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Mapping QTLs associated with grain yield and yield-related traits under aluminium stress in bread wheat

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Table S1. Physical and chemical properties of the soil used for evaluation of wheat lines and meteorological characteristics of the experimental site in normal and Al stress trials

Soil property	2014-2015 (before planting)	2014-15 (after application of Al ³⁺)
Soil Texture	Clay loam	Clay loam
Sand (%)	23.72	25.72
Silt (%)	46.00	38.00
Clay (%)	30.28	36.28
pH	6.10	5.70
EC (dS.m ⁻¹)	1.51	0.39
N (%)	0.044	0.041
P (mg/kg)	14.00	19.00
K (mg/kg)	270.00	230.00
Na (mg/kg)	75.00	37.50
Ca (meq.lit ⁻¹)	11.67	5.67
Mg (meq.lit ⁻¹)	7.66	1.00
Meteorology data		
Year	2014-15 (Normal and Stress)	2015-16 (Normal and Stress)
Rainfall (mm)	159.3	136.4
Average relative humidity (%)	41.4	40.9
Average minimum temperature (°C)	12.3	11.6
Average maximum temperature (°C)	27.7	26.9
Pan evaporation (mm)	5.4	5.6

Table S2. Mean comparison of agronomic and physiological traits of the SeriM82/Babax population under normal and aluminum stress conditions in 2014-2015 and 2015-2016

growing seasons

Trait	(2014-2015)		(2015-2016)	
	Normal	Stress	Normal	Stress
DHE	113 ^a	112 ^a	100 ^a	98 ^b
DMA	153 ^a	153 ^a	144 ^a	142 ^b
SPAD	21.72 ^a	24.52 ^a	26.63 ^a	24.80 ^b
CTm	31.99 ^b	35.81 ^a	33.71 ^b	39.98 ^a
ROL	2.61 ^b	3.01 ^a	2.57 ^b	2.74 ^a
PHT	104 ^a	98.19 ^b	89.91 ^a	83.80 ^b
TSN	18.42 ^b	18.79 ^a	18.80 ^a	18.11 ^b
FSN	8.99 ^b	11.85 ^a	3.46 ^a	3.38 ^a
GSP	53.45 ^a	52.42 ^a	66.60 ^a	63.13 ^b
TGW	41.34 ^a	40.90 ^a	45.09 ^a	45.34 ^a
GYLD	578 ^a	475 ^b	917 ^a	744 ^b
Al	0.30 ^b	0.93 ^a	0.22 ^b	0.50 ^a

Means in each column by similar letter(s) are not significantly different ($\alpha=5\%$)

DHE: Days to heading, DMA: Days to maturity, SPAD: Chlorophyll content unit, CTm: Canopy temperature at seed maturity stage ($^{\circ}\text{C}$), ROL: Leaf rolling, PHT: Plant height (cm), TSN: Total spikelet number per spike, FSN: Fertile spike number per plant, GSP: Grain number per spike, TGW: Thousand grain weight (g), GYLD: Grain yield (g) and Al: Aluminum amount (mg kg^{-1})

Table S3. Best Linear Unbiased Estimates (BLUEs) of traits in SeriM82/Babax wheat population in four trials

