the lowest in 1D, with an increase of 186.49% in the former over the latter. In this study, three subgroups varying evidently in plant day mass including high-, mid-, and low-efficiency could be classified among CSLs, CS, and Synthetic 6x. CSL of 1A behaved to have the highest plant dry mass and accumulative amounts of N and K, suggesting that the chromosome 1A of Synthetic 6x carries the major genes controlling plant growth and improving uptake capacities of nitrogen and potassium. Whereas chromosome 1B of Synthetic 6x carries the major genes only improving uptake capacities of phosphorus.

Regression analysis between plant accumulative N, P, and K and plant dry mass and nutrient utilization traits

Regression analysis was performed between the accumulative amount of N, P, and K and the plant dry mass (Fig. 2A –C), and between the content of N, P, and K (Fig. 2D–F), and the efficiency of N, P, and K, respectively (Fig. 2G–I). It is shown that there are significant correlations ($P < 0.01$) between accumulative N amount and plant dry mass (Fig. 2A), accumulative K amount and plant dry mass (Fig. 2C), accumulative P amount and P content (Fig. 2E), and accumulative P amount and P efficiency (Fig. 2H). Meanwhile, there are also significant correlations ($P < 0.05$) between accumulative amount of N, P, and plant dry mass (Fig. 2A–B), accumulative amount of K and K content (Fig. 2F), accumulative amount of N, K, and efficiency of N, K, respectively (Fig. 2G–I). Thus, the accumulative capacities of N, P, and K in CLSs were closely associated with the plant dry mass, with the accumulative capacities of P and K regulated by the content of phosphorus and potassium.

Effects of genome A, B, and D on accumulative capacities of N, P, and K in CSLs

The plant dry mass, accumulative amount, content, and efficiency of N, P, and K are listed in Table 1. It is clearly observed that there was a large variation of plant dry mass and accumulative capacities of N, P, and K among the CSLs, CS, and Synthetic 6x. The Synthetic 6x had higher contents of N and P and accumulative P amount and K efficiency than CS, without significant differences ($P < 0.05$) of the average values of plant dry mass, content of N and K, accumulative amount of N and K, and N efficiency among the genomes A (1A to 7A), B (1B to 7B), and D (1D to 7D). Among them, the means of N content, P content, accumulative P amount, N efficiency, and P efficiency in CSLs of genomes A, B, and D were all similar to those in CS, whereas the means of plant dry mass, K content, accumulative N, K amount, and K efficiency in CSLs of genomes A, B, and D were all similar to those in Synthetic 6x. The average accumulative N amount in CSLs of genomes A, B, and D was significantly lower than that in CS and Synthetic 6x. On the average, P content and accumulative P amount in CSLs of genome D were significantly lower than those in genomes A and B. However, the average efficiency of P and K was significant higher in CSLs of genome D than that in genomes A and B (Table 1). In short, the integrated effects derived from the donor genomes A, B, and D are varied, showing different genetic effects on plant dry mass and nutrient utilization traits.

Plant growth traits and photosynthetic parameters of CSLs, CS, and Synthetic 6x

Almost all the plant traits including plant height, leaf age, primary root numbers, and leaf area of plant, as well as the photosynthetic parameters including the content of soluble protein, chlorophyll a, b, and a + b, carotenoid, and the photosynthetic rate (P_n) were markedly variable between CS and Synthetic 6x. However, the ratio of Fv/Fm (variable fluorescence to maximum fluorescence) was not obviously different between them (Table 2). The averages, standard errors, and coefficient variations (CVs) of above traits and parameters in CSLs of genomes A, B, D, and the whole

