1 Salt tolerance, date of flowering and rain affect the productivity of wheat and barley
2 cultivars on rainfed saline land

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Abstract

Over two growing seasons, we examined the effects of natural field salinity on grain production by a range of wheat and barley genotypes on rainfed (i.e. non-irrigated) land with a Mediterranean climate. Blocks of wheat and barley were grown at adjacent locations, on saline and non-saline sites. The two growing seasons differed in the amount of rain that fell in late Spring during grain filling, which strongly affected soil moisture, and in the salinity of the soil solution during grain filling. In 2009 (less rain in Spring), on the saline site the average salinity of the soil solution during grain fill was ~ 0.4 M, and the 27 earlier flowering barley cultivars had higher grain yields (5th–95th percentile 1.5–3.1 t ha⁻¹) than the 90 wheat genotypes (0.8–2.3 t ha⁻¹). By contrast on the non-saline site in this year the wheat and barley genotypes had similar 5th–95th percentile ranges of grain yield (barley 0.9–2.1 t ha⁻¹; wheat 0.9–1.9 t ha⁻¹). In 2011 (dry early Spring, rain in late Spring), on the saline site the average salinity of the soil solution was less than 0.2 M during grain filling, and the 320 wheat and 14 barley genotypes had similar 5th to 95th percentile ranges in grain yield to each other under saline conditions (barley 1.1–3.1 t ha⁻¹; wheat 1.3–2.9 t ha⁻¹). Comparisons of genotypes common to both sites showed that there were wheat (e.g. Mace, Tammarin Rock, Binnu) and barley cultivars (e.g. Mundah, Parent 19) with consistently higher yields under saline conditions. We conclude that grain yield by cereals on saltland is associated with the severity of salinity, the adaptation of genotypes to local conditions, their salt tolerance, and (in seasons with a dry spring) early flowering.

Keywords: Salinity; salt tolerance; wheat; barley; flowering date

1. Introduction

Salinity is a major constraint to agriculture in many arid and semi-arid regions of the world (Ghassemi et al., 1995), and is one of the major soil constraints in the Australian wheatbelt (Dang et al., 2006; McDonald et al., 2012). This paper focuses on factors affecting the productivity of wheat and barley cultivars on soils affected by dryland salinity in south-western Australia¹. In Australia, two kinds of salinity are recognised: 'dryland salinity' caused by the presence of a saline shallow watertable, and 'transient salinity' caused by the accumulation of salts from rain (c.f. Hingston and Gailitis, 1975) over many hundreds of years in sodic soils (Rengasamy, 2002); both occur on rainfed (non-irrigated) land. It is estimated that 16% of Australia's rainfed cropping area has the potential for

¹ Definitions

Production on salt affected soils refers to grain yield or biomass production in a saline environment. It is affected by the plant's 'local adaptation' and 'salt tolerance'.

'Local adaptation' refers to the suitability of a plant to its local environment. The range of grain yields on a non-saline soil is a useful index of variation in local adaption.

Salt tolerance/salt sensitivity refers to the increment of gain or loss in growth, grain yield or biomass production in a saline environment relative to a control grown in a non-saline environment. For cereal crops the difference in grain yield between plants grown under saline and non-saline conditions is a useful index of variation in salt tolerance.

The electrical conductivity of the soil saturation extract (EC_e) and 1:5 extract ($EC_{1:5}$) are measures of the salt concentration in the soil. These affect plant growth by influencing the salinity of the soil solution.

The salinity of the soil solution is the causal factor that decreases plant growth on saline soils and is the ratio of salt concentration in the soil to water concentration in the soil. For soils affected by NaCl, the salinity of the soil solution (moles L^{-1}) can be estimated from the $EC_{1:5}$ (dS/m) and percent soil moisture (% DM) using the following formula:

$$\text{Salinity of soil solution} = EC_{1:5} * 5 / \text{Soil moisture}$$

dryland salinity, but 67% of the cropping area has the potential for transient salinity (Rengasamy, 2002).