trait	Normal trial			Aluminum stress trial		
	SeriM82	Babax	Range among RILs	SeriM82	Babax	Range among RILs
2014-2015						
DHE	114	119	108-118	111	109	109-117
DMA	153	154	149-158	156	152	149-158
SPAD	19.00	26.04	14.98-28.97	20.58	30.32	12.59-34.92
CTm	32.97	31.39	27.30-36.54	33.31	36.96	31.55-41.16
ROL	3.48	2.44	1.05-4.51	4.43	2.48	1.53-5.07
PHT	107	103	92-117	104	96.51	86.30-109
TSN	17.66	18.63	16.14-20.98	19.78	18.27	15.88-21.45
FSN	8.36	10.06	6.19-12.08	12.37	14.33	8.82-16.32
GSP	54.85	54.69	36.43-70.09	59.58	50.71	40.68-71.24
TGW	36.56	42.93	34.53-49.79	35.71	42.64	30.88-70.96
GYLD	479	653	253-907	402	359	218-747
Al	0.37	0.38	0.07-0.71	1.59	0.79	0.22-3.37
2015-2016						
DHE	101	99.70	97-102	98.58	96.93	96.47-99.99
DMA	145	144	140-147	141	143	140-145
SPAD	21.75	29.40	16.23-39.83	15.10	29.53	13.32-42.50
CTm	33.06	31.49	27.43-40.72	40.02	39.42	35.99-45.18
ROL	3.50	2.50	1.00-4.50	2.38	4.55	0.97-4.55
PHT	91.81	92.09	53.81-100	79.55	84.67	73.92-93.80
TSN	18.28	19.08	11.02-21.51	16.83	17.29	13.88-21.10
FSN	2.96	3.03	2.41-4.93	2.86	3.27	2.14-4.88
GSP	76.27	68.74	50.01-84.19	55.75	69.40	46.71-79.37
TGW	40.37	45.69	37.79-54.67	40.71	44.00	36.20-52.35
GYLD	1180	980	604-1116	760	785	247-1016
Al	0.24	0.18	0.01-1.07	0.50	0.64	0.18-1.82

DHE: Days to heading, DMA: Days to maturity, SPAD: Chlorophyll content unit, CTm: Canopy temperature at seed maturity stage ($^{\circ}$ C), ROL: Leaf rolling, PHT: Plant height (cm), TSN: Total spikelet number per spike, FSN: Fertile spike number per plant, GSP: Grain number per spike, TGW: Thousand grain weight (g), GYLD: Grain yield (g) and Al: Aluminum amount (mg kg^{-1})

Table S4. Detected QTLs for agronomic and physiological traits by composite interval mapping in SeriM82/Babax wheat population under normal and aluminum stress conditions in 2014-2015 and 2015-2016 growing seasons