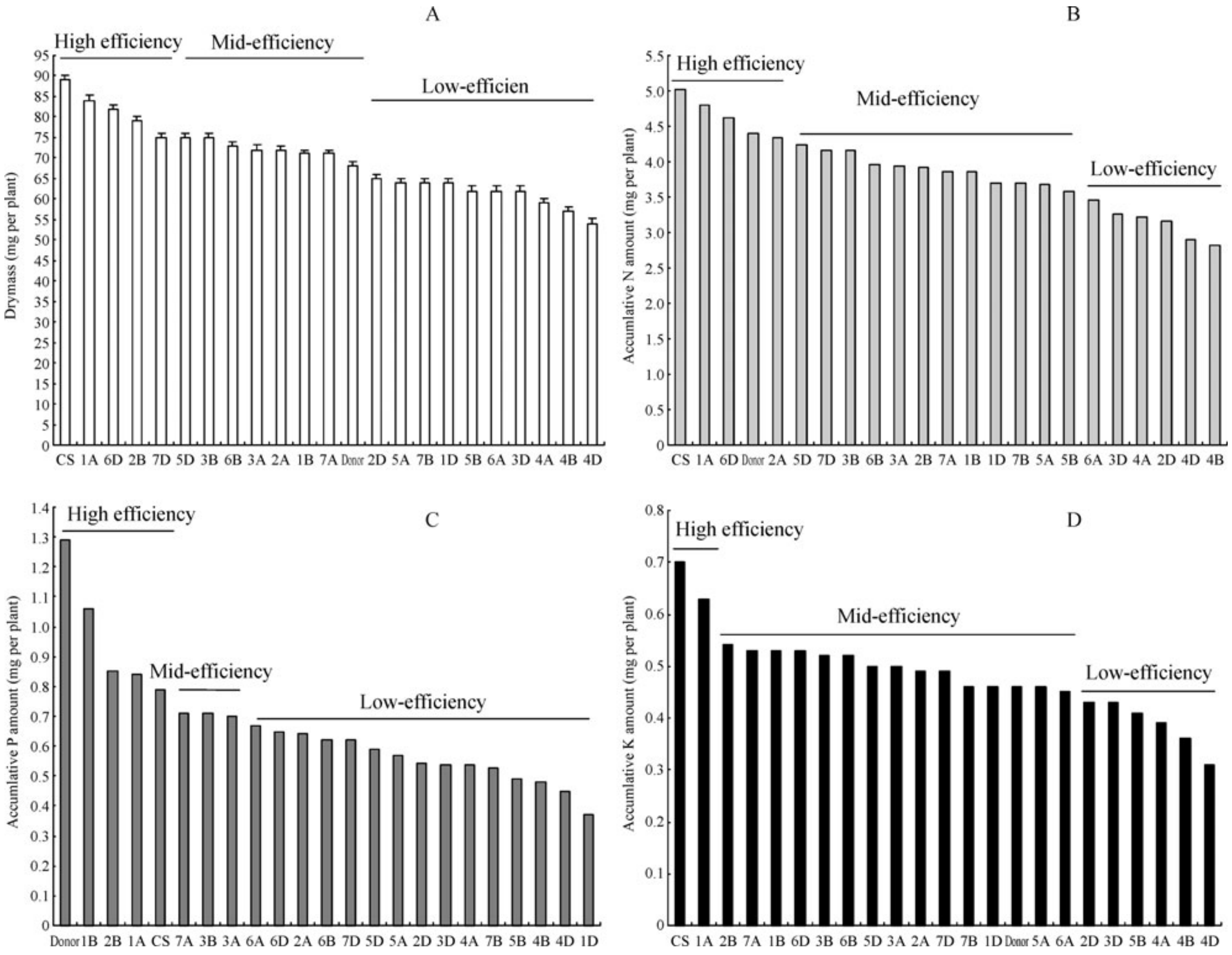

Figure 1 The dry mass and accumulated amount of N, P, and K in plants of CSLs, CS, and Synthetic 6x. Chinese Spring (CS) and Synthetic 6x are used as the recipient and donor of chromosomes, respectively. 1A to 7A, 1B to 7B, and 1D to 7D are chromosome substitution lines (CSLs) with just only a single pair of chromosome in CS substituted by the corresponding one of Synthetic 6x. Fig. 1A is the plant dry mass of CS, Synthetic 6x, and CSLs. The data shown are average±standard errors (*SE*). Fig. 1B is the plant accumulative N of CSLs, CS, and Synthetic 6x. Fig. 1C is the plant accumulative P of CSLs, CS, and Synthetic 6x. Fig. 1D is the plant accumulative K of CSLs, CS, and Synthetic 6x.

genome are listed in Table 2. Compared to CS and Synthetic 6x, the means of plant height, primary root number, leaf area per plant, *F*v/*F*m, and Pn in CSLs of genomes A, B, and D did not obviously vary, while the means of leaf age, soluble protein content, and Chla in CSLs of genomes A, B, and D were similar to those of CS, and the means of Chlb and carotenoid in CSLs of genomes A, B, and D were similar to those of Synthetic 6x (Table 2).

