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### *Seed Number and 100-Seed Weight of Pearl Millet (*Pennisetum glaucum* L.) Respond Differently to Low Soil Moisture in Genotypes Contrasting for Drought Tolerance*

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**Seed number and 100-seed weight of pearl millet  
(*Pennisetum glaucum* (L.) R. Br.) respond differently to low  
soil moisture in genotypes contrasting for drought tolerance**

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3 1 **Seed number and 100-seed weight of pearl millet (*Pennisetum glaucum L.*)**  
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5 2 **respond differently to low soil moisture in genotypes contrasting for**  
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7 3 **drought tolerance**  
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37 17 **Abstract**  
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39 18 Water stress after flowering, one of the major factors limiting yields of pearl millet, affects both  
40 19 seed setting and grain filling, and is a consequence of more/less water used prior to anthesis.  
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42 20 However, whether genotypes have different sensitivities for seed setting and filling under drought, if  
43 21 exposed to similar stress intensity, is unclear. Experiments were conducted in two pairs of pearl millet  
44 22 genotypes, i.e. PRLT2/89-33 and H77/833-2, 863B and 841B, contrasting for terminal drought  
45 23 tolerance, and two genotypes, ICMR 01046 and ICMR 01029 (IL-QTLs) introgressed with a terminal  
46 24 drought tolerance QTL from PRLT2/89-33 into H77/833-2. Total seed weight, panicle number, 100-  
47 25 seed weight, seed number, and stover biomass were measured at different soil moistures, and  
48 26 throughout-grain filling. Sensitive H77/833-2 had higher seed number and yield under well watered  
49 27 (WW) conditions than in PRLT2/89-33 and IL-QTLs. Upon increases in water stress intensity,  
50 28 H77/833-2 suffered losses mostly in stover biomass (45%) and seed number (60%) at 0.3 FTSW  
51 29 whereas the biomass and seed number of PRLT2/89-33 decreased little (20% and 25%). The 100-seed  
52 30 weight of H77/833-2 decreased only 20% under stress. Tolerant 863B also maintained a higher seed  
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3 31 number and biomass under water stress than 841B. Seed growth duration in PRLT2/89-33 and IL-  
4 32 QTLs was similar to that of H77/833-2 under WW conditions but lasted longer than in H77/833-2  
5 33 under water stress (WS). Similarly, seed growth of 863B was longer than 841B under WS. It is  
6 34 concluded that the higher seed yield of tolerant parents PRLT2/89-33 and 863B, and of IL-QTLs  
7 35 under WS was explained by the retention of a higher number of seeds than in sensitive lines, while the  
8 36 decrease in the 100-seed weight was proportionally less than the decrease in seed number. Phenotype  
9 37 with lesser number and larger size of panicles and larger grain size, like genotypes PRLT2/89-33 and  
10 38 863B, withstood post-anthesis water stress better. IL-QTL inherited part of these characteristics,  
11 39 indicating a role for the terminal drought QTL in maintaining larger seed number and higher 100-seed  
12 40 weight. The continuous stover biomass increase under WW in H77/833-2, due to tillering, might  
13 41 indicate that tiller growth and grains are in competition for resources after anthesis and this may relate  
14 42 to the relatively shorter grain filling period.  
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23 44 **Key words:** Post flowering water stress, carbohydrates, transpiration, biomass, yield  
24 45 components  
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## 30 48 **Introduction**

31 49 Pearl millet is widely grown in the arid zone of northwestern India and also in the  
32 50 Sahelian zone where there is no alternative. Drought stress is a regular feature in these  
33 51 environments, occurring at unpredictable time and intensity (Sharma and Pareek, 1993; van  
34 52 Oosterom et al., 1996), but being most common during grain filling. Successful grain filling  
35 53 is therefore one of the criteria in selecting the genotypes for improved adaptation to stress.  
36 54 Farmers preferentially grow high tillering landraces particularly when drought stress is highly  
37 55 unpredictable as in the case of arid areas of western Rajasthan (Van Oosterom et al., 1996).  
38 56 High tillering genotypes are associated with small sized panicles and low individual grain  
39 57 mass, which can be further decreased if the grain filling ability is impaired by water stress.  
40 58 However, genotypes with this type of development pattern are better able to cope with  
41 59 unpredictable stress because of their better capacity to compensate for the failure of the main  
42 60 panicle than low tillering large sized panicles (Bidinger and Hash, 2004). By contrast,  
43 61 genotypes with large grain size and low tillering have been widely adopted (Kelley et al.,  
44 62 1996; van Oosterom et al., 1996) in the wetter eastern areas of Rajasthan where pre-flowering  
45 63 drought stress is unlikely to occur but post-anthesis drought is predominant. The question of  
46 64 grain size under stress conditions is also important to address for grain quality since larger  
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3 65 seeds have a higher flour yield (Rooney and McDonough, 1987) and a stress effect on grain  
4 66 size could decrease flour yields.  
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6 67 One of the unanswered questions is whether these different grain types are differently  
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8 68 affected by water stress. In pearl millet grain yield is highly correlated with grain number  
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10 69 (Bidinger and Raju, 2000). Large grain number correlates with small individual grain mass  
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12 70 and short grain filling periods, and is an important adaptive feature of pearl millet to the arid  
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14 71 climates (DeWet et al., 1992). In contrast, large grain size is a highly preferred characteristic  
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16 72 according to farmer survey, allowing higher market price (Phul and Athwal, 1969, IARI  
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18 73 report in magazine- National Herald 2006). Large grain mass also confers faster rates of  
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20 74 seedling emergence, faster initial seedling and early crop growth (Lawan et al., 1985, Siband  
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22 75 et al., 1978, Chhina and Phul, 1982), improved processing quality of the grain, easy  
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24 76 decortications, and better flour yield with both commercial milling and hand-pounding  
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26 77 milling methods (Rooney and McDonough, 1987). Whether different grain types are  
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28 78 differently affected by terminal stress is not known in pearl millet.

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30 79 A major drought QTL on linkage group two (LG2) explaining 23% of variation in grain  
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32 80 yield under severe drought environments was identified (Yadav et al., 2002; Yadav et al.  
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34 81 2004; Bidinger et al 2007), and accounted for a better seed set and a better grain filling. This,  
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36 82 in turn, was explained by a conservative water use when water was non-limiting, which made  
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38 83 more water remains available for grain filling (Kholová et al., 2010a, 2010b; Vadez et al.,  
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40 84 2013). Since the QTL is responsible for differences in grain filling, another possible  
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42 85 explanation for the difference between tolerant and sensitive lines could be differences in the  
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44 86 soil moisture thresholds where grain filling stops. Such information is not available in pearl  
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46 87 millet and the existence of lines (ILs) introgressed with a major terminal drought tolerance  
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48 88 QTL allows this exploration. Here, we address this question by following grain filling in  
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50 89 different soil moisture conditions. Our hypothesis is that grain filling may stop at different  
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52 90 levels of soil moisture in different genotypes which could explain part of the grain yield  
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54 91 differences under terminal drought conditions.

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56 92 The first objective of this study was to evaluate whether the response of yield  
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58 93 components to drought stress differed between tolerant and sensitive genotypes, which was  
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60 94 done by measuring grain yield, grain number, grain size, and stover biomass under different  
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96 95 levels of soil moisture. The second objective was to assess how these different components  
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98 96 evolved during the grain filling period in different genotypes, and this was done by sequential  
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100 97 harvests during grain filling and until maturity. The work was carried out using contrasting

98 genotypes, including ILs containing a terminal drought tolerance QTL in order to assess  
99 whether mechanisms related to differences in seed filling are underlying this QTL.

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102 **Materials and methods:**

103 **Plant material**

104 Parental genotypes: Pearl millet genotypes differing in terminal drought tolerance were  
105 selected. Two pairs of parents PRLT2/89-33 (tolerant) and H77/833-2 (sensitive), ICMB 863-  
106 P2 (tolerant, then referred to as 863B) and 841B-P3 (sensitive, then referred to as 841B)  
107 selected for the study contrasted for seed yield under terminal drought conditions based on  
108 previous experiments (Yadav et al., 2002; Serraj et al., 2005). Both pairs of parental lines  
109 were tested in that study because a terminal drought tolerance QTL was identified in both  
110 derived mapping populations. Tolerance/sensitivity was assessed using testcross hybrids of  
111 these parental inbred lines, using 843A and H77/833-2A as a male sterile tester for each pair  
112 respectively. PRLT2/89-33 is a low tillering, large panicle experimental line (Andrews and  
113 Anand Kumar, 1996) and H77/833-2 is a high tillering line with small panicles (Kapoor et al.,  
114 1989). More details describing the two parental pairs can be found in Kholová et al., (2010a).

115 Introgression lines (IL-QTLs): QTL introgression lines were developed in the background of  
116 sensitive parent H77/833-2 (recurrent parent) by introgressing the QTL from drought tolerant  
117 donor parent PRLT2/89-33 (QTL identified on LG2 by Yadav et al., 2002; Yadav et al. 2004;  
118 Bidinger et al., 2007) and the resulting F1 was backcrossed to the recurrent parent H77/833-2  
119 for four generations (more details in Kholová et al., 2010a). IL-QTLs in H77/833-2  
120 background (ICMR01029 and ICMR01046) were also tested as test-cross hybrids using 843A  
121 as a male sterile tester.

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123 **Assessment of grain filling and seed number under different levels of soil moisture**

124 Experiment 1 (Exp.1) was designed to assess the response of transpiration and of agronomic  
125 characteristics, including grain size and grain number, to different levels of moisture stress, in  
126 two parental pairs; i.e. PRLT 2/89-33 and H77/833-2, 863B and 841B . Plants were grown in  
127 pots filled with 9.5 kg of a mixture of Alfisol, sand, and manure (5:2:1) under glass house  
128 conditions with 17.6°C min and 35.5°C max temperature and 40-75% relative humidity (RH).  
129 Growth in the pots was very satisfactory and plant height was similar to the field conditions.  
130 Although small pot size could have affected the root/shoot ratio, these growth conditions

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3 131 were unlikely to have affected genotypic differences in response to drought. Five water  
4 132 treatments were used: One well-watered control and four water stress treatments in which the  
5 133 soil moisture content was re-adjusted daily to a constant value of 50%, 40%, 30%, and 20%  
6 134 of the fraction of transpirable soil water (i.e. 0.5, 0.4, 0.3, 0.2 FTSW) by deducting 890,  
7 135 1070, 1250 and 1420g of water, respectively, from the pots maintained at field capacity. This  
8 136 was based on previous experiments in which it was shown that, when exposed to a  
9 137 progressive water stress: (i) genotypes did not vary in the amount of water they could extract  
10 138 for transpiration from a given soil weight; (ii) there was approximately 180g of transpirable  
11 139 water per kg of soil. These FTSW values reflected an average for the entire pot and it does  
12 140 not exclude the possibility that, at re-watering, the top part of the pot would have been wet  
13 141 while the remaining part of the pot would have been dry. We believe this was not an issue for  
14 142 the plant response. First, this would be a similar situation in nature. Second, the most limiting  
15 143 factor for the plant was the limited amount of water that was received every day and this was  
16 144 relatively similar for each genotype. The experimental design was a complete block design  
17 145 with water treatment as main block and genotypes as sub-factor in each main block and  
18 146 randomized five times.