Plant traits	QTL name	Markers interval	Nearest marker	QTL position ^a	QTL interval (95%)	LOD score ^b	Allele	Additive effect	R ^{2c}	Total R ^{2d}
Normal environment										
DHE	<i>QDHE-2B.NO16</i>	2B-aag/ctg-12-2B-act/ctc-11	2B-act/ctc-11	38.90	37.90-47.70	2.87	B	-0.30	6.52	21.86
	<i>QDHE-4B.NO15</i>	4B-wPt-1708-4B-wmc048a	4B-wPt-1708	56.90	49.90-59.6	3.11	B	-0.49	7.50	17.30
	<i>QDHE-4B.NO15</i>	4B-aac/ctc-9-4B-wPt-5606	4B-aac/ctc-9	64.40	59.60-68.20	2.59	B	-0.50	7.75	17.55
DMA	<i>QDMA-1A.NO16</i>	1A-aag/cta-8-1A-agg/cac-6	1A-aag/cta-8	42.40	38.00-51.80	4.05	B	-0.39	9.59	26.95
	<i>QDMA-6B.NO16</i>	6B-aca/cac-3-6B-gwm0626	6B-gwm0626	77.41	76.40-78.70	4.69	B	-0.57	10.41	25.76
	<i>QDMA-7A.NO15</i>	7A-gwm0276-7A-barc0049	7A-gwm0276	92.10	86.70-97.50	3.04	B	-0.52	8.52	18.60
SPAD	<i>QSPAD-6B.NO15</i>	6B-agg/ctg-8-6B-agc/cta-10	6B-agg/ctg-8	78.70	75.50-80.40	2.09	S	0.69	4.80	21.69
	<i>QSPAD-6B.NO15</i>	6B-aac/ctc-3-6B-barc0178	6B-aac/ctc-3	84.00	81.40-89.00	2.95	S	0.84	7.13	24.01
	<i>QSPAD-7A.NO15</i>	7A-gwm282-7A-aca/cag-10	7A-gwm282	77.00	70.10-83.90	3.82	B	-0.97	9.97	24.86
	<i>QSPAD-7A.NO15</i>	7A-cfa2123-7A-aca/caa-1	7A-cfa2123	85.90	83.90-90.00	2.19	B	-0.71	5.23	20.12
ROL	<i>QROL-2B.NO16</i>	2B-wPt-7320-2B-aac/cta-1	2B-aac/cta-1	9.80	1.80-21.20	2.37	B	-0.19	5.34	22.08
	<i>QROL-7A.NO16</i>	7A-wPt-5533-7A-acc/cat-9	7A-wPt-5533	4.30	0.60-5.20	3.62	B	-0.26	8.35	21.69
PHT	<i>QPHT-1D-a.NO15</i>	1D-wPt-9380-1D-barc169	1D-wPt-9380	44.80	43.90-63.90	2.49	B	-1.36	6.47	23.59
	<i>QPHT-4A.NO16</i>	4A-acc/cat-5-4A-wPt-7821	4A-wPt-7821	102.80	102.1-103.1	2.75	S	1.40	7.24	10.04
	<i>QPHT-4A.NO15</i>	4A-act/cag-4-4A-aca/cag-1	4A-aca/cag-1	106.50	106.3-109.6	2.12	B	-1.19	4.80	21.92
	<i>QPHT-6A-a.NO15</i>	6A-acg/cta-7-6A-barc0003	6A-acg/cta-7	63.20	58.70-65.90	2.78	B	-1.34	6.56	23.84
TSN	<i>QTSN-4B.NO15</i>	4B-wPt-5606-4B-cn1123	4B-wPt-5606	69.40	63.40-70.40	2.22	B	-0.26	7.01	20.46
	<i>QTSN-7A.NO15</i>	7A-gwm282-7A-aca/cag-10	7A-gwm282	77.00	67.80-83.90	2.81	S	0.28	7.72	19.28
	<i>QTSN-7A.NO15</i>	7A-cfa2123-7A-aca/caa-1	7A-cfa2123	85.90	83.90-97.40	2.52	S	0.25	6.20	17.76
FSN	<i>QFSN-1A.NO15</i>	1A-cfd0021-1A-barc0263	1A-barc0263	1.90	1.40-2.30	3.50	S	0.38	8.02	22.10
	<i>QFSN-1B.NO15</i>	1B-aca/cac-2-1B-agc/cag-5	1B-aca/cac-2	62.80	61.90-64.20	2.07	S	0.34	4.86	18.58
	<i>QFSN-3B.NO15</i>	3B-barc087-3B-aag/ctc-1	3B-barc087	104.40	102.4-119.4	2.05	S	0.41	9.04	31.14
GSP	<i>QGSP-3B.NO16</i>	3B-wPt-4412-3B-acc/ctc-8	3B-wPt-4412	33.60	17.70-44.60	3.27	B	-2.26	12.08	24.47
	<i>QGSP-3B.NO16</i>	3B-wPt-0021-3B-barc0077	3B-wPt-0021	48.60	46.50-62.80	3.78	B	-1.99	8.78	21.18
	<i>QGSP-4B.NO15</i>	4B-aac/ctc-9-4B-wPt-5606	4B-aac/ctc-9	64.40	60.40-68.40	2.65	B	-1.86	8.91	19.34
	<i>QGSP-4B.NO15</i>	4B-wPt-5606-4B-cn1123	4B-wPt-5606	69.40	68.40-70.40	2.33	B	-1.72	8.45	18.88
	<i>QGSP-6A-a.NO16</i>	6A-wmc0163-6A-aag/ctc-10	6A-wmc0163	65.90	65.70-68.90	3.47	B	-2.41	8.01	22.60
	<i>QGSP-6A-a.NO16</i>	6A-aag/ctg-8-6A-aac/ctg-1	6A-aag/ctg-8	71.50	71.00-74.50	2.90	B	-1.94	6.64	21.23
TGW	<i>QTGW-1D-a.NO15</i>	1D-acc/ctc-1-1D-wPt-7038	1D-acc/ctc-1	23.30	19.50-29.60	2.17	B	-0.71	6.84	18.09
	<i>QTGW-2A-a.NO16</i>	2A-acc/ctg-8-2A-gwm636	2A-acc/ctg-8	0.00	0.00-24.30	4.10	B	-0.09	8.98	27.05
	<i>QTGW-3B.NO16</i>	3B-acc/ctc-8-3B-wPt-8021	3B-acc/ctc-8	39.50	27.20-40.20	2.87	S	1.11	6.63	20.92
	<i>QTGW-3B.NO16</i>	3B-gwm301e-3B-wPt-0021	3B-gwm301e	44.60	40.70-47.90	3.12	S	0.81	7.17	21.20