Regression analysis of plant growth traits, photosynthetic parameters, and nutrient utilization traits

Regression analysis suggested that there were positive correlations between the plant accumulative N and all the tested plant growth traits or photosynthetic parameters, with significant ($P < 0.05$) correlation coefficients between plant accumulative N and plant height, primary root number, content of Chla and Chla + b, and P_n. There also existed positive correlations between plant accumulative K and plant growth traits or photosynthetic parameters; however, only those between plant leaf area and plant accumulative K with P_n were significant ($P < 0.05$). The correlations between plant accumulative P and plant growth traits or photosynthetic parameters varied more markedly, showing a negative correlation with plant height and primary root number, a low positive one with leaf age, soluble protein content, Chla, Chlb, Chla + b, and *F*v/*F*m, and a significant positive ($P < 0.05$) one with P_n (Table 3). It is shown that photosynthetic rate (P_n), a physiologic parameter having significantly positive correlations with the accumulative amount of N, P, and K, could be used as an indicator for evaluation of the nutrient utilization efficiency in CSLs.

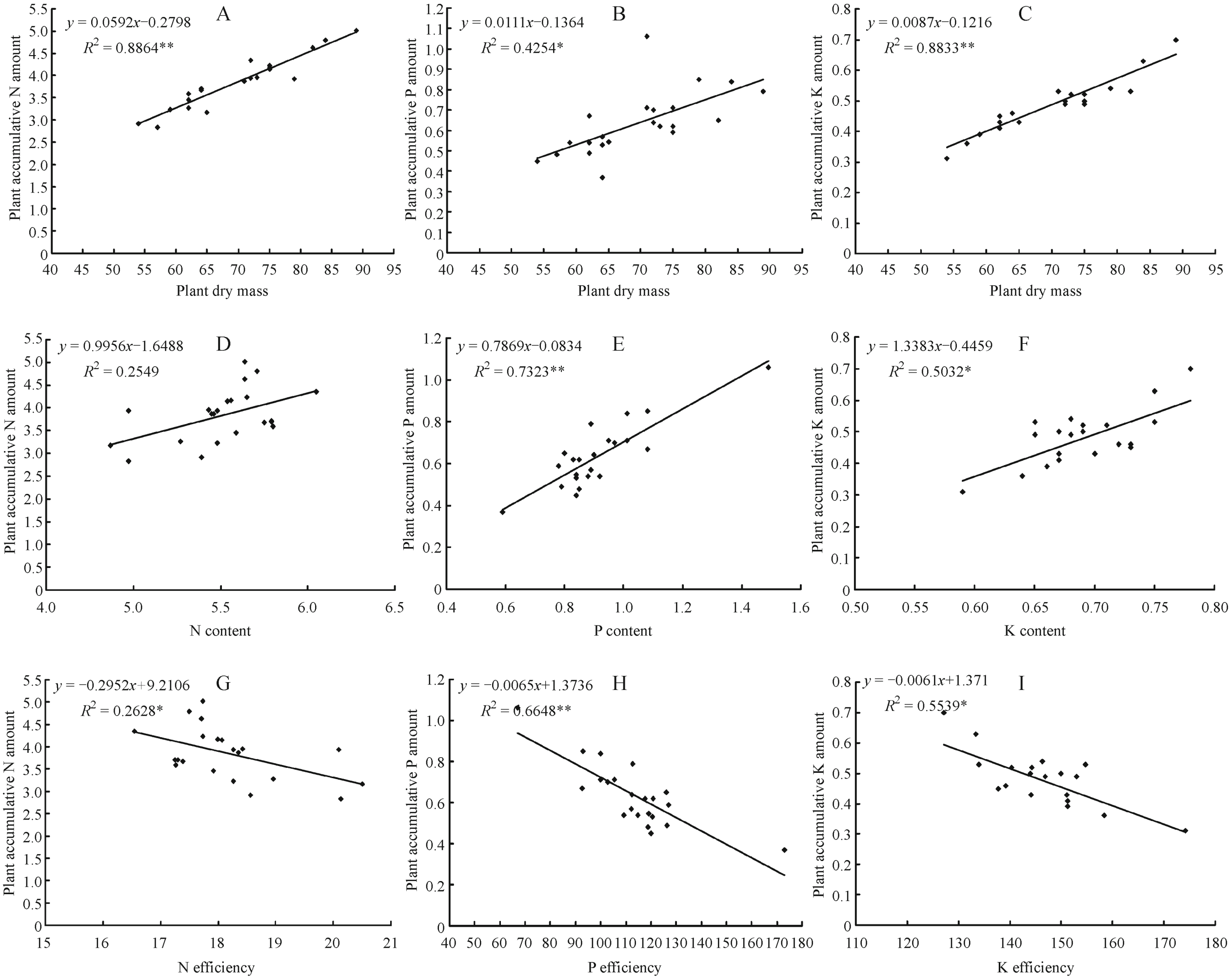

Figure 2 Regression analysis of plant accumulative amount of N, P, and K based on plant dry mass and nutrient utilization traits derived from CSLs, CS, and Synthetic 6x. A, D, and G show the results of regression analyses between plant accumulative N amount and plant dry mass (A), N content (D), and N efficiency (G), respectively. B, E, and H show the results of regression analyses between plant accumulative P amount and plant dry mass (B), P content (E), and P efficiency (H), respectively. C, F, and I show the results of regression analyses between plant accumulative K amount and plant dry mass (C), K content (F), and K efficiency (I), respectively.* and ** indicate that the regression coefficient reaches significant levels of 5% and 1%, respectively.