One of the major challenges in determining differences in production between crop genotypes in response to salinity under dryland conditions in the field is that the severity of salinity can be highly temporally variable during the growing season and highly spatially variable over short distances. Temporal variation is caused by the fact that plant growth responds to the salinity of the soil solution, which is proportional to the salt concentration of the soil (of which EC_e and $EC_{1:5}$ are measures) and inversely proportional to the water concentration of the soil (Bennett et al., 2009). On non-irrigated saltland soils in Mediterranean environments, we might therefore expect the salinity of the soil solution to be initially high at the start of winter (the growing season for annual plants) because salt has risen to the soil surface by capillarity from deeper in the soil profile over the preceding summer and autumn, and this salt becomes dissolved in the relatively small amounts of water that are available at the start of the growing season. Later in the growing season we might expect the salinity of the soil solution to decrease because the increasingly abundant winter rains leach salt and also hydrate the soil. Then towards the end of Spring and the start of summer, we might expect the salinity of the soil solution to increase again as the soil dries out. Spatial variation is inherent in salt affected landscapes. Within one field salinities may vary from being negligible to being so high that even halophytes will not grow (Richards, 1983; Barrett-Lennard et al., 2013). Many researchers now use electromagnetic induction to estimate and map spatial variation in soil salinity (e.g. Huang et al., 2016).

1 85 A range of physiological studies suggests that barley has greater tolerance to
2 86 internal Na^+ ions than wheat and is therefore more salt tolerant than wheat (see
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4 87 review by Colmer et al., 2005). Reflecting this physiological understanding,
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6 88 agronomic studies conducted under conditions of controlled salinity have shown
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8 89 greater persistence of leaves and higher grain yields in barley than in wheat. For
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10 90 example, Rawson et al. (1988) grew 5 barley cultivars and 6 bread wheats in
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12 91 irrigated gravel cultures with ~4 weeks exposure to salinities of 0–250 mM NaCl.
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14 92 With an external salinity of 175 mM NaCl, the proportion of the total shoot DM that
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16 93 died was ~13 and 24% for the barley and wheat respectively, whereas at 250 mM
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18 94 NaCl, these proportions had increased to ~34 and 57% of shoot DM respectively
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20 95 (calculated from data of Rawson et al., 1988). In a longer-term trial, Ayers et al.
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22 96 (1952) grew 4 barley and 2 wheat cultivars in 18.2 m² plots irrigated with water
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24 97 salinised to 10,000 ppm with equal parts of NaCl and CaCl_2 to produce soils with an
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26 98 average EC_e (0–30 cm) of 8.7 dS m⁻¹. Under saline conditions, the barley cultivars
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28 99 had final grain yields of 1.9–4.0 t ha⁻¹, whereas the wheat cultivars had average
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30 100 grain yields of ~1.9 t ha⁻¹.
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41 102 There is limited consistent evidence for higher grain yields in barley compared with
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43 103 wheat on saline sites in the field. In one study by Bole and Wells (1979), 7 cultivars
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45 104 of bread wheat, 7 cultivars of 2-row barley and 7 cultivars of 6-row barley were
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47 105 grown under conditions of dryland salinity (average EC_e at 0–30 cm of 9.2 dS m⁻¹)
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49 106 and ~320 mm of seasonal rainfall in Alberta Canada. At harvest, the wheat cultivars
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51 107 had lower grain yields than the 2-row and 6-row barleys, but there were overlapping
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53 108 yield ranges between the three groups of cultivars (wheat 0.8–1.5 t ha⁻¹, 2-row barley
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55 109 1.2–1.8 t ha⁻¹, 6-row barley 1.8–2.6 t ha⁻¹). By contrast, in another study on an
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irrigated field site in the San Joaquin Valley of California, at an EC_e of $\sim 20 \text{ dS m}^{-1}$, 17 wheat cultivars had virtually the same range of grain yields (5th–95th percentile; 1.5–4.1 t ha⁻¹) as 16 barley cultivars (~ 0.8 – 3.9 t ha^{-1}) (Richards et al., 1987). Clearly, the extrapolation of results from simple physiological experiments conducted under controlled conditions to plant performance on saline land in the field should be questioned.

