**Table S1.** Significant quantitative trait loci (QTLs) for wheat grain traits identified in the Pubing3228/Jing4839 recombinant inbred lines (RIL) populations under different environments.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Trait | QTL | Environment | Chromosome | Left-Marker | Right-Marker | Position(cM) | LOD | PVE(%) | Add |
| GL |  |  |  |  |  |  |  |  |  |
| 1 | QGl.wa-1A.e3 | E3 | 1A | AX-108830701 | AX-110931131 | 108 | 3.26 | 8.42 | -0.16 |
| 2 | QGl.wa-1D.e3 | E3 | 1D | AX-110413459 | AX-110390201 | 178 | 2.88 | 7.33 | -0.15 |
| 3 | QGl.wa-2D.e3 | E3 | 2D | AX-109853665 | AX-110586878 | 129 | 2.88 | 7.71 | -0.15 |
| 4 | QGl.wa-2D.e1 | E1 | 2D | AX-111601893 | AX-109459272 | 112 | 3.29 | 9.82 | -0.14 |
| 5 | QGl.wa-4A.e2 | E2 | 4A | AX-110906643 | AX-110559956 | 126 | 3.08 | 6.61 | -0.16 |
| 6 | QGl.wa-4D.e2 | E2 | 4D | AX-111088452 | AX-94736483 | 676 | 3.99 | 4.83 | -0.22 |
| 7 | QGl.wa-5A.e3 | E3 | 5A | AX-108792246 | AX-109273136 | 46 | 4.98 | 12.35 | -0.19 |
| 8 | QGl.wa-5A.e2.1 | E2 | 5A | AX-109511251 | AX-110379085 | 195 | 6.04 | 4.66 | -0.21 |
| 9 | QGl.wa-5A.e2.2 | E2 | 5A | AX-109466244 | AX-111102603 | 202 | 14.91 | 12.23 | 0.34 |
| 10 | QGl.wa-5B.e1 | E1 | 5B | AX-108886889 | AX-108976571 | 90 | 2.86 | 10.65 | -0.14 |
| 11 | QGl.wa-5D.e3 | E3 | 5D | AX-95631806 | AX-95659017 | 697 | 3.24 | 8.48 | -0.16 |
| 12 | QGl.wa-5D.e3 | E3 | 5D | AX-110602003 | AX-109323365 | 949 | 2.86 | 6.92 | -0.14 |
| 13 | QGl.wa-5D.e2 | E2 | 5D | AX-110421468 | AX-108803037 | 829 | 4.49 | 9.15 | -0.18 |
| 14 | QGl.wa-5D.e3 | E2 | 5D | AX-109360538 | AX-94916071 | 934 | 3.12 | 6.48 | -0.15 |
| 15 | QGl.wa-7A.e3 | E3 | 7A | AX-111634483 | AX-109418049 | 483 | 4.55 | 10.85 | -0.21 |
| 16 | QGl.wa-7A.e2 | E2 | 7A | AX-111634483 | AX-109418049 | 486 | 5.52 | 11.61 | -0.21 |
| 17 | QGl.wa-7B.e3 | E3 | 7B | AX-110608303 | AX-109943789 | 61 | 4.19 | 10.29 | -0.18 |
| 18 | QGl.wa-7B.e2 | E2 | 7B | AX-108795893 | AX-109871179 | 57 | 4.98 | 10.63 | -0.19 |
| 19 | QGl.wa-7Da.e3 | E3 | 7Da | AX-111732641 | AX-110981319 | 98 | 2.81 | 7.12 | -0.14 |
| 20 | QGl.wa-7Da.e2 | E2 | 7Da | AX-111061288 | AX-110826147 | 106 | 3.00 | 6.25 | -0.14 |
