

Mapping the *Bo_d2* gene associated with boron efficiency in wheat

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ABSTRACT: Genotypic variation for response to boron (B) deficiency in wheat (*Triticum aestivum* L.) was determined as grain set index (GSI, %) and found to be controlled by two major genes, *Bo_d1* and *Bo_d2*. Breeding for B efficiency may be enhanced by molecular markers associated with quantitative trait loci (QTL) for B efficiency. Two mapping populations, (Bonza × SW 41) BC₂ and Fang 60 × Bonza, were made from Bonza (B inefficient), SW 41 (B moderately inefficient), and Fang 60 (B efficient) parents. Leaf samples from F₂ plants from each cross were used for DNA analysis. GSI was measured in F₂-derived F₃ families. Seven hundred and eighty-seven simple sequence repeat (SSR) markers were used. Bulked segregant analysis and QTL analysis were performed to identify the chromosomal location for B efficiency. One QTL for B efficiency was identified and mapped in (Bonza × SW 41) BC₂F₃, and was found to be flanked by two SSR markers, gwm192, and gwm165. This QTL is located on the long arm of chromosome 4D between gwm165 and gwm192. This QTL region corresponded for 21% of the variation in GSI, suggesting that the chromosome segment of SW 41 parent containing the *Bo_d2* locus was inherited by the progenies and that is located on 4D. Additional markers and further examination are required to locate *Bo_d1*, the other B efficient gene. Linked markers will enable applications of marker-assisted selection for B-efficient genotypes in wheat.

KEYWORDS: quantitative trait loci (QTL), SSR markers, *Triticum aestivum*

INTRODUCTION

Boron (B), an essential micronutrient for plants, is often present at insufficient levels for crops to growth in coarse textured soil in humid regions¹. Boron deficiency usually affects young growing parts of plants. In cereals including wheat, symptoms mostly occur in reproductive tissues². In wheat, B deficiency affects reproductive growth by causing abnormal development of the pollen, resulting in male sterility and failure to set grain. Boron deficiency in wheat has been reported in several wheat-growing countries including Bangladesh, Brazil, Bulgaria, China, Finland, India, Madagascar, Nepal, Pakistan, South Africa, Sweden, Tanzania, Thailand, USA, Russian Federation, Yugoslavia, Zambia³.

A wide range of genotypic variation in B efficiency in wheat has been reported^{4–6}. As B deficiency is closely associated with grain set index (GSI), which measures grain set in basal florets of the central spikelets of the wheat ear, it has been used effectively as a measure of B efficiency in wheat⁶. The range

of B efficiency of genotypes is expressed as the GSI ranging from 0–100%.

The use of B efficient genotypes was suggested as means of avoiding sterility induced by B deficiency of wheat in low B soils⁷. To do this effectively, the genetics of B efficiency must be better understood so that the trait can be incorporated in breeding programs, targeting areas prone to B deficiency. Recently, molecular markers are increasingly used to accelerate selection. Mapping traits for a desirable quality, disease resistance, and nutrient uptake by molecular means has allowed considerable improvement in the efficiency of wheat breeding⁸ which can pinpoint gene location and quantitative trait loci (QTL) controlling traits of interests.

For wheat, B efficiency has been reported to be controlled by two major genes, *Bo_d1* and *Bo_d2*⁷. These were identified by assessing grain set index in F₁- hybrids and F₂-derived F₃ populations in three wheat genotypes with different levels of B efficiency; however, mapping and QTL for B efficiency have yet to be described. In the case of B toxicity, several

major additive genes have been reported to control the accumulation of B in both root and shoots in tolerant genotypes⁹. In addition, Jefferies et al¹⁰ mapped and validated genes for B toxicity tolerance on the chromosome 7B and 7D in wheat, using RFLP markers which were associated with leaf symptom and root growth. On the other hand, previous studies reported that genetic control of B efficiency entails a single gene in some plants such as celery¹¹, tomato¹², and red beet¹³. For barley, B efficiency is controlled by incomplete to completed dominance, depending on cross combination and the severity of B deficiency¹⁴. In *Brassica napus*, it is expressed as a dominant trait, controlled by a major gene¹⁵, but by additive gene action in sunflower¹⁶. A QTL for B efficiency has been identified in *Arabidopsis thaliana*¹⁷ and *Brassica napus*^{18,19}.

The objectives of this study were (1) to identify the chromosomal location(s) of genes conferring B efficiency in wheat and (2) to use QTL analysis to assess the genetic effect of the B efficiency gene(s). Understanding chromosomal location and genetic effects will facilitate breeding for B efficiency by marker-assisted selection.

MATERIALS AND METHODS

Genetic materials

Three bread wheat (*Triticum aestivum* L.) genotypes, B-inefficient Bonza (genotype *bo_d1bo_d1bo_d2bo_d2*), B-moderately inefficient SW 41 (genotype *bo_d1bo_d1Bo_d2Bo_d2*) and B-efficient Fang 60 (genotype *Bo_d1Bo_d1Bo_d2Bo_d2*)⁷ were used as parental lines to construct three mapping populations. Two F₂ populations were made from crosses between (Bonza × SW 41) BC₂ (BSW) (Bonza was used as the recurrent parent and SW 41 as *Bo_d2*-donor parent) and Fang 60 × Bonza (FB).