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29 147 Plants were grown under fully irrigated conditions until panicle emergence. As soon  
30 148 as panicles were emerged all the pots were watered and allowed to drain overnight to reach  
31 149 field capacity. The following morning, pots were wrapped with plastic bags around the base  
32 150 of the stem to cease soil evaporation and pots were subsequently weighed. Pots from all  
33 151 treatments were maintained under well-watered (WW) conditions by daily re-watering the  
34 152 pots up to 80% field capacity (0.8 FTSW) until flowering. Water stress treatments were  
35 153 imposed from flowering time onwards by gradually decreasing the water level to 0.5, 0.4, 0.3,  
36 154 and 0.2 FTSW. All genotypes flowered within about two to three days from one another, so  
37 155 that there was only a minimum time difference with the time when water stress was initiated.  
38 156 The FTSW represents how much water is available for transpiration in the pot, as a  
39 157 proportion of what is available at field capacity (1, or 100%). In order to impose a gradual  
40 158 stress, the desired soil moisture levels were reached only 4-5 days after flowering. The  
41 159 purpose of this was also to ensure that reproduction would take place under WW conditions  
42 160 and before the stress levels were imposed. The pot weights were maintained at these set  
43 161 levels of FTSW until maturity (between 30 and 38 days after flowering), by daily weighing  
44 162 and re-watering to set target pot weight. Harvested plants were oven-dried in a forced-air  
45 163 oven at 70°C for three days. Stover biomass, panicle number, total seed weight, seed number,  
46 164 and 100- seed weight were then measured.



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3 1654 166 **Dynamics of grain filling**

5 167 Experiment 2 and 3 (Exp.2 and Exp.3) followed up how grain yield, grain number, grain size,  
6 168 stover biomass, and transpiration evolved during the grain filling period in plants exposed to  
7 169 two water regimes: (i) a well-watered control (WW); (ii) a soil moisture content of 0.3 FTSW  
8 170 (with 30% moisture) from four days after flowering and until maturity. Exp.2 included ICMR  
9 171 01029 and ICMR 01046, PRLT2/89-33 and H77/833-2. Exp.3 included 863B and 841B. The  
10 172 transpiration values, obtained from daily weighing, were normalized against control plants to  
11 173 get normalized transpiration ratio. For that, the transpiration value of each replicate was  
12 174 divided by the average transpiration of WW plant to get a transpiration ratio. A second  
13 175 normalization was carried out to take care of plant to plant variation in size, by dividing the  
14 176 transpiration ratio by the mean transpiration ratio value of the first three days of the  
15 177 experiment, before the occurrence of any stress. Sequential harvests were carried out at 10,  
16 178 20, and 30 days after flowering, the last harvest corresponding to maturity. The experimental  
17 179 design was a complete block design with the three sequential harvests as main blocks, water  
18 180 regimes as sub-blocks, and genotypes as sub-factor in each main sub-block and randomized  
19 181 five times. Plants were grown under same conditions. Treatment imposition and harvest  
20 182 procedures followed those of Exp.1.

21 183 Extraction and determination of total carbohydrates was done from the penultimate  
22 184 internodes (below the peduncle) harvested at maturity, by grinding 200mg of fresh tissue  
23 185 twice with 70% ethanol at 90°C. These ethanol extracts were pooled, centrifuged at 10,000 g  
24 186 for 10min and the supernatant was taken for estimation. Total sugars were estimated by  
25 187 Dubois et al. (1956) method using phenol and sulphuric acid.

26 188

27 189 **Statistical analysis:**

28 190 One way ANOVA was carried out for genotypic differences within the treatment. ANOVA  
29 191 was done with the statistical program package CoStat version 6.204 (Cohort Software,  
30 192 Monterey, CA, USA). Grouping of the genotypes in between the treatments was done using  
31 193 Duncan's multiple range tests through the statistical program SAS version 9.2 to compare the  
32 194 treatment effect from Exp.1. For Exp.2 and Exp.3, Duncan's multiple range tests through  
33 195 SAS version 9.2 was used to compare the genotypes at different times of harvests separately  
34 196 for control and stress during the grain filling period. ANOVA was carried out for genotypic  
35 197 differences in carbohydrates separately under WW and water stress.



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200 **Results:**201 **Grain yield response to varying water stress treatments**

202 Seed yield decreased significantly at 0.4 FTSW compared to the WW treatment, and then  
203 further decreased significantly at 0.3 and 0.2 FTSW in both the parental pairs ( $P < 0.0001$  Fig.  
204 1a and 1b, Exp.1). However, genotypic differences in total seed weight were observed under  
205 WW conditions and 0.3 FTSW in both pairs. There were significant genotype-by-treatment  
206 interactions for the seed yield ( $P < 0.02$ ), so that under WW conditions, H77/833-2 had  
207 significantly higher total seed weight than PRLT2/89-33 ( $P < 0.1$ ), whereas at 0.3 and 0.2  
208 FTSW, PRLT2/89-33 had higher total seed weight than H77/833-2 ( $P < 0.1$  Fig. 1a, Exp.1).  
209 With the parental pair 863B and 841B (Exp.1, Fig. 1b), genotype 863B (tolerant) had  
210 significantly higher total seed weight than 841B (sensitive) under WW conditions ( $P < 0.01$ )  
211 and water stress treatments 0.4 and 0.3 FTSW ( $P < 0.1$ ).

212 The evolution of seed weight over time after flowering at 0.3 FTSW and under WW  
213 conditions was followed in Exp.2 (Fig. 1c). Under WW conditions, the seed weight of  
214 H77/833-2 significantly increased in all sequential harvests ( $P < 0.0001$ ), with the highest  
215 seed yield ( $P < 0.05$ ) at maturity, whereas in PRLT2/89-33, ICMR 01046, and ICMHR 01029  
216 the total seed weight did not increase significantly beyond 20 days after flowering. Under WS  
217 conditions (0.3 FTSW), the increase in seed weight was somewhat slower, with a gradual  
218 increase in total seed weight. All genotypes attained their maximum seed weight at 20 days  
219 after flowering except ICMR 01046 that reached its highest total seed weight at 30 days after  
220 flowering (Fig. 1c). PRLT2/89-33, ICMR 01029 and ICMR 01046 had significantly higher  
221 total seed weight than H77/833-2 at maturity ( $P < 0.05$ ), in agreement with Exp. 1. Under  
222 WW conditions in the parental pair 863B and 841B (Exp.3, Fig: 1d), the total seed weight  
223 increased significantly until the last harvest ( $P < 0.05$ ). Under WS conditions, both the  
224 parental lines showed maximum seed weight at 20 days after flowering (Fig. 1d). There,  
225 863B (tolerant) had significantly higher seed weight than 841B (sensitive) under WW and  
226 WS conditions in agreement with Exp.1 ( $P < 0.05$ ).

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228 **Panicle number, seed number and 100-seed weight response to water stress**

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3 229 Water stress strongly decreased panicle number, especially in the high tillering types. Indeed,  
4 230 panicle number decreased at treatment 0.3 FTSW ( $P < 0.0001$ , Exp.1, Fig.2a) and these  
5 231 changes were driven by a sharp decrease in panicle number of high tillering H77/833-2  
6 232 (sensitive parent, ( $P < 0.01$ ), reflecting significant genotype-by-treatment interaction ( $P$   
7 233  $< 0.05$ ). In the parental pair 863B and 841B (Exp.1, Fig.2b) significant treatment differences  
8 234 were observed at 0.4 FTSW with no further decrease at more severe treatment ( $P < 0.0001$ ).  
9 235 Similar to the above parental pair 841B (sensitive parent) had significantly higher number of  
10 236 panicles in all the treatment except at 0.3 FTSW ( $P < 0.01$ ).

16 237 The seed number of the parental pair PRLT2/89-33 and H77/833-2 decreased  
17 238 significantly at 0.4 FTSW although this decrease affected only H77/833-2 compared to WW  
18 239 conditions. The seed number of the parental pair then further decreased at 0.2 FTSW ( $P$   
19 240  $< 0.0001$ ) and seed number decreased in both genotypes compared to 0.4 FTSW (Exp.1, Fig.  
20 241 3a). The genotype-by-treatment interaction for seed number was also highly significant ( $P$   
21 242  $< 0.001$ ). H77/833-2 (sensitive parent) had significantly higher seed number than PRLT2/89-  
22 243 33 (tolerant parent) under WW, 0.5 FTSW, and 0.4 FTSW ( $P < 0.01$ ) but both genotypes had  
23 244 similar seed number at 0.3 and 0.2 FTSW. At these FTSW levels, the seed number of  
24 245 H77/833-2 was 65% less than the WW conditions. In the parental pair 863B and 841B  
25 246 (Exp.1, Fig. 3b), the seed number decreased significantly at 0.4 FTSW compared to WW  
26 247 conditions, with a further significant decrease at 0.3 and then 0.2 FTSW ( $P < 0.0001$ ).  
27 248 Genotypes 863B and 841B had similar seed number at all FSTW levels except 0.3 ( $P < 0.05$ ).

34 249 In Exp.2 (Fig. 3c) the evolution in the seed number over time after flowering was  
35 250 observed. Under WW conditions the seed number remained similar in PRLT2/89-33  
36 251 throughout the grain filling period. By contrast, the seed number increased throughout the  
37 252 seed filling period in the other genotypes. In ICMR 01029 the maximum seed number was  
38 253 observed at 20 days after flowering whereas ICMR 01046 and H77/833-2 reached the highest  
39 254 seed number at 30 days. This was likely related to the development of reproductive tillers in  
40 255 these three high tillering types. Under WS conditions the seed number of PRLT2/89-33 and  
41 256 ICMR 01046 remained similar across the different harvests. By contrast, the seed number  
42 257 increased in H77/833-2 and ICMR 01029 and the highest seed number was reached at 20  
43 258 days and 30 after flowering respectively. However, even at its highest seed number (20 days  
44 259 after flowering) the seed number of H77/833-2 had decreased drastically compared to the  
45 260 WW treatment while it did decrease relatively less in the other genotypes, in agreement with  
46 261 Exp.1. In the parental pair 863B and 841B under WW conditions the maximum seed number

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3 262 was reached at the last harvest i.e., 30 days after flowering in both 863B (tolerant) and 841B  
4 263 (sensitive) (Exp.3, Fig. 3d). Under water stress, there was no further significant increase in  
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6 264 seed number in both genotypes beyond 20 days after flowering.