| 21 | QGl.wa-1A.e4 | E4 | 1A | AX-109313554 | AX-108884942 | 80 | 3.63 | 8.00 | -0.13 |
| 22 | QGl.wa-1D.e4 | E4 | 1D | AX-108882911 | AX-111730467 | 204 | 3.43 | 7.11 | -0.13 |
| 23 | QGl.wa-3A.e4 | E4 | 3A | AX-111824379 | AX-95631471 | 301 | 3.88 | 9.13 | -0.18 |
| 24 | QGl.wa-3D.e4 | E4 | 3D | AX-111676471 | AX-109865767 | 599 | 3.23 | 8.88 | -0.16 |
| 25 | QGl.wa-4A.e4 | E4 | 4A | AX-108771516 | AX-110498003 | 15 | 4.77 | 9.12 | -0.16 |
| 26 | QGl.wa-4D.e4.1 | E4 | 4D | AX-86165534 | AX-94672822 | 301 | 2.82 | 3.33 | -0.15 |
| 27 | QGl.wa-4D.e4.2 | E4 | 4D | AX-169335624 | AX-109987236 | 612 | 4.40 | 5.88 | -0.19 |
| 28 | QGl.wa-5A.e4.1 | E4 | 5A | AX-111102603 | AX-109860489 | 207 | 15.33 | 10.66 | 0.27 |
| 29 | QGl.wa-5A.e4.2 | E4 | 5A | AX-109471543 | AX-110036471 | 217 | 8.10 | 5.53 | -0.19 |
| 30 | QGl.wa-5D.e4.1 | E4 | 5D | AX-108957941 | AX-111549976 | 220 | 3.70 | 7.19 | -0.13 |
| 31 | QGl.wa-5D.e4.2 | E4 | 5D | AX-109274468 | AX-110502158 | 1037 | 6.29 | 12.22 | -0.16 |
| 32 | QGl.wa-7A.e4.1 | E4 | 7A | AX-109289312 | AX-109868635 | 254 | 3.89 | 7.99 | -0.13 |
| 33 | QGl.wa-7A.e4.2 | E4 | 7A | AX-111634483 | AX-109418049 | 486 | 5.19 | 10.85 | -0.16 |
| 34 | QGl.wa-7B.e4 | E4 | 7B | AX-108795893 | AX-109871179 | 57 | 7.59 | 14.19 | -0.18 |
| 35 | QGl.wa-7Da.e4 | E4 | 7Da | AX-109872474 | AX-111638626 | 317 | 2.55 | 4.77 | -0.11 |
| 36 | QGl.wa-7Db.e4 | E4 | 7Db | AX-109860838 | AX-110425647 | 216 | 2.81 | 5.93 | -0.12 |
| GW |  |  |  |  |  |  |  |  |  |
| 1 | QGw.wa-2D.e2 | E2 | 2D | AX-109459272 | AX-111857979 | 113 | 3.71 | 7.97 | -0.09 |
| 2 | QGw.wa-4A.e2 | E2 | 4A | AX-111099057 | AX-111081911 | 21 | 2.59 | 5.61 | -0.07 |
| 3 | QGw.wa-4B.e2 | E2 | 4B | AX-110976982 | AX-109966618 | 4 | 2.68 | 6.17 | -0.08 |
| 4 | QGw.wa-5D.e3 | E3 | 5D | AX-110050695 | AX-110717927 | 854 | 2.51 | 6.67 | -0.10 |
| 5 | QGw.wa-5D.e2 | E2 | 5D | AX-108906106 | AX-111019979 | 937 | 2.87 | 6.67 | -0.08 |
| 6 | QGw.wa-7A.e1.1 | E1 | 7A | AX-109408769 | AX-109971619 | 234 | 2.88 | 7.91 | 0.09 |
| 7 | QGw.wa-7A.e1.2 | E1 | 7A | AX-110402440 | AX-108847997 | 335 | 3.03 | 9.25 | -0.11 |
| 8 | QGw.wa-7B.e2 | E2 | 7B | AX-109860542 | AX-111478329 | 9 | 2.93 | 6.18 | -0.08 |