Screening for response to B

Boron efficiency evaluation was made with GSI (percentage grain set in the first two florets of 10 central spikelets²⁰) in parents and their F₂-derived F₃ families. Plants were grown in sand culture in earthenware pots (0.3 m diameter, 0.3 m deep) containing washed quartz river sand with undetectable B. The sand substrate contained no added B (B0) as described by Jamjod et al⁷. Seeds were pre-germinated on moist filter paper in Petri dishes and stored at room temperature for two days and transplanted at 10 plants/pot for F₂ and 11 plants/family/pot for F₃ with one plant of Bonza as a control at the centre of the pot. There were also six pots of each parent with 10 plants/pot. Plants

in each pot were watered twice daily with 1.0 l of complete nutrient solution containing 1000 μM CaCl₂, 250 μM MgSO₄, 500 μM KH₂PO₄, 10 μM Fe-EDTA, 250 μM K₂SO₄, 1 μM MnSO₄, 0.5 μM ZnSO₄, 0.2 μM CuSO₄, 0.1 μM CoSO₄, 0.1 μM Na₂MoO₄ (modified from Broughton and Dilworth²¹), and 5000 μM KNO₃.

Phenotyping for B efficiency

Parents and F₂s of all crosses were grown in sand culture as above, but with 10 μM B (B10) added to the nutrient solution. At tillering, leaf samples from each plant were collected and kept in silica gel for simple sequence repeat (SSR) analysis. At maturity, each F₂ plant was harvested separately, and the progeny represented each F₃ family. The number of families from each cross were 70 for BSW and 126 for FB. Response to B was evaluated in the F₃ generation and F₃ families from the two crosses were grown in sand culture without added B (B0). Each pot contained one family with 11 plants/family. Six pots of each parent were included as controls. At maturity, two spikes from each plant were collected for GSI determination. Frequency distributions were drawn to display segregation for B efficiency in terms of GSI (%) in F₃ populations. Mean, range, and variance within family related to those of parents were calculated to indicate the variation induced by B deficiency in each cross. The significant difference between means of families within each cross was assessed using the least significant difference (LSD) at 95% confidence.

SSR analysis

The DNA of each leaf sample of F₂ individuals was extracted using the CTAB method²². PCR and fragment detection were performed as described²³. DNA amplification was carried out using 50 ng/μl of DNA from each sample. Denaturation was induced by heating to 94 °C, and published annealing temperatures were used for each marker. Finally, the temperature was shifted to 72 °C. The cycle was then repeated 30–35 times (30–35 cycles). Annealing temperatures of each marker used touchdown cycling (the annealing temperature was decreased by one degree every cycle). Fragments of PCR products were identified and separated on 8% polyacrylamide gel electrophoresis (PAGE), run at 80 V, 400 mA, for 14–17 h overnight and visualized by ethidium bromide staining. Three parents, Bonza, SW 41, and Fang 60, were screened for polymorphism at 787 SSR markers. Polymorphic markers between parents were selected for each cross and then screened in the F₂ progenies.

Bulked segregant analysis

Bulked segregant analysis²⁴ was performed with polymorphic markers to find markers linked to the trait. For each cross, two bulks of DNA representing the 6–12 plants with the highest and the lowest GSI were formed. Polymorphic markers between the bulks were selected and screened among individuals of each bulk. Markers identified as potential linked markers in individuals from the bulks were then used for the final screening of F₂ individuals.

QTL analysis

Goodness of fit between the expected and observed segregation ratios was tested by χ^2 analysis. Markers that skewed from the expected distribution were omitted from the analysis. Single factor ANOVA was performed to compare marker classes and phenotypic means to describe locus effects. Significant difference ($P < 0.05$) was determined using SX release 8.0 (Analytical software, Tallahassee, USA). Linkage maps were constructed and QTL analysis was performed by MAP MANAGER QTX b20²⁵ to establish a map and identify associations between markers and the B efficiency trait. Recombination frequencies were converted using the Kosambi mapping function²⁶. Significant QTL were accepted with the logarithm of odds (LOD) threshold at 3.0 ($P = 0.001$) to indicate the marker to be tightly linked with the trait²⁷.

RESULTS

Evaluation for B efficiency

The three parents and two F₃ populations showed a large range of responses to low B in sand culture (Table 1). The range in GSI of Bonza, SW 41, and Fang 60 were 26–49, 75–83, and 98–100%, respectively. Mean GSI of F₂-derived F₃ families were within the range of their parents. Within line variance of B inefficient Bonza was 13–60, variance of B efficient Fang 60 was 1–8 whereas variance of moderately inefficient SW 41 was 50–217. Within family variances of F₃ varied from 0–1897.