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8 265 The 100-seed weight started to decrease at lower soil moisture levels than biomass  
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10 266 and seed yield. In the PRLT2/89-33 and H77/833-2 pair (Exp.1, Fig. 4a), there was no  
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12 267 significant treatment effect on the 100-seed weight until FTSW was down to 0.2. The  
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14 268 genotype-by-treatment interaction for the 100-seed weight was also highly significant ( $P$   
15 269  $<0.004$ ). The 100-seed weight decreased gradually in PRLT2/89-33 from 0.5 to 0.3 FTSW,  
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17 270 and the 100-seed weight of PRLT2/89-33 was about 23% lower at 0.3 FTSW than under WW  
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19 271 conditions, with a rapid drop between 0.3 and 0.2 FTSW. By contrast, in H77/833-2 there  
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21 272 was no change in the 100-seed weight between the WW control and 0.3 FTSW, but there was  
22  
23 273 a rapid drop at 0.2 FTSW. Therefore, PRLT2/89-33 (tolerant parent) had significantly higher  
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25 274 100-seed weight than H77/833-2 (sensitive) until FTSW was down to 0.3 ( $P <0.001$  at WW  
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27 275 and  $P <0.05$  at 0.3 FTSW) but both the genotypes had similar low 100-seed weights at 0.2  
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29 276 FTSW. In the parental pair 863B and 841B the 100-seed weight decreased significantly at 0.3  
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31 277 FTSW compared to the WW treatment, and then further decreased at 0.2 FTSW ( $P <0.0001$ ,  
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33 278 Exp.1, Fig. 4b). Genotypic differences were significant until FTSW was down to 0.4 with  
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35 279 863B parent having a significantly higher seed weight than 841B ( $P <0.01$ ). At 0.3 and 0.2  
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37 280 FTSW the 100-seed weight was not significantly different between the two genotypes.

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39 281 The evolution of the 100-seed weight was followed at 0.3 FTSW and under WW  
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41 282 conditions in the post-flowering and grain filling period. Under WW conditions all the  
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43 283 genotypes attained the maximum 100-seed weight (used as a proxy for seed filling) at 20  
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45 284 days after flowering and there was no further significant increase at 30 days after flowering.  
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47 285 Under water stress conditions the increase in 100-seed weight was more gradual. For instance  
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49 286 PRLT2/89-33, ICMR 01046, and ICMR 01029 reached their maximum 100-seed weight at  
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51 287 30 days after flowering. By contrast, the 100-seed weight did not change in H77/833-2 across  
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53 288 the different harvests (Exp. 2; Fig. 4c). Unlike Exp.1, the 100-seed weight of H77/833-2  
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55 289 decreased at 0.3 FTSW compared to the WW conditions. However, in both experiments it  
56  
57 290 was the large seed number decreased that affected the seed yield of H77/833-2. In the  
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59 291 parental pair 863B and 841B under both WW and WS conditions both genotypes 863B and  
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292 841B reached their maximum 100-seed weight at 20 days after flowering (Exp. 3; Fig. 4d).

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3 294 **Stover biomass, transpiration and total soluble sugars response to water stress**

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5 295 Stover biomass decreased gradually with increase in the water stress treatment (Exp.1, Fig.  
6 296 5a). In the parental pair PRLT2/89-33 and H77/833-2 it was not until 0.3 FTSW that a  
7 297 significant decrease in biomass was observed ( $P < 0.0001$ ). However, the genotype-by-  
8 298 treatment interaction for stover biomass was not significant. Within treatment, significantly  
9 299 higher biomass was observed in PRLT2/89-33 (tolerant) than H77/833-2 (susceptible) at 0.3  
10 300 FTSW only ( $P < 0.05$ , Fig. 5a). In the parental pair 863B and 841B (Exp. 1, Fig. 5b) stover  
11 301 biomass decreased significantly compared to the WW control at 0.3 and 0.2 FTSW ( $P$   
12 302  $< 0.0001$ ). Within treatments 863B (tolerant) had significantly higher biomass than 841B  
13 303 (sensitive) at 0.3 and 0.2 FTSW treatments ( $P < 0.05$ , Fig. 5b).

14  
15 304 The evolution of stover biomass over time after flowering was followed at 0.3 FTSW  
16 305 and under WW conditions at different timings after flowering. Under WW conditions there  
17 306 was no increase in the vegetative biomass across the three different harvests in PRLT2/89-33  
18 307 (Exp. 2; Fig. 5c). By contrast, in the other three lines stover biomass increased between  
19 308 flowering and maturity. In H77/833-2 the highest accumulation of stover biomass was  
20 309 observed at the last harvest (30 days after flowering) while in ICMR 01046 and ICMR 01029,  
21 310 there was no significant increase in stover biomass beyond 20 days after flowering (Fig. 5c).  
22 311 Under WS conditions none of the genotypes showed any significant increase in stover  
23 312 biomass after flowering (Fig. 5c) but at maturity PRLT2/89-33 (tolerant) had significantly  
24 313 higher biomass than H77/833-2 (sensitive), in agreement with Exp.1 ( $P < 0.05$ ). In the  
25 314 parental pair 841B and 863B there was no increase in the stover biomass after flowering  
26 315 irrespective of the time of harvest in any of the water treatment (Fig. 5d). Under WS  
27 316 conditions, 863B had significantly higher biomass than 841B in agreement with Exp.1 ( $P$   
28 317  $< 0.05$ ).

29  
30 318 The transpiration of the WW plants was higher than in the different FTSW treatment  
31 319 although the difference with the 0.5 FTSW was small. Within the WW (well watered) and the  
32 320 different water stress treatments (0.5, 0.4, 0.3, 0.2 FTSW) of Experiment 1 (Fig. 6a) there  
33 321 were only slight differences between tolerant and sensitive genotypes. However, after  
34 322 normalizing the transpiration data for each individual genotype tolerant parent PRLT2/89-33  
35 323 had lower NTR (normalized transpiration ratio) than the sensitive parent H77/833-2 at 0.3  
36 324 FTSW (Fig. 6b). Similar results were observed in the case of 863B and 841B parental pair  
37 325 where the difference in transpiration showed no clear trend (Fig. 6c) but where 863B (tolerant  
38 326 parent) had lower NTR than 841B (sensitive parent) at 0.3 and 0.5 FTSW (Fig. 6d). In Exp.2,  
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3 327 transpiration (Supplementary Fig. 1a) was similar in PRLT 2/89-33, H77/833-2, ICMR  
4 328 01046, and ICMR 01029 but the NTR of tolerant parent PRLT2/89-33 and ICMR 01029 was  
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6 329 lower than the sensitive parent H77/833-2 and ICMR 01046 (Supplementary Fig. 1b). Similar  
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8 330 results were found in Exp.3, where transpiration (Supplementary Fig. 1c) was similar in both  
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10 331 the genotypes but NTR (Supplementary Fig. 1d) of tolerant parent 863B was lower than  
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12 332 sensitive parent 841B in the middle of the grain filling period. This trend of lower NTR was  
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14 333 also observed in Experiment 1 (Fig. 6d) although it was not significant then.

15 334 Under WW conditions and water stress in Experiment 2 and 3 (Fig. 7), soluble sugars  
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17 335 differed significantly among the genotypes. Soluble sugars decreased dramatically under WS  
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19 336 in PRLT2/89-33, ICMR 01029 and 863B, whereas it did not decrease in H77/833-2, ICMR  
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21 337 01046 and 841B. The soluble sugars were expressed per unit of fresh weight. We do not  
22  
23 338 expect the stem relative water content to vary much between genotypes under WS at 30 days  
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25 339 after flowering (i.e. their absolute transpiration was similar across genotypes), so that  
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27 340 genotypic differences under WS conditions would likely not change if data were expressed  
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29 341 per unit of dry weight.

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## 32 343 **Discussion**

### 33 344 **Grain yield decrease under drought was due to a greater effect on seed number than on** 34 35 345 **seed size**

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37 346 The higher seed yield of sensitive parent H77/833-2 under WW conditions was explained by  
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39 347 its higher number of productive tillers (Fig. 2a) which would also explain why seed yield  
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41 348 increased between the harvest at 20 days after flowering and the harvest at maturity (Fig. 1c).  
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43 349 Under WS conditions the large seed yield decrease of H77/833-2 was then mostly due to a  
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45 350 decrease in seed number, which was in part explained by a decreased number of panicles  
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47 351 whereas in PRLT2/89-33 the yield decrease was related to a decrease in the 100-seed weight.  
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49 352 However, the reduction of 100-seed weight in PRLT2/89-33 was proportionally less (23% at  
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51 353 0.3 FTSW compared to the WW conditions, Fig. 4a) than the reduction of seed number in  
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53 354 H77/833-2 (about 65% lower at 0.3 FTSW than under the WW conditions, Fig. 3a). This  
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55 355 explained the lower seed yield of H77/833-2 than PRLT2/89-33 under WS conditions.  
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57 356 Therefore, the lower seed yield in H77/833-2 was due to combined effect of a reduction in  
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59 357 panicle number (productive tillers) and a drastic reduction in seed number. The reduced seed  
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358 number might itself result from a combination of decreased number of panicles bearing seeds



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3 359 and abortion of some of the grain after flowering, although we don't have sufficient data to  
4 360 fully conclude on this. Therefore, future work should look at each individual tiller to assess  
5 361 the decrease in seed number and seed size in each of these, in relation to the timing of  
6 362 flowering of these tillers. An interesting insight would then be to compare sink strength in  
7 363 each tiller and carbohydrate content. In the 841B and 863B pair the number of seeds also  
8 364 decreased relatively more in 841B than in 863B at 0.3 FTSW and decrease yield more in  
9 365 841B. These results are in agreement with Blum et al. (1990) who suggested that yield  
10 366 reduction under water stress at later stages was mainly due to the number of grains per spike.  
11 367 These data agree with earlier work in pearl millet (eg Bidinger et al., 1987; 2004). Similar  
12 368 results were reported by Izanloo et al. (2008) in wheat who reported that water stress reduced  
13 369 yield through tiller abortion and lower grain number per spike. Interestingly, similar  
14 370 observations have been made in legumes, i.e. in bean (Szilagyi., 2003), and chickpea  
15 371 (Zaman-Allah et al., 2011), where the reduction in seed yield under water stress was due to a  
16 372 decrease in pod number per plant and in seed number per pod, but not to a reduction in the  
17 373 100-seed weight.

18 374 The higher seed yield of PRLT2/89-33 under WS conditions was then due to its capacity to  
19 375 retain seed number relatively unchanged at 0.3 FTSW (about 75% of that under WW  
20 376 conditions) and to limit the reduction in seed size. This may be related to the fact that the  
21 377 increase in grain size is limited in high tillering genotype H77/833-2 either due to genetically  
22 378 maximum grain size or inadequate availability of assimilates for grain filling. Response of  
23 379 stronger sink towards higher yields has been reported in barley and wheat (Voltas et al.,  
24 380 1997; Cartelle et al., 2006). Similarly, the low-tillering large seeded genotype PRLT2/89-33  
25 381 have greater ability to adjust grain number and individual grain mass thus affecting panicle  
26 382 productivity (Bidinger and Raju, 2000). These genotypes have been bred for higher yield  
27 383 through maintaining higher individual grain mass.