Discussion

Genetic diversities have been widely reported on various plant growth traits, physiologic and biochemical parameters, as well as on nutrient use efficiencies of nitrogen, phosphorus, and potassium (Trehan, 2005, 2009). In wheat, it is observed that there is a drastic variation of utilization efficiencies of nitrogen, phosphorus, and potassium among genotypes, varieties, or cultivars (Karrou and Maranville, 1994; Foulkes et al., 1998).

Previously, studies on comparison of the utilization efficiencies of N, P, and K among the cultivars and the corresponding physiologic and biochemical mechanisms have been extensively conducted in wheat (Wang et al., 1999; Sun et al., 2004; Han et al., 2006; Li et al., 2006; Zhang et al., 2007; Guo et al., 2008). However, different genetic backgrounds in the tested cultivars frequently result in incomparable consequences and inconsistent conclusions. Chromosome substitution line (CSL), with one pair of distinct chromosome of a recipient substituted by the corresponding one of a donor, has become a valuable genetic material for exploring the chromosome locations of genetic loci of important agronomic traits as well as the potential for determination of the biologic mechanisms endowed by donor chromosome.

Using CLSs derived from CS/CD (recipient/donor of chromosome) as experimental materials, it is found that the homologous chromosome Group 5 carries the chief genes controlling the biosynthesis of arginine, proline, and polyamines, with the locations of chromosomes 5A, 5B, and 5D, respectively (Galiba et al., 1992; Galiba et al., 1993). Analysis on the above CSLs also suggests that 5A and 5D carry the genetic loci of regulating abscisic acid (ABA) biosynthesis and cold endurance capacity (Delauney and

Table 1 Plant day masses and nutrient utilization traits of the CSLs, CS, and Synthetic 6x