One reason physiological experiments under controlled conditions may be a poor mimic of the field situation is that such experiments are usually conducted with a constant salinity of the soil solution. However this approach removes the interaction between increasing water stress and differences in the rate of plant development at the end of the growth cycle from considerations of adaptation. One difference between barley and wheat is that barley often flowers and ripens earlier than wheat (Rawson et al., 1988). This means that in situations of declining water availability towards the end of the growing season, early-flowering barley cultivars might be able to fill their seed with carbohydrates before the soil gets too dry and the salinity of the soil solution increases to unacceptable levels, whereas later-flowering wheat cultivars might not be able to do this. Early flowering date associated with escape from salinity could therefore be a critical attribute in explaining differences in yield between barley and wheat on saltland. An extensive survey of wheat yields on land with subsoil constraints across Australia showed that date of maturity was the trait most frequently associated with yield variation (McDonald et al., 2012). The relative importance of early and late flowering varied across the country, but in Western Australia, yield variation was more associated with early flowering (48% of sites examined) than any other factor (McDonald et al., 2012).

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136 This paper describes comparisons of the relative performance of wheat and barley
137 cultivars to non-irrigated (dryland) salinity in two years 2009 and 2011 at a location in
138 Western Australia (Ballidu) with a Mediterranean climate and an annual average
139 rainfall of 335 mm. In each year we planted the wheat and barley cultivars at a non-
140 saline site (enabling us to determine the local adaptation of each cultivar) and at a
141 nearby saline site (enabling us to determine the salt tolerance of each cultivar).

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143 We focus on three issues. Firstly, in situations of moisture constraint or high salinity
144 of the soil solution at the end of the growing season, barley may have higher yields
145 than wheat, but this could be at least partly associated with early flowering.
146 Secondly, on saline sites, the salinity of the soil solution varies seasonally and
147 spatially, and measurement of this variation is important in accounting for the
148 apparent relative differences in tolerance between wheat and barley cultivars.
149 Thirdly, high production on saline field sites is associated with traits associated with
150 both local adaptation and salt tolerance.

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152 **2. Materials and methods**

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154 *2.1. Location of trials and experimental design*

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156 Field trials to evaluate the salinity tolerance of wheat and barley accessions under
157 rain fed conditions were conducted in the 2009 and 2011 growing seasons on saline
158 and non-saline sites near Ballidu, Western Australia. The trials were located on the
159 farm of Mr David Hood, in an area that had been used for cereal cropping over the

160 prior 80 years. In 2009, the saline (S30.5699° E116.8142°) and non-saline
161 (S30.5721° E116.8142°) trial locations were approximately 100 m apart. In 2011, the
162 saline (S30.5700° E116.8148°) and non-saline (S30.6102° E116.8673°) trial
163 locations were ~6.7 km apart.

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165 At each site, the blocks of wheat and barley were planted immediately adjacent to
166 each other, i.e. separated by only two rows of buffer plots. A spatial row-column
167 design with replication in two directions (along rows and columns) was generated
168 using DiGger (Coombes, 2002) and applied. In 2009 we tested 90 wheat cultivars
169 (82 hexaploid bread wheats and 8 durum wheats) and 27 barley cultivars, whereas
170 in 2011 there were 320 bread wheats (including 274 accessions from 2 wheat
171 doubled haploid populations) and 14 barleys; 35 bread wheat cultivars and 8 barley
172 cultivars were common to both years. Data reported in this paper are for the
173 commercial bread wheat, durum wheat and barley cultivars: all data (the commercial
174 cultivars, double haploid and breeders' lines) are reported in the Supplementary
175 Content (Tables S1, S2, S3 and S4). International genotypes of reputed salt
176 tolerance (see Munns et al., 2006) included in our trials were: KRL1-4 and Kharchia
177 65 (both years) and SARC1 (2009 season). In addition, we were able to test several
178 bread wheat (cultivar Westonia) lines containing the *Nax1* and *Nax2* genes; these
179 genes had previously been shown to be associated with improved Na⁺ exclusion
180 (James et al., 2006, 2011).