Variation in GSI was observed within all mapping populations. There was a continuous distribution of GSI values with a large range of response to B deficiency in the crosses FB and BSW (Fig. 1).

SSR analysis

Among the 787 markers tested, three parents, Bonza, SW 41, and Fang 60, differed in about 344–380 markers (44–48%) depending on the pair being compared. SSRs revealing polymorphisms between two bulks and the individual plants are shown in Table 2. In

Table 1 Range of mean GSI (%) and variance within family of parents and F₂-derived F₃ populations. Values are based on 11 plants per family.

Genotypes	N	GSI (%)			Variance		
		min	mean	max	min	mean	max
Parents							
Bonza (I)	6	26	40	49	13	39	60
SW 41 (MI)	6	75	78	83	50	91	217
Fang 60 (E)	6	98	98	100	1	4	8
F₃ populations							
(Bonza × SW 41) BC ₂ F ₃	70	26	80	98	0	281	1137
(Fang 60 × Bonza) F ₃	126	30	81	100	0	420	1897

N = Number of parental lines or F₃ families; I = Inefficient, MI = Moderately Inefficient, E = Efficient.

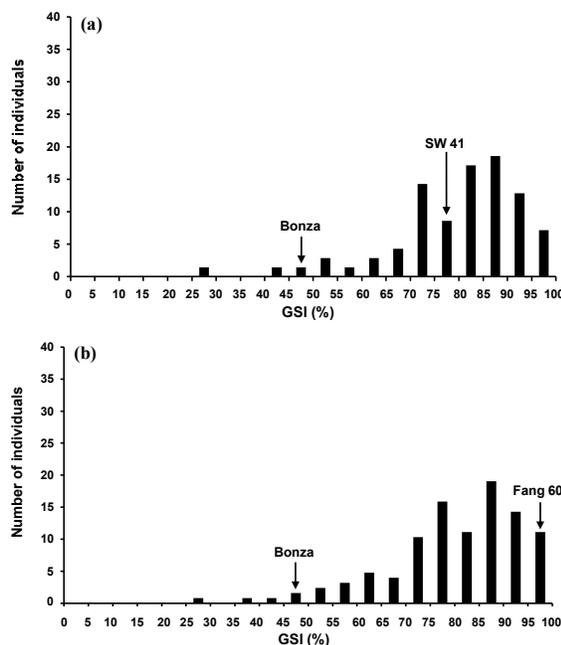


Fig. 1 Frequency distributions of mean GSI (%) in F₂-derived F₃ families and their parents grown in sand culture without added B. Mean and variance (in parentheses) presented for F₃ and their parents. (a) (Bonza × SW 41) BC₂F₃, 80(281); and (b) (Fang 60 × Bonza) F₃, 81(420). Parents: Bonza, 40(39); SW 41, 78(91); and Fang 60, 98(4). Data were transformed by arcsine transformation.

the BSW cross, eight potentially linked markers were found and that distributed on chromosomes 2B, 3D, 4D, and 7B. In the FB cross, there were four potential linked markers, gdm35 (chromosome 2D),

Table 2 Allele patterns between parents and bulks (BS and BT) and between individuals within bulks detected by eight polymorphic markers in (Bonza \times SW 41) BC₂F₃ and four markers in (Fang 60 \times Bonza) F₃ crosses. The number of individuals from the bulks of each cross that showed an allele different from their parents is shown.

P1 \times P2	Marker	Chromosome	Number of individuals									
			Parents		Bulk		BS			BT		
			P1	P2	BS	BT	+	+/-	-	+	+/-	-
Bonza \times SW 41	barc200	2BS	-	+	-	+			6	3		7
	gwm120	2BL	-	+	-	+	1		5	2		8
	gwm52	3DL	-	+	-	+			6	3		7
	gwm341	3DL	-	+	-	+			6	3		7
	gwm192	4DL	-	+	+	-	6					10
	gwm165	4DL	-	+	+	-	4	2			3	7
	gwm131	7BL	-	+	-	+			6	3		7
	gwm111	7BL 7DS	-	+	-	+			6	3		7
Fang 60 \times Bonza	gdm35	2DS	+	-	-	+	4	5	3	5	7	
	gwm513	4BS	+	-	-	+	4	6	1	4	5	1
	gwm192	4DL	+	-	+/-	+/-	2	7	3	3	8	
	gwm165	4DL	+	-	+/-	+/-	2	6	4	4	6	

BS = Bulk sensitive, BT = Bulk tolerant; P1 and P2 = Parent 1 and parent 2 each cross; + = presented as homozygous efficient, - = presented as homozygous inefficient, +/- = presented as both parents (heterozygote).

gwm513 (chromosome 4B), gwm192 and gwm165 (chromosome 4D). The segregation of gwm192 and gwm165 deviated from the expected 1:2:1 ratio in the FB-F₂ population. In the BSW-F₂, the segregation of only two markers, gwm192 and gwm165, was consistently with a 1:2:1 ratio. PCR product of bulk and individuals of BSW cross amplified with gwm192 and gwm165 are shown in Fig. 2.