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### 29 385 **Traits dynamics in parental and introgression lines**

30 386 Under well watered conditions, in PRLT2/89-33, there was no increase in vegetative  
31 387 biomass after flowering whereas the vegetative biomass of H77/833-2, but also that of  
32 388 introgressed lines having drought QTL of tolerant donor parent PRLT2/89-33, increased  
33 389 during grain filling. This increase in both vegetative biomass and in grain yield in the high  
34 390 tillering material was also possible because of the fairly wide spacing of the plants in the

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3 391 glasshouse (about 5 plant m<sup>-2</sup>). Under water stress (0.3 FTSW), a significant decrease in the  
4 392 vegetative biomass of high tillering H77/833-2 genotype was likely related to a decrease in  
5 393 the number of productive tillers, in part shown in Fig. 2a. Therefore, this led to a significantly  
6 394 lower yield than in PRLT2/89-33 and ILs. The advantage conferred by the introgression of  
7 395 the QTL over H77/833-2 was in two ways: (i) larger seed size than in H77/833-2 and the  
8 396 capacity to sustain seed filling well into the drought period, whereas the seed filling duration  
9 397 of H77/833-2 was short; (ii) having a seed number intermediate between the two parents and  
10 398 the capacity to retain a relatively high seed number under WS conditions. These experimental  
11 399 results are in agreement with previous findings (Serraj et al., 2005). Another advantage of the  
12 400 IL lines could have been in having larger panicle size than the recurrent parent, although we  
13 401 have no data to support this and only qualitative observations. Similar conclusions have also  
14 402 been drawn by Bolanos (1995) where superior yield of hybrids was mostly due to larger sink  
15 403 (larger ear weight and ear growth rate). PRLT2/89-33 and ILs had indeed a high grain filling  
16 404 ability under both WW and WS conditions, shown by their capacity to sustain seed filling  
17 405 until maturity, whereas the seed size of H77/833-2 was the same at each of the three harvests  
18 406 under WS conditions (Fig. 4c). ICMR 1046 maintained the 100-seed weight similar to  
19 407 drought tolerant PRLT2/89-33 parent under WS conditions. This provides us evidence that  
20 408 the donor QTL help in maintaining the grain filling ability. The seed number in ILs was also  
21 409 decreased less dramatically than in recurrent parent H77/833-2. Among the two introgression  
22 410 lines that are nearly isogenic, ICMR 01046 and ICMR 01029 were highly similar to  
23 411 PRLT2/89-33 parent for most traits. Thus, besides a large grain size with low grain number to  
24 412 keep up the yield under post flowering drought stress (Bidinger and Raju, 2000), as shown in  
25 413 the previous section, the added advantage of tolerant materials seems to be in the capacity to  
26 414 maintain grain filling for a longer period. This was not related to a higher water extraction  
27 415 capacity, but rather from having water saving mechanisms operating earlier in the crop cycle  
28 416 and making water available during the grain filling period (Kholova et al., 2010a; Vadez et  
29 417 al., 2013).

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#### 419 **Carbohydrate translocation and transpiration**

420 Synthesis, storage and mobilization of carbohydrates under water stress are essential  
421 processes for grain filling (Gupta et al., 2011). Reduction of assimilates under water stress  
422 that limits grain filling has been reported (Mahalakshmi et al., 1993). The percentage  
423 decrease in total soluble sugars was high in ICMR 01029 (52%) and tolerant parents



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3 424 PRLT2/89-33 (24%), 863B (25%). However, there was no reduction under WS conditions in  
4 425 sensitive parents H77/833-2 and 841B (Fig.7). Therefore, we may interpret that part of the  
5 426 seed setting or seed filling failure was related to the inability to remobilize sugars from the  
6 427 stem in sensitive lines. The reasons for that are unknown but could be related to poor  
7 428 translocation or enzymatic activities, and further research would be needed in the  
8 429 mechanisms that regulate grain filling.

13 430 Transpiration, which was used as a simple proxy for photosynthesis, decreased with  
14 431 progressive exposure to water stress. The absolute transpiration values were not very  
15 432 different between genotypes at any of the treatment although relative to the control, the NTR  
16 433 of tolerant genotypes was below that of the sensitive parents. Interestingly, once the FTSW  
17 434 was set at each of the pre-determined levels, transpiration remained relatively constant and  
18 435 did not vary much between genotypes. Since the vegetative biomass did not increase in  
19 436 PRLT2/89-33 during grain filling under WW conditions, and it increased only slightly in ILs,  
20 437 the transpiration occurring during the grain filling period would have mostly supported the  
21 438 filling of grains. By contrast, in H77/833-2, the large increase in vegetative biomass during  
22 439 the grain filling period under WW implies that tiller growth continued well into the grain  
23 440 filling period and then contributed to grain yield, if water was available. Under water stress,  
24 441 although there was no significant increase in vegetative biomass, we may hypothesize that  
25 442 competition may have occurred between grain filling of the early tillers and the developing  
26 443 tillers, which may in part explain the failure of a number of grains, but also an inadequate  
27 444 carbon accumulation that limits tiller growth and then limits yield under WS. In the case of  
28 445 863B, the higher transpiration efficiency of this line, reported earlier (Kholová et al., 2010b),  
29 446 might have also contributed to the higher vegetative biomass than in 841B under 0.3 FTSW,  
30 447 and therefore a higher yield. Therefore, higher yield of 863B parent was apparently due to its  
31 448 combined effort in keeping up the number of reproductive tillers and seed number in  
32 449 comparison to the sensitive parent 841B which had lower vegetative biomass (likely linked to  
33 450 lesser number of reproductive tillers, Fig.2b) and seed number under water stress (0.3  
34 451 FTSW). This data is in support with previous results on these two lines (Yadav et al., 2004).

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## 52 53 453 **Conclusion**

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55 454 Water stress affected the seed yield dramatically under terminal drought conditions,  
56 455 especially in sensitive genotypes (H77/833-2 and 841B). This was related to their yield

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3 456 architecture causing a decline in the number of productive panicles thereby effecting the seed  
4 457 number, ultimately the total seed weight. The seed number started showing the effect of water  
5 458 stress at levels of soil moisture where the 100-seed weight was still not affected and the  
6 459 magnitude of the decrease in seed number was higher than the magnitude of the decrease in  
7 460 the 100-seed weight. By contrast, the 100-seed weight was more affected in tolerant  
8 461 genotypes by water stress than in sensitive genotypes, even though all the genotypes had very  
9 462 severe 100-seed weight reductions at the most severe stress. Thus, retention of seed number  
10 463 and sustained seed filling under water stress resulted in higher yield in tolerant parents  
11 464 PRLT2/89-33 and 863B. However, these criteria may not be suited for unpredicted and pre-  
12 465 flowering water stress conditions. IL-QTL's followed the pattern of tolerant parent  
13 466 PRLT2/89-33 under water stress in their seed number and seed filling, which suggests that  
14 467 the terminal drought tolerance QTL may have some role to play in the maintenance of a  
15 468 higher number of seeds under water stress and a relatively higher grain size than recurrent  
16 469 parent H77/833-2.  
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## 479 **References**

480 Andrews, D. J., and K. Anand Kumar, 1996: Use of the West African pearl millet landrace  
481 Iniadi in cultivar development. *Plant Genet. Res. Newslett.* 105, 15–22.  
482 Bidinger, F. R., and C. T. Hash, 2004: Pearl millet. In: Nguyen, H.T., Blum, A. (Eds.),  
483 *Physiology and Biotechnology Integration for Plant Breeding.* Marcel Dekker, New York,  
484 USA, pp. 225-270.

- 1  
2  
3 485 Bidinger F. R., V. Mahalakshmi, and G. D. P. Rao, 1987: Assessment of drought resistance in  
4 486 pearl millet [*Pennisetum americanm* (L.) Leeke]. II estimation of genotype response to  
5 487 stress. *Aust. J. Ag. Res.* 38, 49-59
- 6  
7  
8 488 Bidinger, F. R., and D. S. Raju, 2000: Response to Selection for Increased Individual Grain  
9 489 Mass in Pearl Millet. *Crop Sci.*, 40, 68-71.
- 10  
11 490 Bidinger, F. R., T. Nepolean, C. T. Hash, R. S. Yadav, and C. J. Howarth, 2007:  
12 491 Identification of QTLs for grain yield of pearl millet (*Pennisetum glaucum* (L.) R. Br.) in  
13 492 environments with variable moisture during grain filling. *Crop Sci.* 47, 969–980.
- 14  
15  
16 493 Bidinger, F. R., R. Serraj, S. M. H. Rizvi, R. S. Yadav, and C. T. Hash, 2004: Comparison of  
17 494 drought tolerance QTL and field performance as a basis for selection of component lines  
18 495 for pearl millet [*Pennisetum glaucum* (L.) R. Br.] topcross pollinators. *Field Crops Res.*  
19 496 94, 14-32.
- 20  
21  
22 497 Blum, A., S. Ramaiah, E. T. Kanemasu, and G. M. Paulsen, 1990: Wheat recovery  
23 498 from drought stress at the tillering stage of development. *Field Crops Res.* 24, 67-  
24 499 85.
- 25  
26  
27 500 Bolanos, J. 1995: Physiological bases for yield differences in selected maize cultivars  
28 501 from Central America. *Field Crops Res.* 42, 69-80.
- 29  
30  
31 502 Cartelle, J., A. Pedro, R. Savin, G. A. Slafer, 2006: Grain weight responses to post  
32 503 anthesis spikelet –trimming in an old and a modern wheat under Mediterranean  
33 504 conditions. *Eur. J. Ag.* 25, 365-371.
- 34  
35  
36 505 Chhina, B.S., and P. S. Phul, 1982: Association of seed size and seedling vigour with various  
37 506 morphological traits in pearl millet. *Seed Sci. Tech.* 10: 541-545.
- 38  
39  
40 507 DeWet, J. M. J., F. R. Bidinger, and J. M. Peacock, 1992: Pearl Millet (*Pennisetum glaucum*)  
41 508 a cereal of the Sahel. In G.P. Chapman (ed.) *Desertified grasslands: Their biology and*  
42 509 *management.* Academic Press, London. p. 259–267.
- 43  
44  
45 510 Dubois, M., K. A., J. K. Gilles, P. Hamilton, A. Rebers, F. Smith, 1956: Colorimetric method  
46 511 for the determination of sugars and related substances. *Annal. Chem.*, 28, 350–356.
- 47  
48 512 Gupta, A. K, K. Kaur, and N. Kaur, 2011: Stem Reserve Mobilization and Sink activity in  
49 513 Wheat under Drought Conditions. *Am. J. Plant Sci.* 2, 70-77
- 50  
51 514 IARI reports, 2006: New varieties of millet released for dry land. *Magazine National*  
52 515 *Herald.*
- 53  
54  
55 516 Izanloo, A, A. G. Condon, P. Langridge, M. Tester, and T. Schnurbusch, 2008: Different  
56 517 mechanisms of adaptation to cyclic water stress in two South Australian bread wheat  
57 518 cultivars. *J. Exp. Bot.* 59, 3327–3346.