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182 The plots in all trials were arranged in a rectangular array indexed by rows and
183 columns. In 2009, each block had a completely randomised design with at least 4
184 replicate plots per genotype, in an augmented design with spatial analysis check

cultivars. The incorporation of more frequent plots of standard cultivars was used to identify and account for patterns of spatial variation in the statistical analysis of the growth parameters. In 2009 the wheat trial was arranged in 12 columns by 34 rows, and comprised 4 replicates of 84 test lines, 8 replicates of the commercial cultivars Callingiri, Carnamah, Halberd, Tammarin Rock, Westonia and Wyalkatchem, and 12 replicates of Datatine and Bullaring. The barley trial of the same year was arranged at one end of the wheat trial in 12 columns by 14 rows, and comprised 4 replicates of 19 test lines, 8 replicates of the commercial cultivars Baudin, Gairdner, Skiff and Stirling, 12 replicates of Hamelin and Vlamingh, 16 replicates of Clipper and 20 replicates of Mundah.

In 2011 the wheat trial was arranged in 12 columns by 67 rows; the trial was partly replicated; 99 test lines were not replicated, 170 test lines were replicated twice and the remaining commercial cultivars were replicated between 4 and 8 times (c.f. Cullis et al., 2006). The barley trial in 2011 was arranged in 12 columns by 5 rows; the trial was replicated 4 times with cultivars Stirling and Baudin having 8 replicates.

Agronomic details of the trials are summarised in Table 1. The trials were planted on 16 June 2009 and 31 May 2011. Each plot was 5 m long and 1 m wide, with 5 rows at 20 cm spacing, and therefore had an area of 5 m², 3 m² of which was harvested. Fertiliser and herbicide treatments at sowing were consistent with industry standards in the area (Table 1).

INSERT TABLE 1 NEAR HERE

2.2. Data collected

Rainfall and temperature data were collected from weather stations located at Ballidu (5–9 km from sites) and Wongan Hills Research Station (~30 km from sites) respectively (Bureau of Meteorology, 2016). The temperature data were used to estimate thermal time. The timing (days after sowing; DAS) and thermal times (degree days after sowing; °DAS) associated with all key measurements are reported in Table 1.

Salinity was measured on the saline sites by electromagnetic induction using an EM38 (Geonics Ltd, Mississauga, Ontario, Canada) in the vertical orientation. In each year the trials on the saline sites were situated so that the plot replicates were blocked across the salinity gradient. In 2009 and 2011, EM38 values changed 2–3 fold over the direction of this gradient, but varied little in the other direction. EM38 readings were taken on the saline blocks on 5 occasions in 2009 and on 4 occasions in 2011, and these values were correlated against 5–9 ‘calibration’ soil samples taken on the day of survey at 0–25 cm depth at locations representative of the variation in these EM38 readings. Calibration samples were analysed for salinity ($EC_{1:5}$; dS/m) and soil water (% DM), and these parameters were used to estimate the salinity of the soil solution (NaCl equivalent – see formula for calculation in ‘Definitions’). These measurements enabled us to define the timing, duration and severity of salinity in the field, and to evaluate why EM38 measurements affected grain yields in each season.