QTL analysis

ANOVA on each marker (gwm192 and gwm165) in Table 3 was performed to identify the association between markers and GSI of F₂-derived F₃ families. GSI and marker genotypes (homozygous P1 type, heterozygous and homozygous P2 type) were compared. A significant difference in GSI between marker genotypes was found in BSW for both gwm192 and gwm165. In this cross, Bonza marker alleles (P1) at both loci were associated with high GSI and significantly higher than SW 41 marker alleles (P2), while heterozygotes were closest to the high GSI type.

By QTL analysis, the QTL for B efficiency was found to be flanked by two SSR markers, gwm192 and gwm165 in BSW cross (Table 4). Twenty one percent of the total variation in GSI for B efficiency was explained by this QTL region with a dominance and additive effect of 5.6 and 9.5, respectively. The ratio of dominance effect was relatively high (0.6) for the QTL in this region which indicated partially dominant gene action. This QTL is located on the

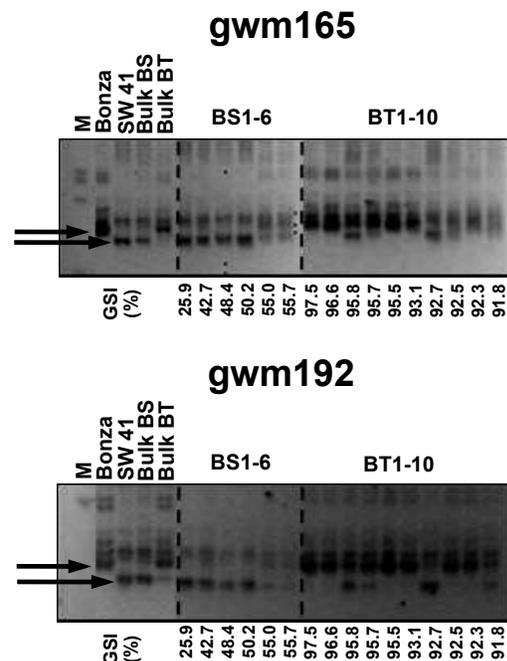


Fig. 2 PCR product of DNA amplified with linked markers, gwm165 and gwm192, in F₂ bulks of Bonza \times SW 41 population. The first lane (M) was 100-bp ladder followed by parents; Bonza (inefficient), SW 41 (moderately inefficient), bulk sensitive (BS) and bulk tolerant (BT). PCR product was run on 8% PAGE, 80 V, 400 mA, 999 minutes, run overnight.

Table 3 Mean effect of the presence of either the P1 or P2 marker allele on GSI (%) of (Bonza × SW 41) F₃ and (Fang 60 × Bonza) F₃ mapping populations grown at low B.

P1 × P2 / SSR marker	Marker allele	GSI (%)	Number of lines within class	SE	<i>P</i>	LSD _{0.05}
(Bonza × SW 41) BC ₂ F ₃						
gwm192	P1	85.0 ^a	25	2.6	0.013	4.4
	H	79.9 ^{ab}	26	2.5		
	P2	73.2 ^b	19	2.9		
gwm165	P1	83.8 ^a	23	2.7	0.019	4.3
	H	81.0 ^a	30	2.4		
	P2	71.8 ^b	16	3.2		
(Fang 60 × Bonza) F ₃						
gwm192	P1	82.8	20	3.1	0.372	
	H	81.1	79	1.6		
	P2	77.2	23	2.9		
gwm165	P1	83.3	23	2.9	0.176	
	H	75.7	82	1.5		
	P2	80.1	21	3.0		

P1 = Parent 1, H = Heterozygous, P2 = Parent 2; SE = Standard error of mean from individuals in each class. Different letter separated significant difference between mean GSI in each row.

Table 4 QTL analysis for chromosome 4D associated with GSI (%) of (Bonza × SW 41) BC₂F₃ populations by MAP MANAGER QTX b20 using LOD threshold of 3.0 (*P* = 0.001). Phenotypic variation explained by marker interval for GSI presented in R² (%).

Marker interval	Distance (cM)	LOD	R ²	a [†]	d [†]	[a/d] [†]
(Bonza × SW 41) BC ₂ F ₃						
gwm192–gwm165	7.6	3.54	21	9.5	5.6	0.6
(Fang 60 × Bonza) F ₃						
gwm192–gwm165	4.3	0.98	4	-4.9	-0.2	24.5

[†] a and d represent additive effect and dominance effect of main effect QTL. QTL was classified according to their [a/d] (degree of dominance).

long arm of chromosome 4D between gwm165 and gwm192, 6 cM from gwm192 with 3.54 of LOD. A partial linkage map for *Bo_d2* was constructed from this backcross population (Fig. 3). The chromosome length of 4D on which the QTL for *Bo_d2* was located on was 145.1 cM. No QTL was detected in the F₃-FB cross.