Table S4 (Continued)

Plant traits	QTL name	Markers interval	Nearest marker	QTL position ^a	QTL interval (95%)	LOD score ^b	Allele	Additive effect	R ^{2c}	Total R ^{2d}
Normal environment										
GYLD	<i>QGYLD-4A.NO16</i>	4A-wmc048c-4A-act/cag-5	4A-wmc048c	5.00	0.00-11.10	2.07	S	27.85	6.79	20.69
	<i>QGYLD-4A.NO16</i>	4A-gha44-4A-gwm397	4A-gha44	19.20	13.70-23.70	3.27	B	-33.63	9.88	23.77
	<i>QGYLD-6A-a.NO16</i>	6A-wmc0163-6A-aag/ctc-10	6A-aag/ctc-10	66.50	65.80-71.00	2.84	B	-36.77	6.61	20.15
Al	<i>QAI-1A.NO15</i>	1A-gwm135-1A-aca/cta-2	1A-gwm135	30.40	15.90-40.20	2.27	S	0.03	5.14	21.24
	<i>QAI-2B.NO15</i>	2B-wPt-0047-2B-agc/cta-8	2B-wPt-0047	85.70	76.10-87.00	2.46	S	0.03	5.93	17.07
	<i>QAI-5A.NO15</i>	5A-agg/ctg-12-5A-barc186	5A-agg/ctg-12	40.90	40.70-51.50	2.41	S	0.03	5.48	21.24
Stress environment										
DHE	<i>QDHE-2A-a.AL15</i>	2A-acc/ctg-8-2A-gwm636	2A-acc/ctg-8	0.00	0.00-32.50	2.12	S	0.42	5.16	18.01
	<i>QDHE-4A.AL16</i>	4A-aac/caa-6-4A-aac/caa-3	4A-aac/caa-3	67.80	66.50-71.60	2.81	B	-0.21	6.65	18.90
	<i>QDHE-5A.AL15</i>	5A-agg/ctg-12-5A-barc186	5A-agg/ctg-12	40.90	40.40-47.50	2.85	S	0.50	6.79	18.87
	<i>QDHE-5A.AL15</i>	5A-barc040-5A-gwm0186	5A-barc040	49.40	47.50-55.6	2.29	S	0.46	6.05	17.13
DMA	<i>QDMA-3B.AL16</i>	3B-barc0077-3B-wPt-1804	3B-barc0077	59.00	49.10-72.10	2.35	S	0.31	7.98	27.33
	<i>QDMA-4A.AL15</i>	4A-aac/caa-6-4A-aac/caa-3	4A-aac/caa-3	67.80	66.20-71.60	2.83	B	-0.53	7.22	20.65
	<i>QDMA-4A.AL16</i>	4A-aac/caa-6-4A-aac/caa-3	4A-aac/caa-3	67.80	66.50-71.60	2.05	B	-0.26	4.51	23.87
	<i>QDMA-4A.AL16</i>	4A-wPt-4645-4A-wPt-7280	4A-wPt-4645	94.60	90.10-96.40	3.70	S	0.36	8.29	23.85
SPAD	<i>QDMA-6A-a.AL16</i>	6A-wmc0256-6A-acc/ctg-6	6A-acc/ctg-6	71.00	70.10-74.50	3.17	S	0.30	7.27	24.18