Plant establishment (number of plants m⁻¹ row) was counted 23 DAS in 2009 and 31 DAS in 2011. In addition, on the saline plots in 2009, plant development was scored about twice per week in Spring (76-107 DAS) to determine the date of flowering (Zadoks growth scale 65), and an anthesis biomass cut (harvest of shoots to the soil surface over 0.5 m row length) was taken at 105 (wheat) and 107 (barley) DAS. Grain yields were determined at the final harvest on 162 DAS in 2009 and 171 DAS in 2011. Grain yields (t ha⁻¹) were calculated assuming the area harvested in each plot was 3 m².

3.3. Statistical model and analysis

The traits analysed in 2009 were grain yield (non-saline and saline blocks), shoot biomass (saline blocks) and date of flowering (saline blocks). In 2011 only grain yield was analysed (non-saline and saline blocks). The grain yield and shoot biomass data were analysed using ASReml-R (Butler et al., 2009), which facilitates the joint modelling of blocking structure, spatial variation, treatment effects and extraneous variation.

The aim of the spatial analysis was to adjust for the natural variation (by fitting autocorrelations for the local trend and regressions on row/column number for the global row/column trends respectively), so that entries grown in different plots would be neither disadvantaged nor advantaged. In addition the fitted covariates accounted for the rate of emergence and EM38 readings. Separate analyses were conducted for each combination of block salinity (saline or non-saline), year (2009 or 2011) and crop (wheat or barley). For grain yield, there were therefore 8 analyses (2 salinities x

2 crops x 2 years), but for the shoot biomass there were 2 analyses (1 salinity x 2 crops x 1 year).

Linear mixed models were fitted to each dataset using a randomization-model based approach (Smith et al., 2005). The model for each trait and trial included blocking terms to account for the randomization process and additional terms to model the extra sources of variation, such as spatial trends and extraneous variation. For the analyses we adopted the approach of Gilmour et al. (1997), also using the additional diagnostics for the adequacy of spatial models proposed by Stefanova et al. (2009). The initial base-line mixed model for each trait/trial consisted of three terms: (a) a random replicate relating to the blocking structure of each trial, (b) a fixed cultivar effect, and (c) a separable (column by row) autoregressive process of first order to account for the local spatial trend. After fitting this model, the residuals were checked (residual plots, variogram and faces of the variogram with 95% coverage intervals) to model additional spatial variation (global trend) and/or extraneous variation. This approach allowed for the accounting of salinity effects.

3. Results

3.1. Climate and seasonal rainfall in 2009 and 2011

The Ballidu area has a Mediterranean climate (moist winters, dry summers), with a long-term average rainfall of 335 mm per annum and an average pan evaporation of ~2200 mm per year. It is therefore a highly water-constrained environment for cropping. Average monthly temperatures are typically lowest in July at the start of

the growing season with average $T_{\min}$ and $T_{\max}$ values of ~ 7 and $\sim 16^{\circ}\text{C}$ respectively, and these increase to ~ 14 and $\sim 29^{\circ}\text{C}$ respectively in November at the end of the growing season (Bureau of Meteorology, 2016).

Fig 1 shows the cumulative rainfall against thermal time (degree days after sowing) for the two growing seasons. In the winter and early spring of each year, the pattern of rainfall was relatively similar with 188 mm of rain falling until ~ 1400 degree days after sowing. However, from this point on the seasons differed. In 2009 over the subsequent 1000 degree days there was only a further 47 mm of rain, whereas in 2011 there was twice this amount of rain (Fig. 1).

INSERT FIG. 1 NEAR HERE

3.2. Variation in soil moisture and salinity on saline plots in 2009 and 2011

On the saline sites, there was substantial spatial but little temporal variation in the EM38 data across each site in each year. For example with the wheat blocks, the coefficients of spatial variation were 12.9% ($n = 432$) in 2009 and 22.7% ($n = 720$) in 2011. By contrast, the coefficients of temporal variation were 3.8% ($n = 5$) in 2009 and 6.0% ($n = 4$) in 2011. The non-saline sites had average EM38 readings that were $\sim 1\%$ (2009) and $\sim 9\%$ (2011) of the average EM38 readings of the saline sites, and were therefore assumed to be non-saline.