| 9 | QGw.wa-4A.e2 | E2 | 4A | AX-109508535 | AX-108774567 | 81 | 2.73 | 6.11 | -0.06 |
| 10 | QGw.wa-4D.e2 | E2 | 4D | AX-109033420 | AX-95629315 | 224 | 2.91 | 6.46 | -0.08 |
| 11 | QGw.wa-5D.e2.1 | E2 | 5D | AX-111596945 | AX-95068958 | 363 | 3.43 | 7.35 | -0.07 |
| 12 | QGw.wa-5D.e2.2 | E2 | 5D | AX-111920410 | AX-110557199 | 1046 | 2.55 | 5.28 | -0.06 |
| 13 | QGw.wa-6B.e2 | E2 | 6B | AX-109423504 | AX-112289774 | 253 | 3.00 | 7.09 | -0.11 |
| GT |  |  |  |  |  |  |  |  |  |
| 1 | QGt.wa-2A.e3 | E3 | 2A | AX-94508821 | AX-110608557 | 174 | 2.90 | 7.51 | -0.08 |
| 2 | QGt.wa-2D.e3 | E3 | 2D | AX-109452092 | AX-110567710 | 677 | 2.99 | 8.28 | -0.09 |
| 3 | QGt.wa-3B.e2 | E2 | 3B | AX-109416919 | AX-109966382 | 203 | 3.23 | 7.44 | -0.08 |
| 4 | QGt.wa-4A.e2 | E2 | 4A | AX-110914376 | AX-108922147 | 32 | 3.32 | 6.48 | -0.078 |
| 5 | QGt.wa-4B.e3 | E3 | 4B | AX-110996982 | AX-110919776 | 49 | 3.26 | 8.74 | -0.09 |
| 6 | QGt.wa-4D.e2 | E2 | 4D | AX-94672822 | AX-94578696 | 355 | 4.11 | 8.91 | -0.09 |
| 7 | QGt.wa-5A.e3 | E3 | 5A | AX-110417422 | AX-108792246 | 45 | 3.28 | 9.28 | -0.09 |
| 8 | QGt.wa-5D.e1 | E1 | 5D | AX-89633041 | AX-89700472 | 819 | 2.87 | 8.42 | -0.08 |
| 9 | QGt.wa-5D.e2.1 | E2 | 5D | AX-110670121 | AX-110619828 | 561 | 3.88 | 8.14 | 0.08 |
| 10 | QGt.wa-5D.e2.2 | E2 | 5D | AX-109360538 | AX-94916071 | 935 | 2.68 | 5.05 | -0.06 |
| 11 | QGt.wa-6D.e2 | E2 | 6D | AX-108849732 | AX-109955189 | 208 | 2.65 | 6.06 | -0.07 |
| 12 | QGt.wa-7Da.e3 | E3 | 7Da | AX-111638626 | AX-109833182 | 351 | 2.52 | 5.89 | -0.11 |
| 13 | QGt.wa-7Da.e2.1 | E2 | 7Da | AX-89713293 | AX-110984806 | 133 | 12.81 | 8.24 | -0.15 |
| 14 | QGt.wa-7Da.e2.2 | E2 | 7Da | AX-111250905 | AX-110418373 | 139 | 6.59 | 4.15 | 0.10 |
| 15 | QGt.wa-7Db.e3 | E3 | 7Db | AX-94614654 | AX-111622533 | 319 | 3.43 | 7.81 | -0.13 |
| 16 | QGt.wa-1B.e5 | E5 | 1B | AX-111464755 | AX-109102987 | 145 | 3.62 | 7.68 | -0.06 |
| 17 | QGt.wa-5D.e5 | E5 | 5D | AX-110041472 | AX-94711964 | 129 | 2.95 | 6.56 | -0.05 |
| 18 | QGt.wa-4D.e4.1 | E4 | 4D | AX-111483158 | AX-111054538 | 56 | 13.99 | 12.86 | 0.54 |
| 19 | QGt.wa-4D.e4.2 | E4 | 4D | AX-94672822 | AX-94578696 | 357 | 3.69 | 0.20 | -0.07 |
| 20 | QGt.wa-6A.e4 | E4 | 6A | AX-108767470 | AX-111013769 | 81 | 2.63 | 5.98 | -0.06 |