	<i>QSPAD-7A.AL15</i>	7A-gwm0276-7A-barc0049	7A-gwm0276	90.10	86.20-95.40	2.37	S	0.95	5.44	20.92
CTm	<i>QCTm-3B.AL15</i>	3B-gwm301e-3B-wPt-0021	3B-gwm301e	44.60	42.10-60.60	2.73	B	-0.41	6.38	19.39
	<i>QCTm-6A-a.AL15</i>	6A-aca/cac-4-6A-agg/cat-6	6A-agg/cat-6	22.40	14.60-50.40	2.28	B	-0.40	5.65	19.84
ROL	<i>QROL-4A.AL15</i>	4A-wPt-8271-4A-wPt-7354	4A-wPt-8271	103.70	103.4-106.5	2.40	S	0.19	5.93	14.53
	<i>QROL-6A-b.AL16</i>	6A-aca/ctg-8-6A-agc/cta-5	6A-aca/ctg-8	36.40	35.00-43.00	4.93	S	0.27	12.24	23.84
	<i>QROL-7D-b.AL16</i>	7D-gwm130-7D-acc/cat-10	7D-gwm130	0.00	0.00-20.70	2.75	S	0.19	6.30	22.68
PHT	<i>QPHT-2B.AL16</i>	2B-wPt-7320-2B-aac/cta-1	2B-aac/cta-1	9.80	0.00-18.30	2.91	B	-0.74	6.25	26.14
	<i>QPHT-3A-b.AL16</i>	3A-act/cag-6-3A-wPt-9268	3A-act/cag-6	0.00	0.00-4.80	3.40	S	0.80	7.35	26.13
	<i>QPHT-3A-b.AL16</i>	3A-wPt-6234-3A-wPt-0398	3A-wPt-6234	9.30	8.30-12.30	2.06	S	0.64	4.54	23.32
	<i>QPHT-5B.AL16</i>	5B-wPt-9814-5B-aag/ctg-6	5B-wPt-9814	1.20	0.00-4.20	4.90	S	1.03	11.83	28.06
TSN	<i>QPHT-5B.AL16</i>	5B-aac/caa-7-5B-gwm213	5B-aac/caa-7	8.90	6.90-12.90	4.73	S	0.98	10.77	27.00
	<i>QTSN-1A.AL16</i>	1A-wPt-8016-1A-wPt-8644	1A-wPt-8016	91.00	73.20-110.0	2.62	B	-0.30	7.03	14.92
	<i>QTSN-2B.AL15</i>	2B-acg/cta-1-2B-gwm191a	2B-gwm191a	36.60	35.70-37.90	2.77	S	0.26	6.50	20.07
	<i>QTSN-2B.AL15</i>	2B-wPt-9736-2B-aca/caa-4	2B-wPt-9736	47.00	42.30-49.80	3.97	S	0.32	9.11	22.68
	<i>QTSN-2B.AL15</i>	2B-wPt-0047-2B-agc/cta-8	2B-wPt-0047	85.70	85.50-87.00	2.35	B	-0.24	5.26	22.96
	<i>QTSN-2B.AL15</i>	2B-gwm301c-2B-gwm301a	2B-gwm301a	91.70	89.70-97.90	2.00	B	-0.23	4.38	22.07
	<i>QTSN-2D.AL15</i>	2D-acg/cta-6-2D-aac/ctg-6	2D-aac/ctg-6	12.00	9.60-17.1	2.45	B	-0.24	5.48	22.67
<i>QTSN-6B.AL16</i>	6B-wPt-2786-6B-gwm132b	6B-wPt-2786	47.40	33.80-64.50	2.76	B	-0.39	11.01	25.32	

Table S4 (Continued)