On saline sites, EM38 calibration samples at 0–25 cm depth (6–9 samples per visit in 2009; 5–7 samples per visit in 2011) were taken at locations representative of the

variation, and these provided information about how the soil salinity, soil moisture and salinity of the soil solution varied with time within each site. In both years, the average salinity of the soil solution was high (~0.5 M) at the start of the growing season (Fig. 2C), but with the increased rainfall in winter (Fig. 1), there was a decrease in average soil salinity (Fig. 2A), and an increase in average stored soil moisture (Fig. 2B), so that by ~850 °DAS the average salinity of the soil solution had decreased to concentrations ~20-25% of the initial estimates (Fig. 2C). However, the salinities of the soil solution differed between sites/years later in the growing season. In 2009 the average salinity of the soil solution increased again (to ~85% of maximum) by 1400-1900 °DAS as the soil dried out (Fig. 2C). By contrast in 2011, the rainfall after 1600 °DAS (Fig. 1) caused the soil to maintain its moisture soil content (Fig. 2B) so that the average salinity of the soil solution remained low (~30% of maximum) at the end of the growing season.

INSERT FIG. 2 NEAR HERE

The significance of correlations between EM38 readings and the characteristics of the calibration samples ($EC_{1:5}$, soil water and salinity of the soil solution) are summarized in Table 2. Correlations between EM38 readings and the calibration samples were more significant in 2009 with the larger sample size (6-9 samples per visit) than in 2011 (5-7 samples per visit). In 2009 correlations were significant ($P < 0.05$) for soil moisture for sampling dates between 10 and 139 DAS, for $EC_{1:5}$ for sampling dates between 10 and 114 DAS, and for the salinity of the soil solution for sampling dates between 41 and 114 DAS (see Table 2A). By contrast, in 2011 correlations were only significant ($P < 0.05$) for $EC_{1:5}$ and salinity of the soil solution

for the samplings at 22 and 104 DAS, and soil moisture at 65 DAS (see Table 2B).

The estimated salinity of the soil solution data for each growing season showed that variation across each site was spatially consistent in each year: plots with lower salinities were consistently low; plots with higher salinities were consistently high.

INSERT TABLE 2 NEAR HERE

The EM38 readings in the vertical orientation had relatively similar frequency distributions at the two sites/years. At each location/year, readings in Spring varied between ~100 and ~350 mS m⁻¹, with median values of 250–270 mS m⁻¹ (Fig. 3A). However, these EM38 values indicated quite different distributions to the salinity of the soil solution (Fig 3B). In Spring 2009, the salinity of the soil solution varied between ~0.2 and 0.6 M NaCl, with a median value of ~0.46 M. By contrast in Spring 2011, the salinity of the soil solution varied between ~0.1 and 0.4 M, with a median value of ~0.27 M (Fig. 3B).

INSERT FIG. 3 NEAR HERE

Although the wheat and barley were established on different but adjacent blocks, salinity had relatively similar degrees of variation in each block in each year. In 2009, EM38 readings averaged over 5 sampling dates varied (5th–95th percentile) between 197 and 323 mS m⁻¹ in the wheat block, and between 164 and 326 mS m⁻¹ in the barley block. Likewise in 2011, EM38 readings averaged over 4 sampling dates varied (5th–95th) percentile between 148 and 309 mS m⁻¹ in the wheat block, and between 150 and 284 mS m⁻¹ in the barley block. Given the similarities of the

distribution of EM38 values in the blocks of the two species it was judged appropriate to compare the results between crops within and between years.

3.3. Variation in grain yield between saline and non-saline plots, between years and between species

The variation in grain yield across all plots for the wheat and barley cultivars is summarized in the relative frequency distribution diagrams in Fig. 4. Consistent with the relatively low annual rainfall of the area, grain yields were rarely less than 0.8 or greater than 3.1 t ha⁻¹.