Lines	Dry mass (mg per plant)	N content (%)	P content (%)	K content (%)	Accumulative N (mg per plant)	Accumulative P (mg per plant)	Accumulative K (mg per plant)	N efficiency (mg per mg N)	P efficiency (mg per mg P)	K efficiency (mg per mg K)
CS	89a	5.64b	0.89bc	0.78a	5.02a	0.79b	0.70a	17.73a	112.66b	127.14c
Synthetic 6x	68b	6.47a	1.91a	0.69b	4.40b	1.29a	0.46b	15.45b	52.71c	147.83ab
1A	84	5.71	1.01	0.75	4.80	0.84	0.63	17.50	100.00	133.33
2A	72	6.05	0.90	0.68	4.35	0.64	0.49	16.55	112.50	146.94
3A	72	5.48	0.97	0.69	3.94	0.70	0.50	18.27	102.86	144.00
4A	59	5.48	0.92	0.66	3.23	0.54	0.39	18.27	109.26	151.28
5A	64	5.75	0.89	0.73	3.68	0.57	0.46	17.39	112.28	139.13
6A	62	5.59	1.08	0.73	3.46	0.67	0.45	17.92	92.54	137.78
7A	71	5.46	1.01	0.75	3.87	0.71	0.53	18.35	100.00	133.96
1B	71	5.45	1.49	0.75	3.87	1.06	0.53	18.35	66.98	133.96
2B	79	4.97	1.08	0.68	3.93	0.85	0.54	20.10	92.94	146.30
3B	75	5.54	0.95	0.69	4.15	0.71	0.52	18.07	105.63	144.23
4B	57	4.97	0.85	0.64	2.83	0.48	0.36	20.14	118.75	158.33
5B	62	5.8	0.79	0.67	3.59	0.49	0.41	17.27	126.53	151.22
6B	73	5.43	0.85	0.71	3.96	0.62	0.52	18.43	117.74	140.38
7B	64	5.79	0.84	0.72	3.7	0.53	0.46	17.30	120.75	139.13
1D	64	5.79	0.59	0.72	3.71	0.37	0.46	17.25	172.97	139.13
2D	65	4.87	0.84	0.67	3.1685	0.545	0.43	20.51	119.27	151.16
3D	62	5.27	0.88	0.70	3.27	0.54	0.43	18.96	114.81	144.19
4D	54	5.39	0.84	0.59	2.91	0.45	0.31	18.56	120.00	174.19
5D	75	5.65	0.78	0.67	4.23	0.59	0.50	17.73	127.12	150.00
6D	82	5.64	0.80	0.65	4.63	0.65	0.53	17.71	126.15	154.72
7D	75	5.56	0.83	0.65	4.17	0.62	0.49	17.99	120.97	153.06
A-D Ave	68.67b	5.51b	0.91bc	0.69b	3.78c	0.63b	0.47b	18.22a	113.34b	146.02ab
A-D SE	8.21	0.30	0.17	0.04	0.52	0.15	0.07	1.01	19.84	9.68
A-DCV (%)	11.96	5.38	18.87	6.00	13.77	24.64	14.96	5.57	17.50	6.63
A Ave	69.14b	5.65b	0.97b	0.71b	3.90c	0.67b	0.49b	17.75a	104.20b	140.92b
A SE	8.38	0.21	0.07	0.04	0.53	0.10	0.07	0.65	7.45	6.73
A CV (%)	12.11	3.76	7.19	5.04	13.66	14.88	15.22	3.67	7.15	4.78
B Ave	68.71b	5.42b	0.98b	0.69b	3.72c	0.68b	0.48b	18.52a	107.05b	144.79ab
B SE	7.89	0.34	0.25	0.04	0.43	0.21	0.07	1.19	20.92	8.12
B CV (%)	11.48	6.31	25.05	5.18	11.61	31.69	14.56	6.40	19.54	5.61
D Ave	68.14b	5.45b	0.79c	0.66b	3.73c	0.54c	0.45b	18.39a	128.76a	152.35a
D SE	9.58	0.31	0.10	0.04	0.64	0.10	0.07	1.10	19.94	11.04
D CV (%)	14.06	5.68	12.03	6.26	17.16	18.28	15.97	5.97	15.49	7.25

The different small letters in the same column indicate the differences at 5% significant level.

Table 2 Plant morphological traits and photosynthetic parameters in CSLs, CS, and Synthetic 6x