- 1  
2  
3 519 Kapoor, R.L., P. S. Karkar, I. S. Khairwal, C. R. Baniwal, D. C. Nijhawan, and H. P. Yadav,  
4 520 1989: Bajra hybrid HHB 67: a major break through. Haryana Farming 18, 17–21.
- 5  
6 521 Kelley, T.G., P. Parthasarathy Rao, R. E. Weltzien, and M. L. Purohit, 1996: Adoption of  
7 522 improved cultivars of pearl millet in an arid environment: straw yield and quality  
8 523 considerations in western Rajasthan. Exp. Agric. 32, 161-171.
- 9  
10 524 Kholová, J., C. T. Hash, A. Kakkera, M. Kochová M, and V. Vadez, 2010a: Constitutive  
11 525 water conserving mechanisms are correlated with the terminal drought tolerance of pearl  
12 526 millet (*Pennisetum americanum* L.). J. Exp. Bot. 61, 369–377.
- 13  
14 527 Kholová, J., C. T. Hash, L. K. Kumar, R. S. Yadav, M. Kočvá , and V. Vadez, 2010b:  
15 528 Terminal drought tolerant pearl millet [*Pennisetum glaucum* (L.) R. Br.] have high leaf  
16 529 ABA and limit transpiration at high vapor pressure deficit. J. Exp. Bot. 61, 1431–1440.
- 17  
18 530 Lawan, M., F. L. Barnett, B. Kaleeq, and R. L. Vanderlip, 1985: Seed density and seed size  
19 531 of pearl millet as related to field emergence and several seed and seedling traits. Agron. J.  
20 532 77, 567-571.
- 21  
22 533 Mahalakshmi, V., S. Sivaramakrishnan, F. R. Bidinger, 1993: Contribution of Pre- and Post  
23 534 anthesis Photosynthates to Grains in Pearl Millet under Water Deficit. J. Agr. Crop Sci.  
24 535 170, 91-96.
- 25  
26 536 Phul, P. S., and D. S. Athwal, 1969: Inheritance in grain size and grain hardness in pearl  
27 537 millet. Indian J. Genet. Pl. Breed. 29, 184-191.
- 28  
29 538 Rooney, L. W., and C. M. McDonough, 1987: Food quality and consumer acceptance of  
30 539 pearl millet. In: Proceedings of the international pearl millet workshop, ICRISAT center,  
31 540 India. 7-11 April 1986. ICRISAT, Patancheru, India. pp.43-61.
- 32  
33 541 Serraj, R., C. T. Hash, S. M. H. Rizvi, A. Sharma, R. S. Yadav, and F. R. Bidinger, 2005:  
34 542 Recent advances in marker-assisted selection for drought tolerance in pearl millet. Plant  
35 543 Prod Sci 8, 332-335.
- 36  
37 544 Sharma, P. C., and R.S. Pareek, 1993: Variability of southwest monsoon in west Rajasthan  
38 545 during last two decades. Mausam 44, 389-391.
- 39  
40 546 Siband, P., I. Dieye, R. E. Weltzien, and B. C. Faye, 1978: Evolution ponderale de  
41 547 l'epuisement du grain. Agron. Trop. 34:250–257.
- 42  
43 548 Szilagyi, L., 2003: Influence of drought on seed yield components in common bean. J.  
44 549 Plant Physiol. 43, 320-330.
- 45  
46 550 Vadez, V., J. Kholova, M. Zaman-Allah, and N. Belko, 2013: Water: the most  
47 551 important 'molecular' component of water stress tolerance research. Funct. Plant  
48 552 Biol. (in press) <http://dx.doi.org/10.1071/FP13149>
- 49  
50  
51  
52  
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54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 553 van Oosterom, E. J., M. L. Whitaker, and R. E. Weltzien, 1996: Integrating genotype x  
4 554 environment analysis, characterisation of drought patterns, and farmer preferences to  
5 555 identify adaptive plant traits for pearl millet. In: Plant adaptation and crop improvement.  
6 556 (Cooper, M. and G.L. Hammer, Eds.). CAB International/IRRI/ ICRISAT, pp. 383-402.  
7  
8 557 Voltas, J., I. Romagosa, J. L. Araus, 1997: Grain size and nitrogen accumulation in  
9 558 sink-reduced barley under Mediterranean conditions. *Field Crops Res.* 52, 117-126.  
10  
11 559 Yadav, R. S., C. T. Hash, F. R. Bidinger, K. M. Devos, and C. J. Howarth, 2004:  
12 560 Genomic regions associated with grain yield and aspects of post-flowering drought  
13 561 tolerance in pearl millet across stress environments and tester background.  
14 562 *Euphytica*, 136: 265-277.  
15  
16 563 Yadav, R. S., C. T. Hash, F. R. Bidinger, G. P. Cavan, and C. J. Howarth, 2002:  
17 564 Quantitative trait loci associated with traits determining grain and stover yield in pearl  
18 565 millet under terminal drought stress conditions. *Theor. Appl. Genet.* 104, 67–83.  
19  
20 566 Zaman-Allah, M., D. Jenkinson, and V. Vadez, 2011: A conservative pattern of water use,  
21 567 rather than deep or profuse rooting, is critical for the terminal drought tolerance of  
22 568 chickpea. *J. Exp. Bot.* 62, 4239-4252. doi: 10.1093/jxb/err139.  
23  
24  
25  
26  
27  
28  
29 569  
30  
31  
32  
33  
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**Figure legends**

Figure 1. Total seed weight of two pairs of pearl millet test cross hybrids PRLT 2/89-33 and H77/833-2 (a), 863B and 841B (b) exposed to different water regimes, i.e. a well-watered control (WW) and four water stress treatments imposed by maintaining soil moisture at 0.5, 0.4, 0.3 and 0.2 FTSW (fraction of transpirable soil water). Treatments with same letters on the x-axis were not significantly different. Star represented above the bar ( $\pm$ SE) indicates significant genotypic differences within the treatment ( $P < 0.1$ ). The total seed weight was also monitored at different days after flowering (DAF, c and d) in two pearl millet test cross hybrids of PRLT2/89-33 (tolerant), H77/833-2 (sensitive) and their NILs ICMR 01046, and ICMR 01029 (c) and in 863B and 841B (d) under well watered (WW) and water stress (WS) conditions (i.e. 0.3 FTSW). Values are means ( $\pm$ SE) of each genotype harvested at 10, 20, and 30 DAF. Values were compared across harvest time for each genotype and harvest time values for with same letters above the bar were not significantly different ( $P < 0.1$ ).

Figure 2. Panicle number of two pairs of pearl millet test cross hybrids: PRLT 2/89-33, and H77/833-2 (a), 863B and 841B (b) exposed to different water regimes, i.e. a well-watered control (WW) and four water stress treatments imposed by maintaining soil moisture at 0.5, 0.4, 0.3 and 0.2 FTSW (fraction of transpirable soil water). Treatments with same letters on the x-axis were not significantly different. Star represented above the bar ( $\pm$ SE) indicates significant genotypic differences within treatment ( $P < 0.05$ ).

Figure 3. Seed number of two pairs of pearl millet test cross hybrids PRLT 2/89-33 and H77/833-2 (a), 863B and 841B (b) exposed to different water regimes, i.e. a well-watered control (WW) and four water stress treatments imposed by maintaining soil moisture at 0.5, 0.4, 0.3 and 0.2 FTSW (fraction of transpirable soil water). Treatments with same letters on the x-axis were not significantly different. Star represented above the bar ( $\pm$ SE) indicates significant genotypic differences within the treatment ( $P < 0.01$ ). Seed number was also monitored at different days after flowering (DAF, c and d) in two pearl millet test cross hybrids of PRLT2/89-33 (tolerant), H77/833-2 (sensitive) and their NILs ICMR 01046, ICMR 01029 (c) and in 863B and 841B (d) under well watered (WW) and water stress (WS) conditions (0.3 FTSW). Values are means ( $\pm$ SE) of each genotype harvested at 10, 20, and 30 DAF. Values were compared across harvest time for each genotype ( $P < 0.05$ ) and harvest time values with same letters above the bar were not significantly different



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4 604 Figure 4. 100 seed weight of two pairs of pearl millet test cross hybrids PRLT 2/89-33 and  
5 605 H77/833-2 (a), 863B and 841B (b) exposed to different water regimes, i.e. a well-watered  
6 606 control (WW) and four water stress treatments imposed by maintaining soil moisture at 0.5,  
7 607 0.4, 0.3 and 0.2 FTSW (fraction of transpirable soil water). Treatments with same letters on  
8 608 the x-axis were not significantly different. Star represented above the bar ( $\pm$ SE) indicates  
9 609 significant genotypic differences within the treatment ( $P < 0.05$ ). The 100 seed weight was  
10 610 also monitored at different days after flowering (DAF, c and d) in two pearl millet test cross  
11 611 hybrids of PRLT2/89-33 (tolerant), H77/833-2 (sensitive) and their NILs ICMR 01046,  
12 612 ICMR 01029 (c) and in 863B and 841B (d) under well watered (WW) and water stress (WS)  
13 613 conditions (0.3 FTSW). Values are means ( $\pm$ SE) of each genotype harvested at 10, 20, and 30  
14 614 DAF. Values were compared across harvest time for each genotype ( $P < 0.05$ ) and harvest  
15 615 time values with same letters above the bar were not significantly different.

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26 617 Figure 5: Stover biomass (Stem + leaves) of two pairs of pearl millet test cross hybrids PRLT  
27 618 2/89-33 and H77/833-2 (a), 863B and 841B (b) exposed to different water regimes, i.e. a  
28 619 well-watered control (WW) and four water stress treatments imposed by maintaining soil  
29 620 moisture at 0.5, 0.4, 0.3 and 0.2 FTSW (fraction of transpirable soil water). Treatments with  
30 621 same letters on the x-axis were not significantly different. Star represented above the bar  
31 622 ( $\pm$ SE) indicates significant genotypic differences within treatment ( $P < 0.05$ ). The stover  
32 623 biomass (leaf and stem) was also monitored at different days after flowering (DAF, c and d)  
33 624 in two pearl millet test cross hybrids of PRLT2/89-33 (tolerant), H77/833-2 (sensitive) and  
34 625 their NILs ICMR 01046, ICMR 01029 (c) and in 863B and 841B (d) under well watered  
35 626 (WW) and water stress (WS) conditions i.e. 0.3 FTSW (fraction of transpirable soil water).  
36 627 Values are means ( $\pm$ SE) of each genotype harvested at 10, 20, and 30 DAF. Values were  
37 628 compared across harvest time for each genotype ( $P < 0.05$ ) and harvest time values with same  
38 629 letters above the bar were not significantly different.