Two general points can be made about these data. Firstly, the distribution of grain yields for crops in the saline plots was relatively similar to the distribution of grain yields for the same crops in the non-saline plots; the main exception to this was with barley in 2009, where the median grain yield under saline conditions was 50% higher than under non-saline conditions (see inserts into Fig. 4). Secondly, the distributions of grain yields in wheat and barley were relatively similar in each situation except on the saline soils in 2009. In 2009, on the saline site the barley cultivars had a median grain yield 40% higher than the wheat cultivars (see inserts into Fig. 4).

INSERT FIG. 4 NEAR HERE

3.4. Calculation of adjusted yields for cultivars taking account of spatial effects and variation in emergence

Our analyses provided best linear unbiased estimates of the biomass production at anthesis for wheat and barley on the saline site in 2009, and of the grain yields for wheat and barley in both years on the saline and non-saline sites. These analyses took account of the spatial variation, and variation in two covariates, date of emergence (saline and non-saline plots) and EM38 readings (saline plots).

The significance of the fixed terms included in the fitted models is presented in Table 3. In the non-saline trials there were highly significant ($P < 0.001$) linear row effects (barley 2009; wheat 2011) but no linear column effects. Also, the effect of emergence fitted as a covariate was not significant (Table 3). By contrast, the saline trials were more variable in grain yield, and were also variable in biomass production at anthesis (2009). This was demonstrated by there being highly significant linear row and column effects in 1 of the 2 trials for biomass, and 3 of the 4 trials for grain yield. Of the two covariates, EM38 readings were more important (highly significant in 5 of 6 trials) than emergence (significant in 4 of the 6 trials) (Table 3). The only saline trial where significant linear row and column effects were not observed was for the grain yield of barley in 2011, although in this trial the covariates (emergence and EM38 reading) were highly significant (Table 3). This absence of spatial effects was probably because this was the smallest trial in our study and it can be difficult to get significant spatial effects in small datasets.

INSERT TABLE 3 NEAR HERE

Fig. 5 shows the scatter plots of the best linear unbiased estimates of the grain yields of the cereal cultivars under non-saline conditions (x-axis) and saline

conditions (y-axis) for 2009 (Fig. 5A) and 2011 (Fig. 5B). In 2009 grain yields under non-saline conditions occurred over a lower range than under saline conditions; under non-saline conditions there was no obvious grouping of grain yield for the three crops (durum wheat, bread wheat and barley); most genotypes had grain yields between 1.2 and 1.6 t ha⁻¹ (Fig. 5A). By contrast, under saline conditions, the grain yields for durum wheat, bread wheat and barley fell into three broad clusters: the durum wheat had grain yields of ~1.0–1.2 t ha⁻¹, the bread wheat had grain yields of 1.1–1.8 t ha⁻¹ (and therefore occurred in a cluster overlying the 1:1 line – Fig. 5A) and the barley had grain yields of 1.5–2.6 t ha⁻¹ (and therefore occurred in a cluster above the 1:1 line – Fig. 5A). This provides the strongest evidence in our work that at the crop level, durum wheat was less salt tolerant, and barley was more salt tolerant, than bread wheat.

With wheat, under non-saline conditions, the bread cultivars Mace, EGA2248 and Guardian had highest grain yields (~1.7 t ha⁻¹), and the durum cultivars WID901 and Kalka had lowest grain yields (~1.0 t ha⁻¹). Under saline conditions the bread cultivars Westonia-Nax2-5924, Guardian and Mace had highest grain yields (~1.8 t ha⁻¹), and the WID901 (durum wheat) and Kharchia 65 (bread wheat) had lowest grain yields (~1.0 t ha⁻¹). With barley under non-saline conditions, Clipper, Sloop and Mundah had highest grain yields (1.6–1.7 t ha⁻¹), and under saline conditions Hindmarsh, Parent 19 and Mundah had highest grain yields (2.5–2.6 t ha⁻¹).