| 21 | QGt.wa-6D.e4 | E4 | 6D | AX-110787660 | AX-109972107 | 239 | 3.37 | 6.89 | -0.07 |
| 22 | QGt.wa-7A.e4 | E4 | 7A | AX-110033859 | AX-108894435 | 160 | 2.84 | 6.32 | -0.07 |
| 23 | QGt.wa-7B.e4 | E4 | 7B | AX-109432492 | AX-108861535 | 174 | 2.98 | 5.91 | -0.07 |
| 24 | QGt.wa-7Db.e4 | E4 | 7Db | AX-110515663 | AX-111585247 | 113 | 2.56 | 5.02 | -0.06 |
| TGW |  |  |  |  |  |  |  |  |  |
| 1 | QTgw.wa-1A.e3 | E3 | 1A | AX-110459479 | AX-94465571 | 164 | 2.57 | 6.57 | -3.28 |
| 2 | QTgw.wa-1D.e3 | E3 | 1D | AX-110413459 | AX-110390201 | 178 | 2.54 | 6.65 | -3.21 |
| 3 | QTgw.wa-1D.e2 | E2 | 1D | AX-110062950 | AX-108731135 | 125 | 2.51 | 6.05 | -2.49 |
| 4 | QTgw.wa-2A.e2 | E2 | 2A | AX-109913197 | AX-108788546 | 108 | 3.38 | 8.30 | -2.91 |
| 5 | QTgw.wa-2D.e3 | E3 | 2D | AX-110465469 | AX-111318850 | 110 | 3.45 | 8.77 | -3.73 |
| 6 | QTgw.wa-2D.e2 | E2 | 2D | AX-111709747 | AX-111512799 | 617 | 2.57 | 5.32 | -2.82 |
| 7 | QTgw.wa-3B.e2 | E2 | 3B | AX-111509174 | AX-109438767 | 170 | 4.86 | 8.35 | -4.25 |
| 8 | QTgw.wa-4D.e2.1 | E2 | 4D | AX-94672822 | AX-94578696 | 357 | 2.97 | 4.12 | -2.77 |
| 9 | QTgw.wa-4D.e2.2 | E2 | 4D | AX-109987236 | AX-111088452 | 639 | 2.87 | 8.58 | -3.99 |
| 10 | QTgw.wa-5A.e3 | E3 | 5A | AX-110417422 | AX-108792246 | 44 | 3.67 | 8.96 | -4.19 |
| 11 | QTgw.wa-5D.e3 | E3 | 5D | AX-95631806 | AX-95659017 | 693 | 3.23 | 8.26 | -4.01 |
| 12 | QTgw.wa-5D.e2.1 | E2 | 5D | AX-109725899 | AX-108827297 | 882 | 2.95 | 5.98 | -2.75 |
| 13 | QTgw.wa-5D.e2.2 | E2 | 5D | AX-108802520 | AX-111465052 | 1059 | 3.82 | 7.27 | -3.06 |
| 14 | QTgw.wa-6D.e3 | E3 | 6D | AX-110261831 | AX-110367735 | 249 | 3.39 | 5.10 | -3.64 |
| 15 | QTgw.wa-6D.e2 | E2 | 6D | AX-110352184 | AX-111500493 | 324 | 3.73 | 8.58 | -3.09 |
| 16 | QTgw.wa-7A.e3 | E3 | 7A | AX-110467450 | AX-110402440 | 322 | 2.61 | 7.92 | -4.56 |
| 17 | QTgw.wa-7B.e2.1 | E2 | 7B | AX-109860542 | AX-111478329 | 8 | 4.74 | 7.66 | -3.25 |
| 18 | QTgw.wa-7B.e2.2 | E2 | 7B | AX-110955130 | AX-108890206 | 326 | 2.94 | 9.11 | -3.48 |
| 19 | QTgw.wa-7Da.e3 | E3 | 7Da | AX-110826147 | AX-108748734 | 107 | 5.24 | 13.13 | -4.60 |
| 20 | QTgw.wa-7Da.e2 | E2 | 7Da | AX-111061288 | AX-110826147 | 106 | 4.62 | 7.45 | -3.15 |