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49 631 Figure 6: Daily transpiration (Exp.1, March 2009) of two pairs of pearl millet test cross  
50 632 hybrids PRLT 2/89-33 and H77/833-2 (a), 863B and 841B (c) exposed to different water  
51 633 regimes, i.e. a well-watered control (WW) and four water stress treatments imposed by  
52 634 maintaining soil moisture at 0.5, 0.4, 0.3, 0.2FTSW after flowering. NTR (normalized  
53 635 transpiration ratio) of these four parental lines PRLT 2/89-33 and H77/833-2 (b), 863B and  
54 636 841B (d) at 0.5 and 0.3 FTSW (fraction of transpirable soil moisture).



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638 Fig. 7: Total carbohydrates from the penultimate internodes of two pearl millet test cross  
639 hybrids of parental lines PRLT2/89-33 (tolerant), H77/833-2 (sensitive), their NILs ICMR  
640 01046, ICMR 01029 ( Exp.2, April 2010 ) and 863B (tolerant), 841B(sensitive) parental  
641 lines harvested at maturity from well watered (WW) and water stress (WS) i.e. 0.3 FTSW  
642 (fraction of transpirable soil water).

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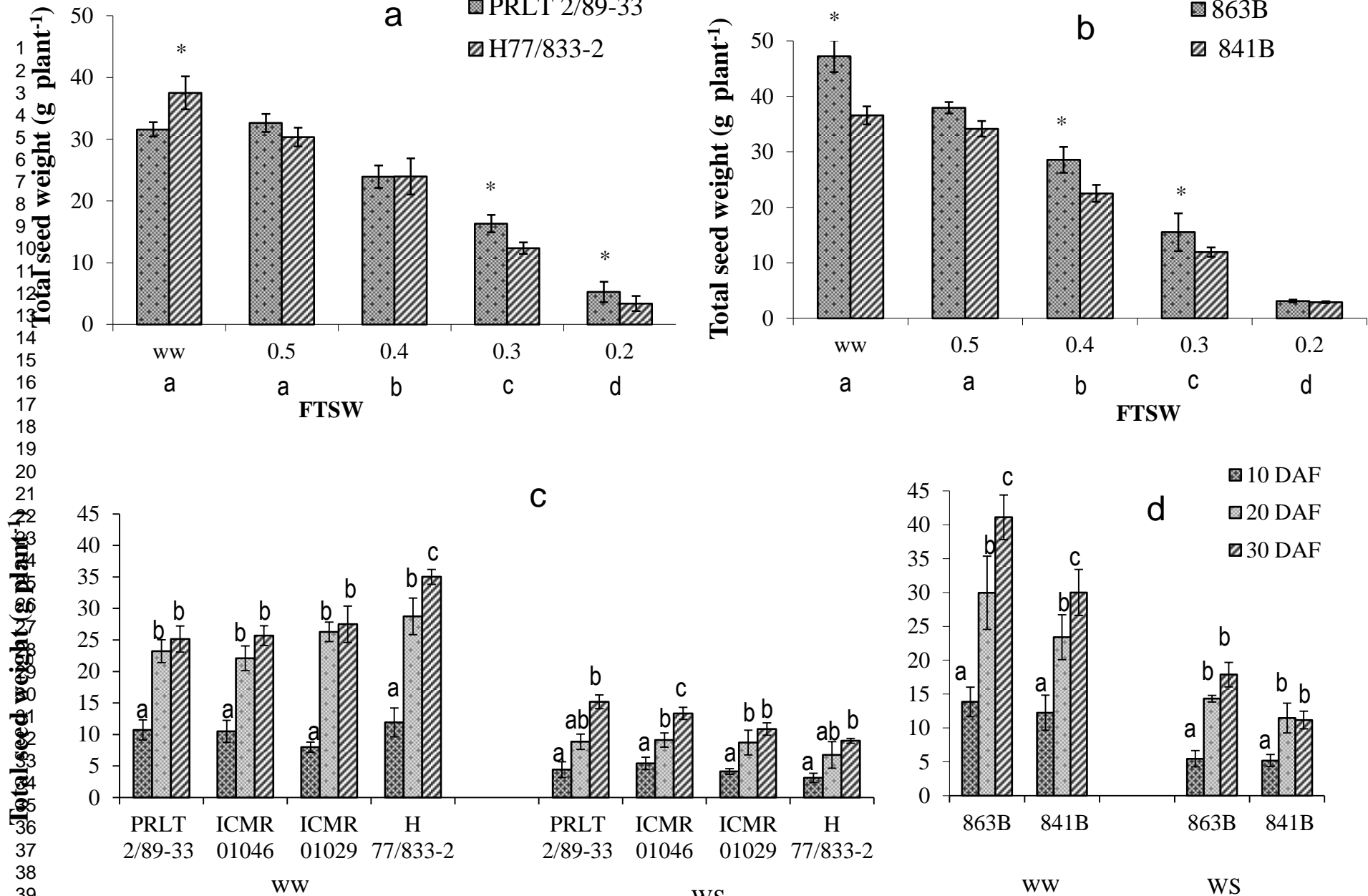


Figure 1

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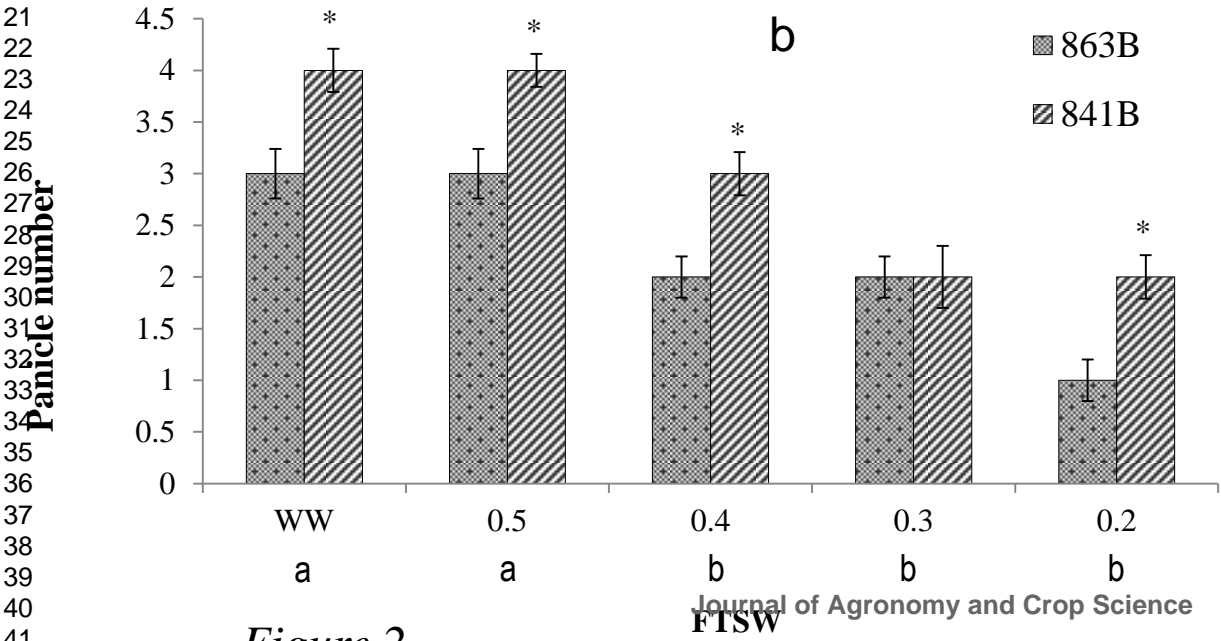
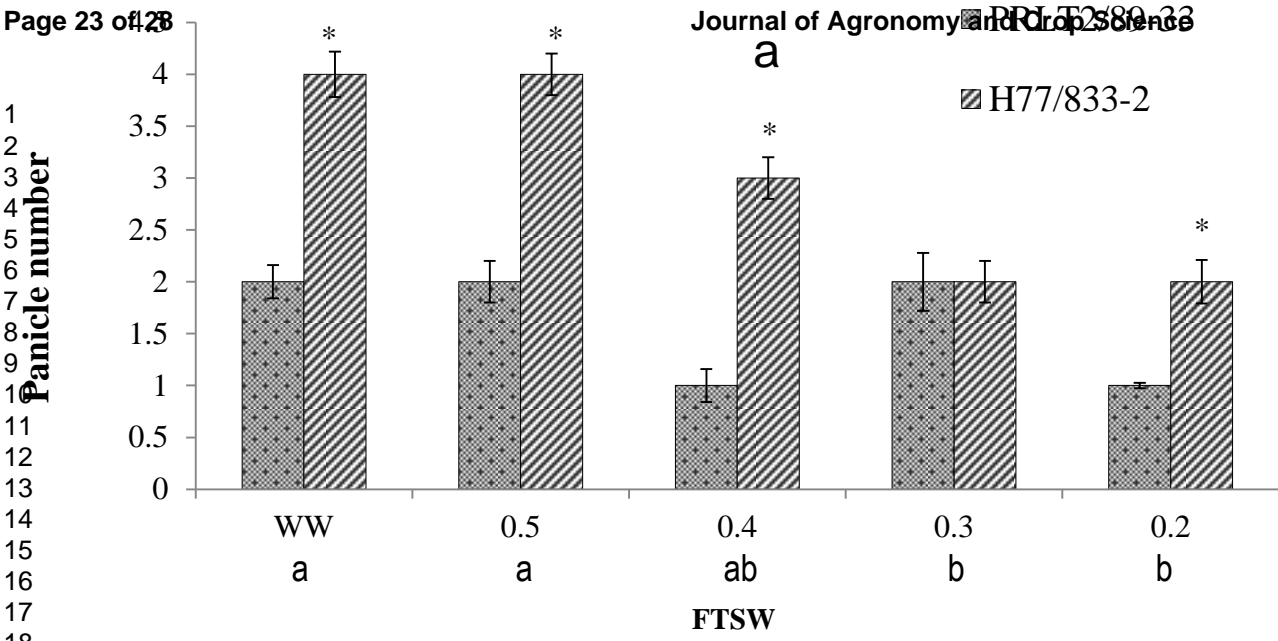