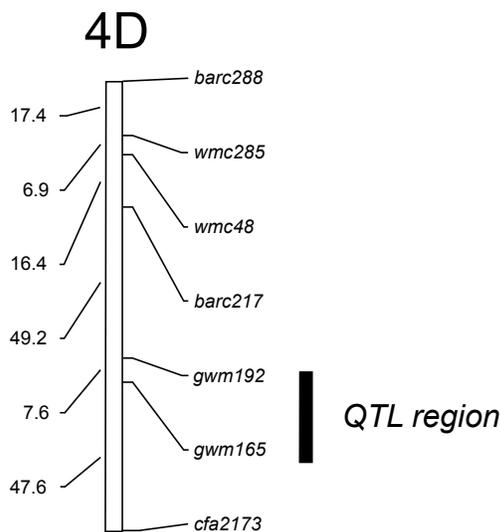


Fig. 3 A partial map and the position of QTL associated with *Bo_d2* on chromosome 4D based on GSI (%) of (Bonza × SW 41) BC₂F₃. Marker names are given on the right side. The left side indicates distance between markers in centimorgan (cM).

DISCUSSION

Genetic control of B efficiency

It has been observed and confirmed that reproductive process is extremely sensitive to boron (B) deficiency, which limits grain set and grain yield in wheat. Incorporation of B efficiency gene(s) in wheat breeding would be highly desirable in regions with low B soils⁶. This study has again demonstrated that reproductive process exhibited in terms of GSI (%) was efficient to use as criteria index for B efficiency as previously reported^{6,7,20}. In this study we showed that genetic variation in B efficiency, quantified in GSI (%), existed in all mapping populations. The distribution of the mean GSI of F₃ families for the two crosses was skewed in the direction of the more efficient parent, indicative of efficiency being dominant. The GSI was depressed in B inefficient progenies, whereas efficient progenies set grain normally. Response to B deficiency in F₃ of Bonza × SW 41 differed at one B efficient locus, whereas F₃ of Fang 60 × Bonza differed at two B efficient loci in the same way as indicated by Jamjod et al⁷. However, segregation of GSI (%) in Bonza × SW 41 was smaller than in Jamjod et al⁷ but with continuous distribution. Response of GSI (%) of progenies varies according to B treatment, the parental combination and environment factors^{7,28}.

Boron efficiency has been reported to be qualitatively inherited and under the control of a single

gene for a number of species including celery, tomato, and red beet^{11–13}. Jamjod et al²⁹ reported that both additive and dominant gene effects were involved in controlling B efficiency in bread wheat but more complicated genetics of B efficiency than a single gene was suggested for wheat³⁰.

QTL analysis

One QTL for B efficiency in wheat was identified and mapped in the Bonza × SW 41 cross in this study. The long arm of chromosome 4D was identified as the region associated with the *Bo_d2* gene from bulked segregant analysis through QTL analysis. That region accounted for 21% of phenotypic variance explained in the population. This QTL was associated with improved grain set in terms of GSI on B-deficient soil for progenies which were as efficient as the SW 41 parent. However, expression of the trait of progenies from only one cross (Bonza × SW 41) was found to have strong association with the marker, whereas in Fang 60 × Bonza, there was a weak association shown by QTL analysis.

A region of chromosome 4D in wheat appears to be involved in B efficiency and uptake and tolerance to other toxicities; for example, K⁺/Na⁺ discrimination^{31,32}, salt tolerance³³, and aluminium tolerance^{34,35}. Miftahudin et al³⁶ reported that the polymorphism rate for 4DL is extremely low, making further analysis in wheat difficult. Thus they exploited the rice/rye syntenic relationship for Al tolerance to develop polymorphic markers to be used in segregating F₂ populations in wheat. Although the D genome contained a number of functional genes in wheat³⁷, low marker polymorphism has impeded genetic studies for the 4D chromosome^{38,39}. Thus further markers such as single nucleotide polymorphism should be used in order to locate other QTL for B efficiency genes including *Bo_d1*. Previous research also demonstrated that other related species such as rye contain the genes responsible for nutrient efficiency, as in the case of Cu (4B/5R wheat-rye translocation)⁴⁰. Furthermore, in barley, chromosome 4H was associated with Mn efficiency⁴¹ and barley-4H also compensates for wheat chromosome 4D for drought stress⁴².

Recently, the QTL for B efficiency were examined in *Arabidopsis*¹⁷ and *Brassica*^{18,19} with suggested benefits in selection of Cruciferae species. In *B. napus*, B efficiency is expressed as a dominant trait and controlled by a major gene in F₂ segregating populations¹⁵ and in F_{2:3} populations⁴³ in terms of seed yield which is tightly linked to growth period (bolting dates and maturity dates). Xu et al¹⁸ also identified a

B-efficient gene in *B. napus*, *BE1*, on linkage group 9 that was found to be linked with one QTL for bolting date, *bd9b*, by using RFLP and AFLP markers. After that, Shi et al⁴⁴ verified that *BE1* is the major gene controlling B efficiency by QTL mapping. Moreover, Zhao et al¹⁹ found new B-efficient locus, *BnBE2*, located on linkage group N14, which is associated with seedling growth. In *Arabidopsis thaliana*, B uptake efficiency, revealed by *BORI* gene transporter, contributed to higher efficiency in xylem loading in low B stress⁴⁵.