Lines	Plant height (cm)	Leaf age	Root number	Leaf area (cm^2 per plant)	SP (mg/gFW)	Chla (mg/gFW)	Chlb (mg/gFW)	Chla + Chlb (mg/gFW)	Caro (mg/gFW)	*Fv*/*Fm*	P_n (μmol/(m^2·s))
CS	33.1a	3.6a	4.8a	22.6a	49.48b	1.36a	0.40a	1.76a	0.29a	0.861a	21.03a
Synthetic 6x	26.1b	3.2b	3.7c	15.1c	58.90a	1.39a	0.37a	1.76a	0.27a	0.855a	16.12b
1A	31.7	3.7	4	19.1	46.79	1.3	0.35	1.65	0.26	0.851	17.67
2A	33.5	3.5	4.2	19.3	46.62	1.39	0.37	1.76	0.29	0.852	22
3A	34.8	3.8	4.3	22.1	48.69	1.4	0.36	1.76	0.27	0.856	17.17
4A	31.2	3.6	3.8	18.9	49.72	1.43	0.4	1.83	0.31	0.847	18.84
5A	31.7	3.7	3.2	19.6	39.99	1.32	0.35	1.67	0.26	0.869	17.17
6A	30.5	3.6	3.2	17.6	34.94	1.29	0.41	1.7	0.29	0.843	16.03
7A	34.1	3.4	4.5	18.6	36.4	1.18	0.33	1.51	0.24	0.850	16.16
1B	32.2	3.5	4.2	20.2	46.44	1.29	0.36	1.65	0.25	0.861	17.15
2B	32.9	3.7	4.8	22.8	55.19	1.36	0.37	1.73	0.27	0.852	17.5
3B	35.8	3.7	4.8	23.0	50.11	1.42	0.38	1.8	0.29	0.874	21.03
4B	31.2	3.6	3.5	18.3	42.64	1.14	0.36	1.5	0.27	0.839	12.33
5B	29.1	3.7	1.8	16.6	52.21	1.45	0.41	1.86	0.3	0.851	18.16
6B	35.5	3.5	4.7	19.4	50.6	1.38	0.38	1.76	0.27	0.861	17.83
7B	34.2	3.4	4.2	19.4	45.98	1.35	0.36	1.71	0.27	0.851	18.33
1D	32.9	3.5	4.5	18.6	42.36	1.28	0.35	1.63	0.26	0.863	15.5
2D	32.7	3.6	3.7	19.5	50.98	1.31	0.34	1.65	0.26	0.864	13.03
3D	29.6	3.6	4	15.4	51.39	1.2	0.31	1.51	0.23	0.854	16.16
4D	30.6	3.5	3.2	16.4	44.58	1.09	0.25	1.34	0.25	0.852	18.1
5D	31.5	3.9	4.7	21.9	46.8	1.42	0.38	1.8	0.29	0.865	17.16
6D	38.9	3.5	4.5	23.9	48.05	1.47	0.4	1.87	0.28	0.862	18.33
7D	32.1	3.9	3.2	22.7	61.4	1.38	0.35	1.73	0.27	0.858	15.16
A-D Ave	32.70a	3.61a	3.95b	19.68b	47.23c	1.33a	0.36ab	1.69a	0.27a	0.856 a	17.18b
A-D Se	2.30	0.14	0.74	2.31	6.02	0.10	0.04	0.13	0.02	0.008	2.20
A-DCV (%)	7.03	5.45	18.72	11.76	12.74	7.82	9.98	7.90	7.35	0.966	12.82
A Ave	32.50a	3.61a	3.89bc	19.31b	43.31d	1.33a	0.37a	1.70a	0.27a	0.856a	17.86b
A Se	1.62	0.13	0.52	1.38	6.08	0.09	0.03	0.10	0.02	0.007	2.05
A CV (%)	5.00	5.15	13.33	7.17	14.04	6.41	7.82	6.06	8.64	0.849	11.50
B Ave	32.99a	3.59a	4.00b	19.96b	49.02b	1.34a	0.37a	1.72a	0.27a	0.853a	17.48b
B Se	2.40	0.12	1.08	2.31	4.25	0.10	0.02	0.12	0.02	0.011	2.60
B CV (%)	7.28	4.70	26.89	11.58	8.68	7.64	4.84	6.77	5.90	1.291	14.87
D Ave	32.61a	3.64a	3.97b	19.77b	49.37b	1.31a	0.34b	1.65b	0.26a	0.860a	16.21b
D Se	3.01	0.18	0.63	3.22	6.22	0.13	0.05	0.18	0.02	0.005	1.86
D CV (%)	9.22	6.86	15.77	16.27	12.59	10.07	14.41	10.90	7.52	0.596	11.46

The different small letters in the same column indicate the differences at 5% significant level.