| 21 | QTgw.wa-5A.e5 | E5 | 5A | AX-110417422 | AX-108792246 | 45 | 2.72 | 5.93 | -2.08 |
| 22 | QTgw.wa-5B.e5 | E5 | 5B | AX-109449543 | AX-108886770 | 101 | 3.03 | 6.21 | -2.26 |
| 23 | QTgw.wa-1A.e4.1 | E4 | 1A | AX-109031990 | AX-110414542 | 46 | 4.05 | 8.57 | -2.59 |
| 24 | QTgw.wa-1A.e4.2 | E4 | 1A | AX-109325332 | AX-111585507 | 104 | 2.79 | 5.85 | -2.14 |
| 25 | QTgw.wa-1D.e4.1 | E4 | 1D | AX-109354064 | AX-109325378 | 216 | 4.49 | 8.98 | -2.74 |
| 26 | QTgw.wa-1D.e4.2 | E4 | 1D | AX-108775918 | AX-109309143 | 441 | 3.15 | 6.07 | -2.27 |
| 27 | QTgw.wa-2D.e4 | E4 | 2D | AX-109471629 | AX-110428417 | 650 | 2.71 | 3.79 | -2.27 |
| 28 | QTgw.wa-3A.e4 | E4 | 3A | AX-111824379 | AX-95631471 | 303 | 4.64 | 11.07 | -3.88 |
| 29 | QTgw.wa-3D.e4.1 | E4 | 3D | AX-111579109 | AX-111676471 | 573 | 4.54 | 8.19 | -4.65 |
| 30 | QTgw.wa-3D.e4.2 | E4 | 3D | AX-111676471 | AX-109865767 | 606 | 5.38 | 8.53 | -4.73 |
| 31 | QTgw.wa-4A.e4 | E4 | 4A | AX-108771516 | AX-110498003 | 12 | 3.36 | 2.95 | -2.78 |
| 32 | QTgw.wa-4B.e4 | E4 | 4B | AX-110571073 | AX-109407721 | 28 | 2.51 | 2.65 | -1.92 |
| 33 | QTgw.wa-4D.e4 | E4 | 4D | AX-111645255 | AX-86165534 | 291 | 3.52 | 4.19 | -2.42 |
| 34 | QTgw.wa-5A.e4.1 | E4 | 5A | AX-110422901 | AX-108785757 | 257 | 2.77 | 3.04 | -2.08 |
| 35 | QTgw.wa-5A.e4.2 | E4 | 5A | AX-110717728 | AX-109483452 | 374 | 5.07 | 15.99 | -4.71 |
| 36 | QTgw.wa-5D.e4 | E4 | 5D | AX-111019250 | AX-111003109 | 529 | 2.72 | 7.04 | -2.25 |
| 37 | QTgw.wa-6B.e4 | E4 | 6B | AX-109282893 | AX-109423504 | 201 | 5.54 | 13.89 | -4.44 |
| 38 | QTgw.wa-6D.e4 | E4 | 6D | AX-109331810 | AX-110007215 | 242 | 3.57 | 4.03 | -2.39 |
| 39 | QTgw.wa-7B.e4 | E4 | 7B | AX-111505592 | AX-110944132 | 47 | 4.35 | 6.08 | -2.65 |
| 40 | QTgw.wa-7Da.e4.1 | E4 | 7Da | AX-110981319 | AX-110468744 | 100 | 3.58 | 4.93 | -2.39 |
| 41 | QTgw.wa-7Da.e4.2 | E4 | 7Da | AX-111638626 | AX-109833182 | 341 | 2.72 | 10.57 | -3.48 |

GL=Grain length, GW=Grain width, GT=Grain thickness, TGW=Thousand grain weight, E1=Pingdingshan-2019, E2= Pingdingshan-2020, E3= Pingdingshan-2021, E4=Xianyang-2020, E5=Yangling-2021, LOD = Logarithm of the odds, PVE = Phenotypic Variance Explained