Mechanisms involved in B efficiency

In genetic studies of tolerance to mineral nutrient deficiencies, selection criteria may have important implications. Different selection criteria may identify different mechanisms. In case of B efficiency, the extent of variation for each genotype or plant species was considered with respect to the physiological nature of the efficiency mechanisms, the genetic basis of inheritance, screening techniques and the practical implications of the genotypic variations³⁰.

Mechanisms for B efficiency differ with the genotypes being compared and with the intensity of deficiency. Generally, B uptake and use in plants plays a major role in overall B efficiency. In case of GSI, the mechanisms involved include greater B uptake and distribution. Nachiangmai⁴⁶ reported that Fang 60 had a greater ability to distribute B into the developing ear under low B during the critical stage of microsporogenesis than SW 41 and suggested that, this is the main mechanism for B efficiency in wheat. Furthermore, a study with ¹⁰B found that Fang 60 was able to retranslocate B from older to younger tissues after B supply to the roots was withdrawn, whereas Bonza did not have this ability⁴⁷. Mechanisms controlling B efficiency in wheat in terms of grain set was suggested to be related to the ability to supply B for reproduction, other mechanisms and genes may be responsible for other phenotypic responses. For example, in cereals such as wheat, grain set is the key trait involved in, so the GSI is the phenotypic expression of B efficiency. In *B. napus*, seed yield, maturity and bolting date are the key traits that are used for screening B efficient genotype¹⁸. It is as yet unclear which mechanism is conferring B efficiency as expressed by high GSI and used as trait for genetic studies described here.

SSR polymorphism

Overall, SSR analysis in this study showed high polymorphisms between three parents (43%). The highest polymorphisms existed between Fang 60 and Bonza

parents and between Bonza and SW 41 parents. The levels of polymorphism reflected genetic similarity of the parental lines and their origins. Boron efficient genotypes are more frequent in wheat germplasm from Thailand⁴⁸, Nepal⁴⁹, and India⁵⁰ where B deficiency in wheat has been identified and active selection for B efficiency has been conducted. Fang 60 (efficient) and SW 41 (moderately inefficient) both originated from CIMMYT, were selected and released in Thailand, whereas Bonza was from Colombia.

In this study, progress has been made in developing markers for B efficiency associated with *Bo_d2*. However, linkage analysis could not locate the other B efficient gene (*Bo_d1*). Additional markers should be examined. Further study of *Bo_d1* will enhance selection and breeding of genotypes with B efficiency in the same range as Fang 60. Improvement of agronomic performance of crop varieties is influenced mainly by complex quantitative traits for yield and quality. Molecular marker technology has made it feasible to identify and localize the contributing genetic factors as quantitative trait loci (QTLs) and to use these QTLs for crop improvement⁵¹. QTL associated with the B efficiency gene identified in this study should bring us closer to breeding wheat for B efficiency on low B soils, although the controlling mechanism for B efficiency is still to be identified.