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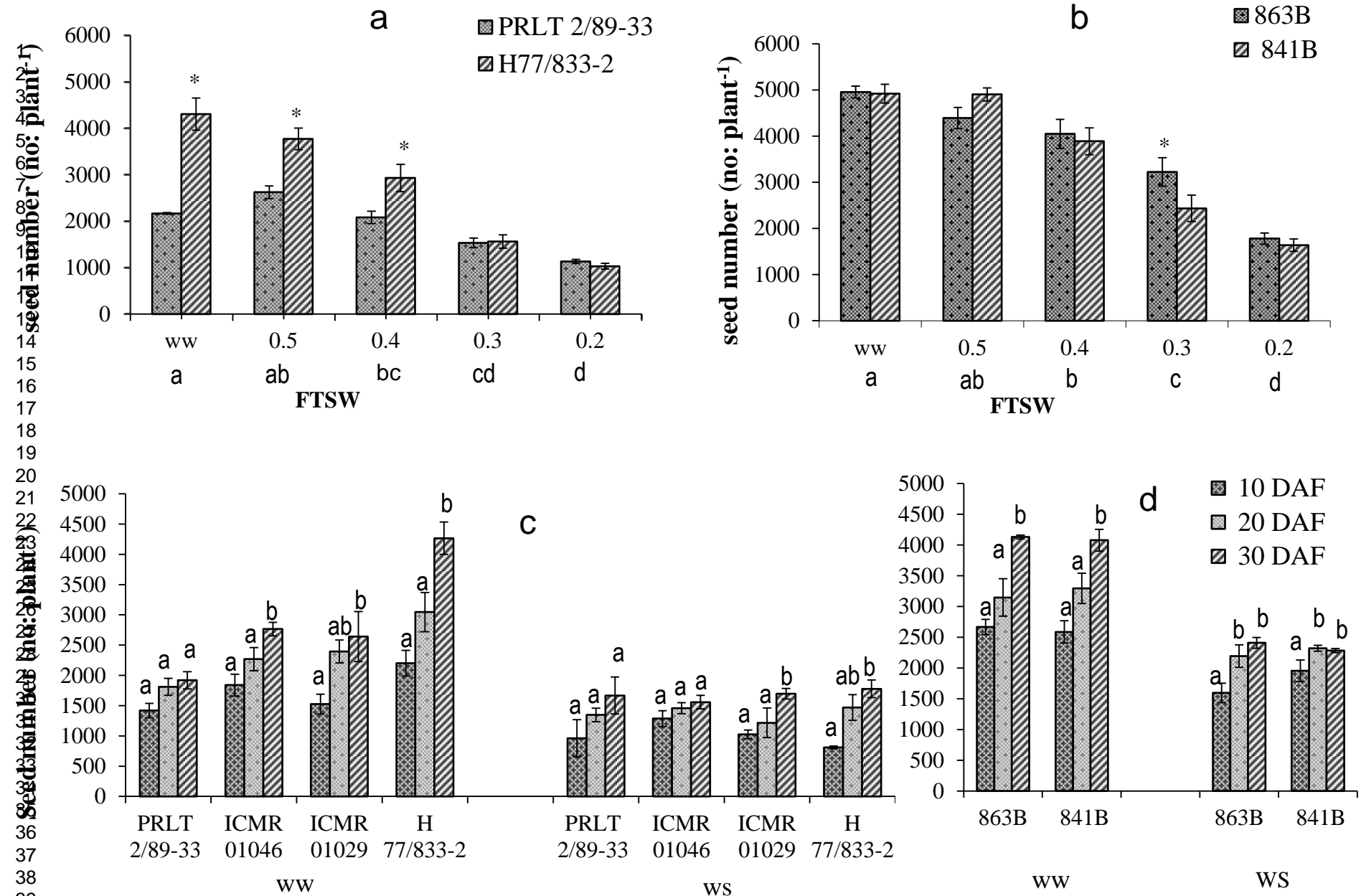
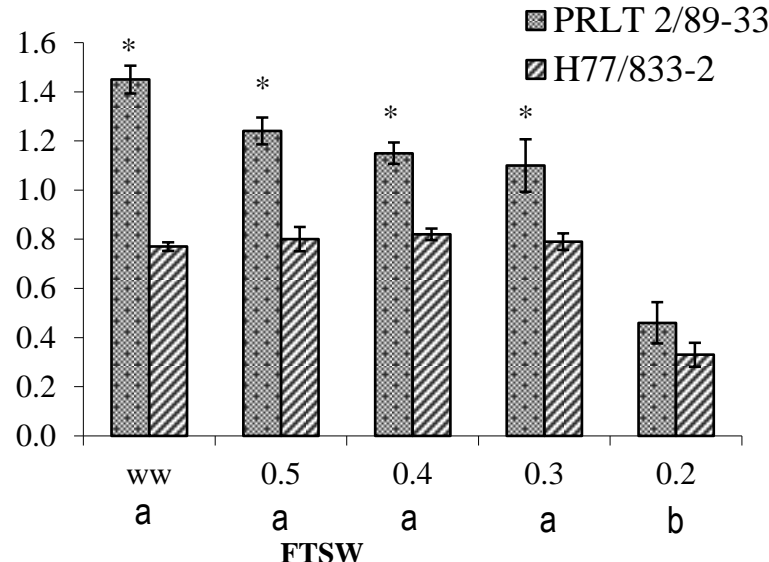
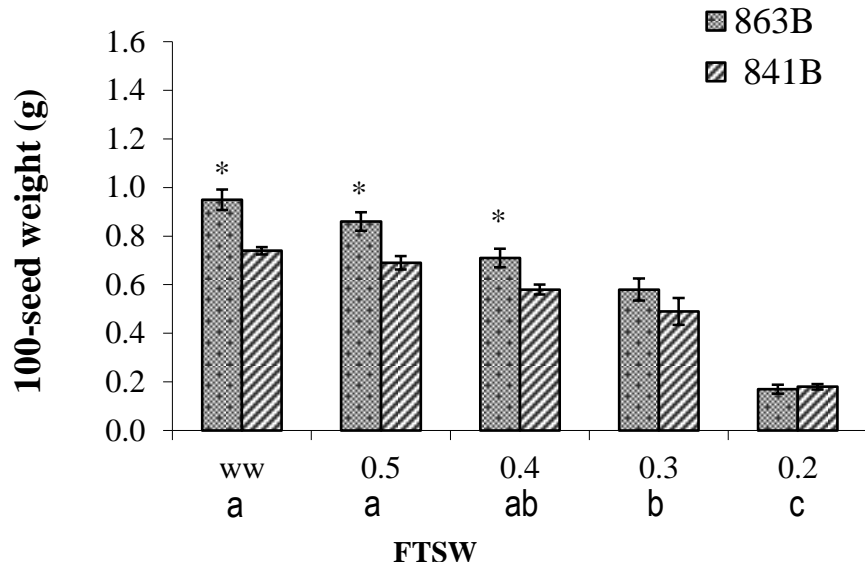


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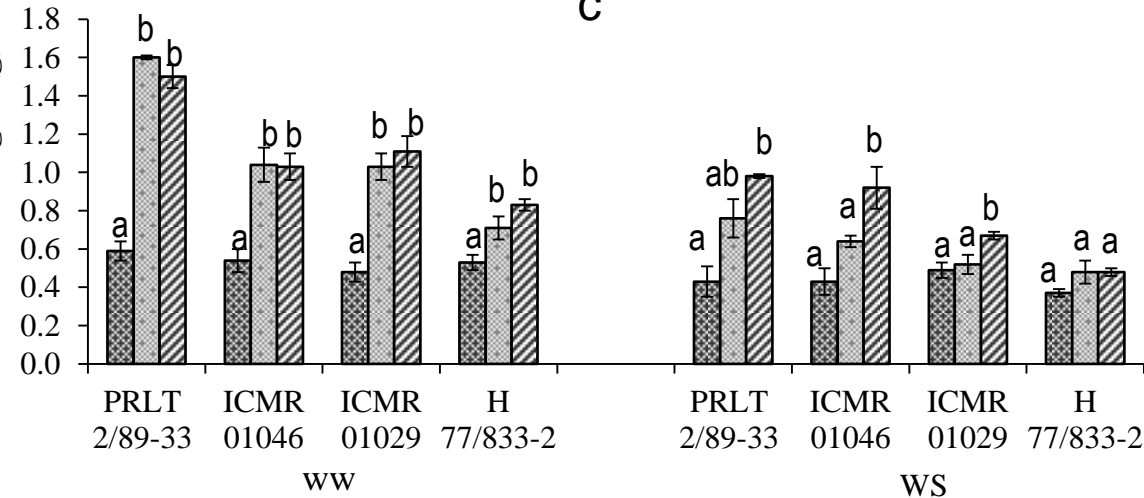
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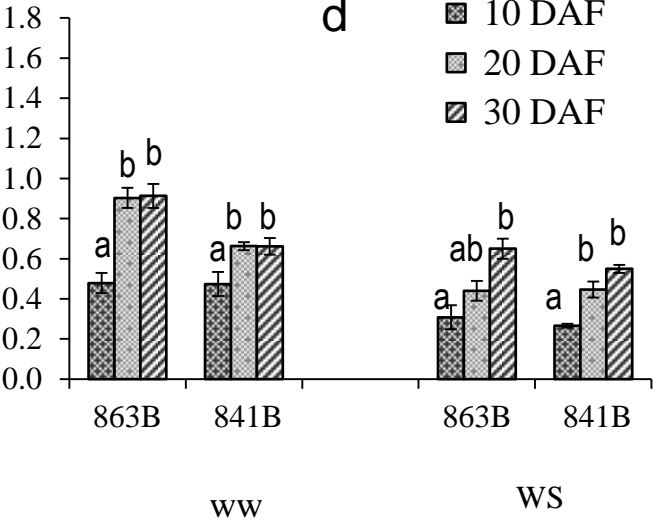