Plant traits	QTL	Markers interval	Nearest marker	QTL position ^a	QTL interval (95%)	LOD score ^b	Allele	Additive effect	R ^{2c}	Total R ^{2d}
Stress environment										
TSN	<i>QTSN-6B.AL16</i>	6B-wPt-2899-6B-wPt-4764	6B-wPt-2899	67.10	64.50-72.30	2.30	B	-0.31	5.55	19.86
GSP	<i>QGSP-2B.AL15</i>	2B-wPt-9736-2B-aca/caa-4	2B-wPt-9736	47.00	41.50-49.00	2.37	S	1.32	5.54	19.25
TGW	<i>QTGW-1B.AL15</i>	1B-agg/cac-3-1B-agg/cta-9	1B-agg/cac-3	65.40	63.30-75.00	2.21	S	1.03	5.27	17.09
	<i>QTGW-2A-a.AL16</i>	2A-acc/ctg-8-2A-gwm636	2A-acc/ctg-8	0.00	0.00-32.20	3.00	B	-0.72	7.65	16.76
	<i>QTGW-6A-a.AL16</i>	6A-aca/caa-5-6A-wPt-7599	6A-aca/caa-5	28.00	11.80-50.80	2.01	S	0.59	4.96	16.42
GYLD	<i>QTGW-6B.AL15</i>	6B-wPt-8412-6B-agg/cat-8	6B-agg/cat-8	64.50	46.90-75.40	2.14	B	-0.89	5.10	17.09
	<i>QGYLD-1A.AL15</i>	1A-wPt-3904-1A-wPt-9592	1A-wPt-3904	19.60	19.30-29.10	2.80	B	-38.20	10.68	23.97
	<i>QGYLD-1A.AL15</i>	1A-aca/cta-2-1A-wmc097	1A-aca/cta-2	31.40	29.10-39.30	2.58	B	-26.69	6.04	19.32
	<i>QGYLD-2B.AL16</i>	2B-wPt-9668-2B-wPt-7320	2B-wPt-9668	0.00	0.00-21.60	2.51	B	-22.55	6.50	16.11
	<i>QGYLD-7A.AL15</i>	7A-wmc0488-7A-aag/cta-3	7A-wmc0488	110.30	100.0-113.30	2.05	B	-24.72	6.14	21.10
Al	<i>QGYLD-7B.AL16</i>	7B-aca/cag-4-7B-wPt-3723	7B-aca/cag-4	11.80	4.50-14.30	3.06	S	24.08	7.41	17.02
	<i>QAl-1A.AL15</i>	1A-wPt-1582-1A-wPt-8016	1A-wPt-1582	87.50	77.60-91.00	2.53	B	-0.14	6.45	16.33
	<i>QAl-2D.AL16</i>	2D-wPt-0298-2D-gwm0448	2D-wPt-0298	70.80	68.70-73.30	2.09	B	-0.06	4.90	18.49
	<i>QAl-7A.AL15</i>	7A-gwm282-7A-aca/cag-10	7A-gwm282	76.00	69.30-83.90	2.65	S	0.16	9.83	14.05

^a QTL position expressed in cM, from origin of the linkage group (end of shortarm)

^b peak value of the LOD

^c proportion of phenotypic variance explained by the QTL

^d total phenotypic variance explained by the model; S: SeriM82 allele increased trait, B: Babax allele increased trait

NO15: Normal environment in first year (2014-2015); AL15: Stress environment in first year (2014-2015); NO16: Normal environment in second year (2015-2016) and AL16: Stress environment in second year (2015-2016)

DHE: Days to heading, DMA: Days to maturity, SPAD: Chlorophyll content unit, CTm: Canopy temperature at seed maturity stage (⁰C), ROL: Leaf rolling, PHT: Plant height (cm), TSN: Total spikelet number per spike, FSN: Fertile spike number per plant, GSP: Grain number per spike, TGW: Thousand grain weight (g), GYLD: Grain yield (g) and Al: Aluminum amount (mg kg⁻¹)