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REFERENCES

- Sillanpää M (1982) *Micronutrients and Nutrient Status of Soils: A Global Study*, FAO Soils Bulletin 48, Food and Agriculture Organization of the United Nations, Rome.
- Rerkasem B, Nirantrayagul S, Jamjod S (2004) Increasing boron efficiency in international bread wheat, durum wheat, triticale and barley germplasm will boost production on soils low in boron. *Field Crop Res* **86**, 175–84.
- Shorrocks VM (1997) The occurrence and correction of boron deficiency. *Plant Soil* **193**, 121–48.
- Budhathoki CB, Subedi M, Subedi KD (1997) Variation in sterility among wheat (*Triticum aestivum* L.) genotypes in response to boron deficiency in Nepal. *Euphytica* **95**, 21–6.
- Ahmed M, Jahiruddin M, Mian MH (2007) Screening of wheat genotypes for B efficiency. *J Plant Nutr* **30**, 1127–38.
- Rerkasem B, Jamjod S (1997) Boron deficiency induced male sterility in wheat (*Triticum aestivum* L.) and implications for plant breeding. *Euphytica* **96**, 257–62.
- Jamjod S, Nirantrayagul S, Rerkasem B (2004) Genetic control of boron efficiency in wheat (*Triticum aestivum* L.). *Euphytica* **135**, 21–7.
- Gupta PK, Varshney RK, Sharma PC, Ramesh B (1999) Molecular markers and their applications in wheat breeding. *Plant Breed* **18**, 369–90.
- Paull JG, Rathjen AJ, Langridge P (1993) Location of genes controlling boron tolerance of wheat. In: *Proceedings of the 8th International Wheat Genetics Symposium*, Beijing, China, pp 1065–9.
- Jefferies SP, Pallota MA, Paull JG, Karakousis A, Kretschmer JM, Manning S, Islam AKMR, Langridge P, Chalmers KJ (2000) Mapping and validation of chromosome regions conferring boron toxicity tolerance in wheat (*Triticum aestivum*). *Theor Appl Genet* **101**, 767–77.
- Pope DT, Munger HM (1953) The inheritance of susceptibility to boron deficiency in celery. *Proc Amer Soc Hort Sci* **61**, 163–72.
- Wall JR, Andrus CF (1962) The inheritance and physiology of boron response in tomato. *Am J Bot* **49**, 758–62.
- Tehrani G, Munger HM, Robinson RW, Shannon S (1971) Inheritance and physiology of response to low boron in red beet (*Beta vulgaris* L.). *J Am Soc Hort Sci* **96**, 226–30.
- Buaphan W (2002) Response of barley genotypes and their F₁ hybrids to boron deficiency. MSc thesis, Graduate School, Chiang Mai Univ, Chiang Mai, Thailand.
- Xu F, Wang Y, Ying W, Meng J (2002) Inheritance of boron nutrition efficiency in *Brassica napus*. *J Plant Nutr* **24**, 901–12.
- Blamey FPC, Vermuelen WJ, Chapman J (1984) Inheritance of boron status in sunflower. *Crop Sci* **24**, 43–6.
- Zeng C, Han Y, Shi L, Peng L, Wang Y, Xu F, Meng J (2008) Genetic analysis of the physiological response to low boron stress in *Arabidopsis thaliana*. *Plant Cell Environ* **31**, 112–22.
- Xu F, Wang Y, Meng J (2001) Mapping boron efficiency gene(s) in *Brassica napus* using RFLP and AFLP markers. *Plant Breed* **120**, 319–24.
- Zhao H, Shi L, Duan X, Xu F, Wang Y, Meng J (2008) Mapping and validation of chromosome regions conferring a new boron-efficient locus in. *Mol Breed* **22**, 495–506.
- Rerkasem B, Lonergan JF (1994) Boron deficiency in two wheat genotypes in a warm, subtropical region. *Agron J* **86**, 887–90.