Table 3 Regression analysis of accumulative N, P, and K, plant morphological traits and photosynthetic parameters in CSLs

Independent variable (x)	Accumulative N per plant (y)		Accumulative P per plant (y)		Accumulative K per plant (y)	
	$y = ax + b$	r	$y = ax + b$	r	$y = ax + b$	r
Plant height	$y = 0.123x - 0.342$	0.501*	$y = -0.011x + 0.762$	−0.463	$y = 0.016x - 0.0394$	0.425
Leaf age	$y = 0.774x + 1.817$	0.188	$y = 0.0778x + 0.4315$	0.071	$y = 0.0638x + 0.3168$	0.105
Primary root number	$y = 0.375x + 2.342$	0.488*	$y = -0.011x + 0.762$	−0.463	$y = 0.066x + 0.220$	0.582
Leaf area per plant	$y = 0.162x + 0.638$	0.661*	$y = 0.030x + 0.036$	0.457	$y = 0.022x + 0.058$	0.597*
Soluble protein content	$y = 0.021x + 2.868$	0.211	$y = 0.003x + 0.513$	0.097	$y = 0.002x + 0.391$	0.137
Chla	$y = 3.099x - 0.276$	0.549*	$y = 0.261x + 0.288$	0.171	$y = 0.311x + 0.071$	0.374
Chlb	$y = 6.524x + 1.476$	0.411	$y = 0.952x + 0.290$	0.222	$y = 0.884x + 0.163$	0.379
Chla + b	$y = 2.352x - 0.135$	0.538*	$y = 0.229x + 0.249$	0.193	$y = 0.254x + 0.055$	0.394
Caro	$y = 6.796x + 1.995$	0.235	$y = -0.556x + 0.786$	0.071	$y = 0.265x + 0.412$	0.062
Fv/Fm	$y = 26.482x - 18.834$	0.391	$y = 2.176x - 1.228$	0.119	$y = 3.390x - 2.419$	0.340
P_n	$y = 0.141x + 1.4011$	0.564*	$y = 0.019x + 0.312$	0.476*	$y = 0.015x + 0.226$	0.485*

The correlation with * indicates that the regression degree reaches a significant level of 5%.

Verma, 1993). Based on the studies of CSLs derived from CS/Hope and CS/E. Oelongata (recipient/donor), it is concluded that the genetic locus for controlling the content of proline, an important osmolyte in leaves, is located at chromosome 6B (Yang et al., 2001a, 2001b).

As the wheat genotype possesses advantages of resistance to several types of abiotic stresses and performance of elite several agronomic traits, therefore, Synthetic 6x is used as a donor to generate a complete set of CSLs with Chinese Spring as the recipient. Using this series of CSLs, the major genes regulating the protein content in root are located on 6A and 1D (Clua et al., 2002), whereas the chief genes controlling the osmoregulation capacity in plants are located on 7A (Morgan, 1991), confirming that 5D carries the chief genes improving proline biosynthesis, while 4A and 4B contain the chief genes promoting protein synthesis, when plants are exposed to osmotic stress (Bai et al., 2007). Therefore, CSLs of CS/Synthetic 6x have a potential for identification of chromosome locations of the chief genes that regulate plant growth and development, yield formation, and biotic/abiotic stress responses (Sun and Quick, 1991; Sivamani et al., 2000; Atienza et al., 2004).

In our study, a complete set of CSLs derived from CS/Synthetic 6x were used for the identification of chromosome effects on nutrient utilization efficiencies. The variation ranges of plant dry mass and accumulative amounts of N, P, and K in plants among CSLs were 55.56%, 69.61%, 186.49%, and 75.00%, respectively, suggesting that part of chromosomes in the donor play important roles in regulation of plant growth and nutrient utilization capacities. Chromosomes 1A, 6D, 2B, and 7D carry the chief genes controlling plant growth, with 1A, 6D, and 2A harboring the chief genes that regulate accumulative N amount, and 1B, 2B, and 1A situating the chief genes that modulated accumulative P amount, and 1A also has the chief genes controlling accumulative K potassium. Therefore, CSLs that harbor the chief genes largely contributing to plant growth and accumulation capacities of N, P, and K have a potential for genetic improvement of plant growth traits and utilization efficiencies in wheat in the future.

Linear regression analysis between plant dry mass and accumulative amount of N, P, and K displays that there are significantly positive correlations ($P < 0.01$) among them, indicating that the plant growth in CSLs is dependent to some extent on the uptake capacities of all the above nutrients. It is also detected that plant accumulative N amount is significantly positively correlated with plant height, primary root number, and content of Chla, Chla + b, and P_n. Similarly, significantly positive correlations are observed between plant accumulative amount of P and K with P_n, as well as between accumulative K amount with leaf area per plant. Therefore, the above plant traits or physiologic parameters can be used as evaluation criteria for identification of CSLs, genotypes, and cultivars with higher utilization efficiencies of N, P, and K in wheat.

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