Figure 4

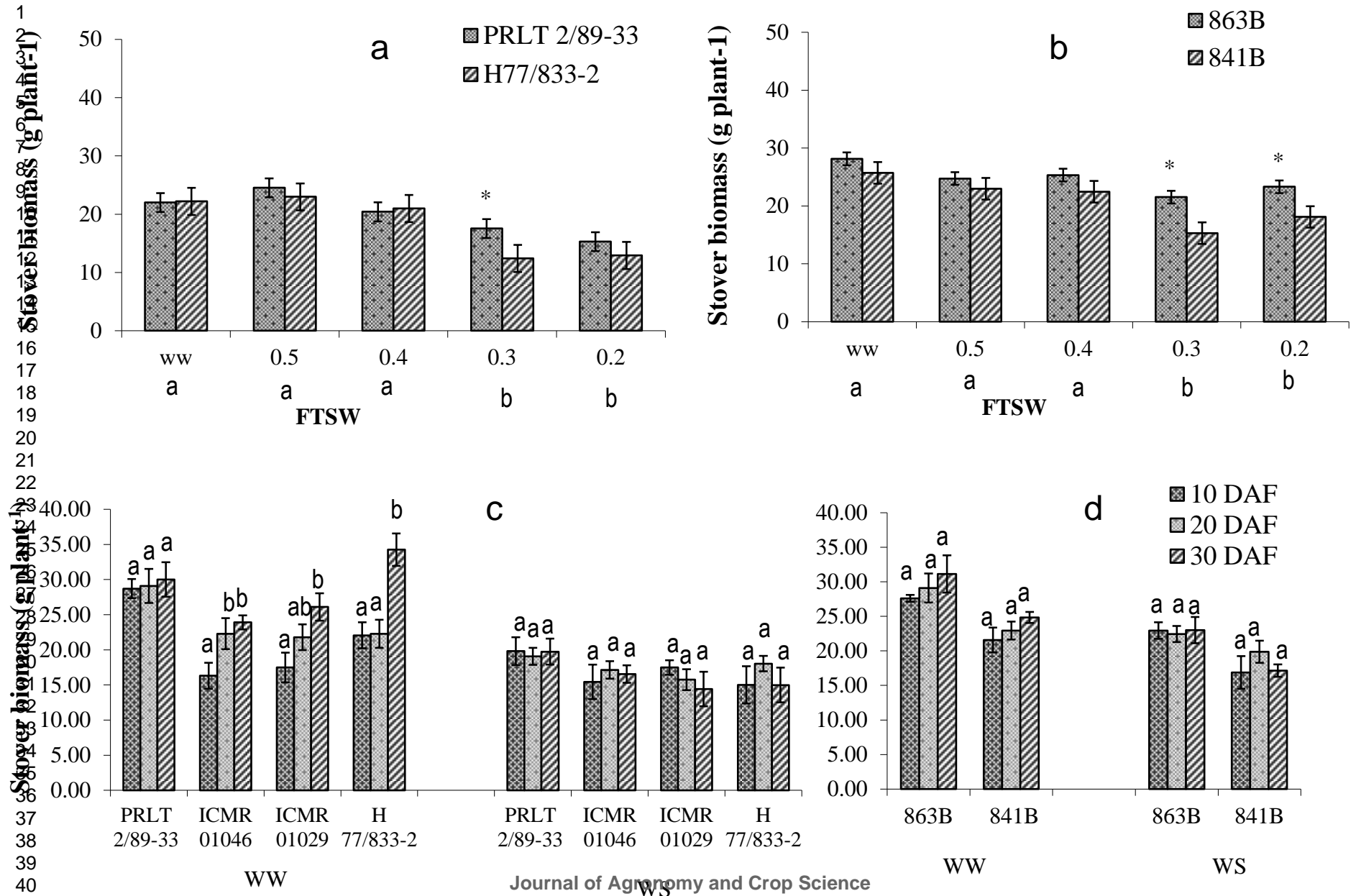


Figure 5

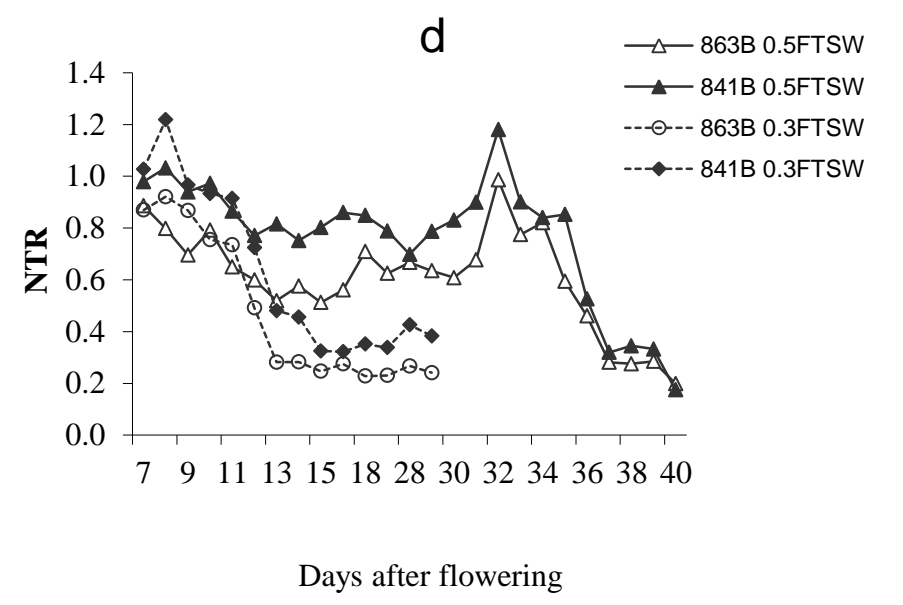
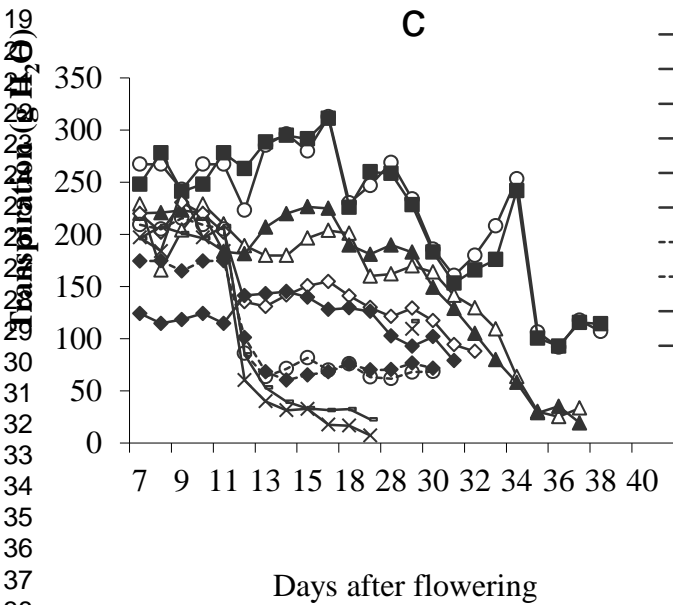
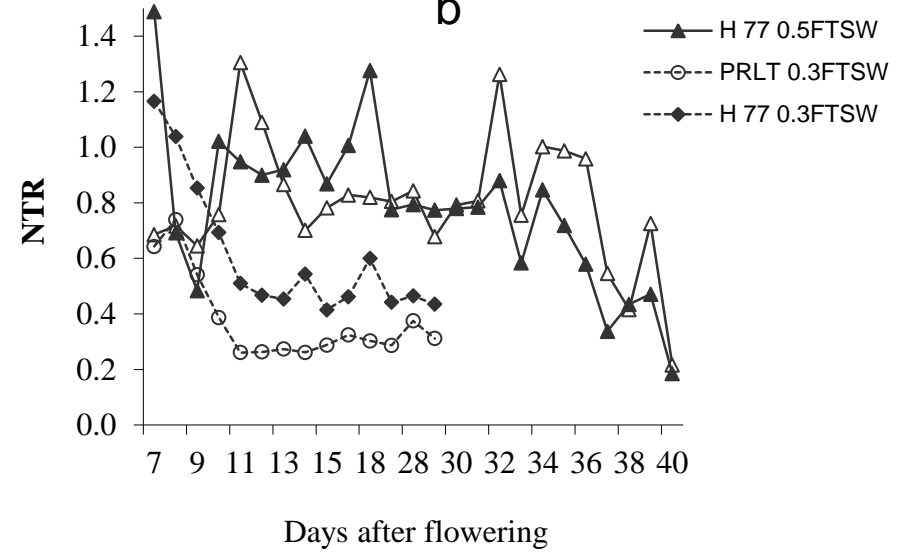
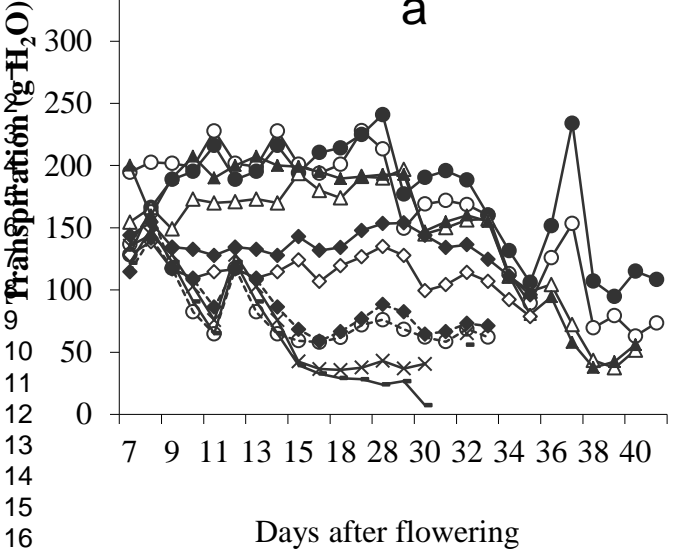


Figure 6



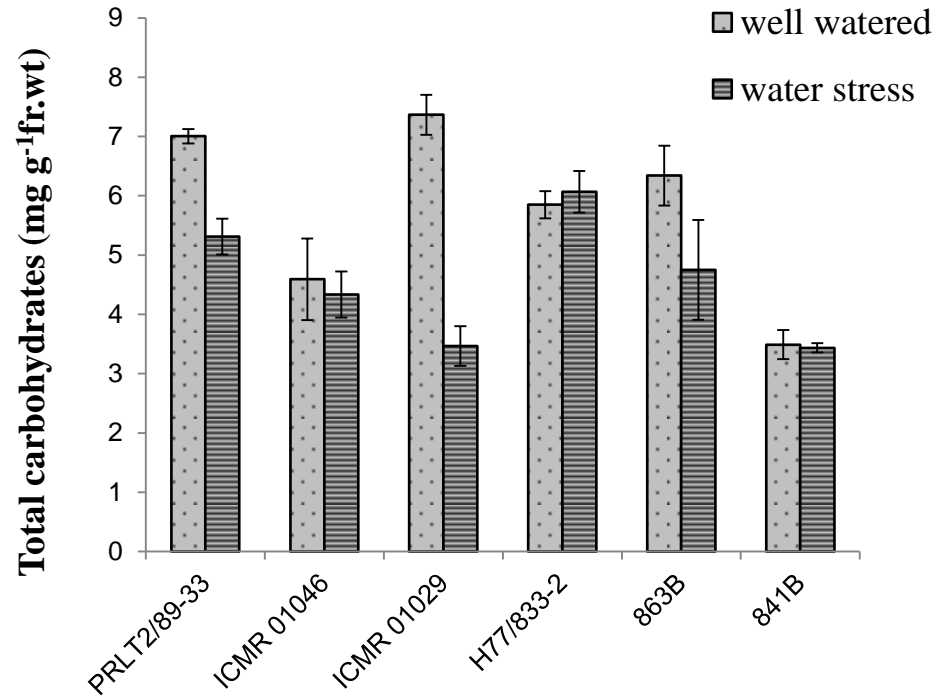


Figure 7