21. Broughton WJ, Dilworth MJ (1971) Control of leg-haemoglobin synthesis in snake beans. *Biochem J* **125**, 1075–80.
22. Doyle JJ, Doyle JL (1987) A rapid DNA isolation procedure for small quantities of fresh leaf tissue. *Phytochem Bull* **19**, 11–5.
23. Cakir M, Appels R, Carter M, Loughman R, Francki M, Li C, Johnson J, Bhave M, et al (2003) Accelerated wheat breeding using molecular markers. In: *Proceedings of the 10th International Wheat Genetics Symposium*, Vol 1. Istituto Sperimentale per la Cerealicoltura, Roma, Italy, pp 117–20.
24. Michelmore RW, Paran I, Kesseli RV (1991) Identification of markers linked to disease-resistance genes by bulked segregant analysis: a rapid method to detect markers in specific genomic regions by using segregating populations. *Proc Natl Acad Sci USA* **88**, 9828–32.
25. Manly KF, Cudmore RH Jr, Meer JM (2001) Map Manager QTX, cross-platform software for genetic mapping. *Mamm Genome* **12**, 930–2.
26. Kosambi DD (1944) The estimation of map distances from recombination values. *Ann Eugen* **12**, 172–5.
27. Lander ES, Botstein D (1989) Mapping Mendelian factors underlying quantitative traits using RFLP linkage maps. *Genetics* **121**, 185–99.
28. Bell RW, Dell B (1995) Environmental factors affecting boron deficiency. In: Bell RW, Rerkasem B (eds) *Proceedings of a Workshop on Causes of Sterility in Wheat*, 25–28 July 1994 Chiang Mai, Thailand, pp 95–106.
29. Jamjod S, Mann CE, Rerkasem B (1993) Combining ability of the response to boron deficiency in wheat. In: Randall PJ, Delhaize E, Richards RA, Munns R (eds) *Genetic aspects of plant mineral nutrition*. *Dev Plant Soil Sci* **50**, 359–62.
30. Rerkasem B, Jamjod S (1997) Genotypic variation in plant response to low boron and implications for plant breeding. *Plant Soil* **193**, 169–80.
31. Allen GJ, Jones RGW, Leigh RA (1995) Sodium transport measured in plasma membrane vesicles isolated from wheat genotypes with differing K^+/Na^+ discrimination traits. *Plant Cell Environ* **18**, 105–15.
32. Dubcovsky J, Santa María G, Epstein E, Luo M-C, Dvořák J (1996) Mapping of K^+/Na^+ discrimination locus *Kna1* in wheat. *Theor Appl Genet* **92**, 448–54.
33. Gao M-J, Travis RL, Dvořák J (1998) Mapping of protein polymorphisms associated with the expression of wheat *Kna1* locus under NaCl stress. In: Slinkard AE (ed) *Proceedings of the 8th International Wheat Genetics Symposium*, Vol. 3, Univ Extension Press, Univ of Saskatchewan, Saskatoon, pp 105–7.
34. Riede CR, Anderson JA (1996) Linkage of RFLP markers to an aluminium tolerance gene in wheat. *Crop Sci* **36**, 905–9.
35. Raman H, Zhang K, Cakir M, Appels R, Garvin DF, Maron Lyza G, Kochian LV, Moroni JS, et al (2005) Molecular characterization and mapping of *ALMT1*, the aluminium-tolerance gene of bread wheat (*Triticum aestivum* L.). *Genome* **48**, 781–91.
36. Miftahudin MA, Milla R, Ross K, Gustafson JP (2003) Mapping aluminum tolerance in cereals using rice/rye synteny. In: Tuberosa R, Phillips RL, Gale M (eds) *Proceedings of the International Congress "In the Wake of the Double Helix: From the Green Revolution to the Gene Revolution"*. 27–31 May 2003, Bologna, Italy, pp 207–15.
37. Gill BS, Appels R, Botha-Oberholster A-M, Buell CR, Bennetzen JL, Chalhoub B, Chumley F, Dvořák J, Iwanaga M (2004) A workshop report on wheat genome sequencing: international genome research on wheat consortium. *Genetics* **168**, 1087–96.
38. Chalmers KJ, Campbell AW, Kretschmer J, Karakousis A, Henschke PH, Pierens S, Harker N, Pallotta M, et al (2001) Construction of three linkage maps in bread wheat, *Triticum aestivum*. *Aust J Agr Res* **52**, 1089–119.
39. Kammholz SJ, Campbell AW, Sutherland MW, Hollamby GJ, Martin PJ, Eastwood RF, Barclay I, Wilson RE, et al (2001) Establishment and characterization of wheat genetic mapping populations. *Aust J Agr Res* **52**, 1079–88.
40. Schlegel R, Kynast R, Schwarzacher T, Römheld V, Walter A (1993) Mapping of genes for copper efficiency in rye and the relationship between copper and iron efficiency. *Plant Soil* **154**, 61–5.
41. Pallotta MA, Graham RD, Langridge P, Sparrow DHB, Barker SJ (2000) RFLP mapping of manganese efficiency in barley. *Theor Appl Genet* **101**, 1100–8.
42. Molnár I, Linc G, Dulai S, Nagy ED, Molnár-Láng M (2007) Ability of chromosome 4H to compensate for 4D in response to drought stress in a newly developed and identified wheat-barley 4H (4D) disomic substitution line. *Plant Breed* **126**, 369–74.
43. Shi L, Wang Y-H, Nian F-Z, Lu J-W, Meng J-L, Xu F-S (2009) Inheritance of boron efficiency in oilseed rape. *Pedosphere* **19**, 403–8.
44. Shi L, Liu J, Meng JL, Xu FS, Wang YH (2005) Locus verification for the boron efficiency gene *BE1* in *Brassica napus*. In: Li CJ, Zhang FS, Dobermann A, Hinsinger P, Lambers H, Li XL, Marschner P, Maene L, et al (eds) *Plant Nutrition for Food Security, Human Health and Environmental Protection*. Tsinghua Univ Press, Beijing, pp 158–9.
45. Miwa K, Takano J, Fujiwara T (2006) Improvement of seed yields under boron-limiting conditions through over expression of *BOR1*, a boron transporter for xylem loading, in *Arabidopsis thaliana*. *Plant J* **46**, 1084–91.
46. Nachiangmai D (2003) The mechanism controlling boron efficiency in wheat genotypes. PhD thesis, Graduate School, Chiang Mai Univ, Chiang Mai, Thailand.
47. Konsaeng S (2007) Boron mobility in tropical crop species. PhD thesis, Graduate School, Chiang Mai Univ, Chiang Mai, Thailand.
48. Rerkasem B, Netsangtip R, Lordkaew S, Cheng C (1993) Grain set failure in boron deficient wheat. *Plant*

- Soil* **155/156**, 309–12.
49. Subedi KD, Budhathoki CB, Subedi M, Tuladhar JK (1993) Survey and research report on wheat sterility problem (1992/93). In: LARC working paper no.93/49. Nepal, Lumle Agricultural Research Centre.
 50. Tandon JP, Naqvi SMA (1992) Wheat varietal screening for boron deficiency in India. In: Mann CE, Rerkasem B (eds) *Wheat Special Report No. 11: Boron Deficiency in Wheat*. CIMMYT, Mexico, DF, pp 76–8.
 51. Langridge P, Chalmers K (2004) The principle: identification and application of molecular markers. In: Lörz H, Wenzel G (eds) *Biotechnology in Agriculture and Forestry, Vol. 55: Molecular Marker Systems in Plant Breeding and Crop Improvement*. Springer-Verlag, Berlin, Heidelberg, pp 3–22.