In 2011 no durum wheat cultivars were included in the trials, and the separation between crops (wheat versus barley) in grain yields occurred more under non-saline rather than saline conditions. At the non-saline site, most wheat genotypes had grain

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434 yields between ~1.9 and 2.4 t ha⁻¹, whereas the barley cultivars had grain yields that
435 ranged between 2.2 and 2.7 t ha⁻¹ (Fig. 5B). By contrast, under saline conditions,
436 there was no apparent separation in grain yields between the wheat and barley, and
437 grain yields varied for the entire range of genotypes between ~1.6 and 2.6 t ha⁻¹.
438 Under non-saline conditions highest grain yields were with the barley IGB1101 (~2.7
439 t/ha) and the bread wheat cultivars Scout and Mace (~2.4 t ha⁻¹). Under saline
440 conditions highest grain yields (2.5–2.6 t ha⁻¹) were with Tammarin Rock (bread
441 wheat) and Beecher (barley).

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445 Ultimately, the value of screening wheat and barley for salt tolerance will depend on
446 the reproducibility of results. In our study there were 34 wheat genotypes and 8
447 barley genotypes that were common across years and sites. Fig. 6 shows scatter
448 plots of the best linear unbiased estimates of grain yield for the common genotypes
449 from 2009 and 2011 under non-saline and saline conditions. With wheat under non-
450 saline and saline conditions, grain yields were positively correlated between the
451 common cultivars of 2009 and 2011 (Fig 6A, $P = 0.004$, 21% of variation accounted
452 for; Fig. 6B, $P < 0.001$, 45% of variation accounted for), but there were no significant
453 correlations for the smaller number of common barley cultivars under non-saline or
454 saline conditions (Fig. 6A, B). With this common set of genotypes under saline
455 conditions, with wheat there were highest yields with Mace, Tammarin Rock, Binnu,
456 Arrino and Magenta, and lowest yields with Ducula4 and EGA Eagle Rock, and with
457 barley there were highest yields with Mundah and Parent 19, and lowest yields with
458 Franklin (Fig. 6B).

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7 462 *3.5. Timing of flowering – Saline plots 2009*
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12 464 The detailed data on the timing of flowering (Zadoks growth scale 65), grain yield
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14 465 and biomass at anthesis for each wheat and barley genotype in the saline plots in
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17 466 2009 are reported in the Supplementary Content (Tables S1 and S2), and the
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19 467 relationships between these parameters for the named cultivars are summarised in
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22 468 Fig. 7. In general the barley had earlier flowering than the wheat; the barley cultivars
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24 469 flowered between 1037 and 1206 °DAS (84–97 DAS), whereas the wheat cultivars
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27 470 flowered mostly between 1206 and 1381 °DAS (97–109 DAS) (Fig. 7; Tables S1 and
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29 471 S2). Overall, there was no clear relationship between plant development scores and
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32 472 biomass production at anthesis (Fig. 7A), but there was a strong curvilinear
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34 473 relationship between plant development scores and grain yield at the end of the
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36 474 growing season (Fig. 7B).
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41 476 At anthesis there was little difference in biomass production between the barley,
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44 477 bread wheat and durum wheat cultivars (Fig. 7A). Barley and bread wheat produced
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46 478 (5th–95th percentile) 0.14–0.19 and 0.12–0.18 kg m⁻¹ row respectively, and durum
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49 479 wheat produced (range) 0.12–0.15 kg m⁻¹ row. Of the cultivars tested, greatest
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51 480 biomass production at anthesis was with two bread wheat cultivars (Krichauff and
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54 481 Westonia-Nax2-5915) and the barley (Mundah), and lowest biomass production was
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56 482 with the wheat Calingiri. There was no general effect of the timing of flowering on
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58 483 biomass production (Fig. 7A). By contrast, with final grain yield there was a strong
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effect of the timing of flowering on production (Fig. 7B). The earliest flowering barley cultivars YU6472 (flowering at 1037 °DAS or 84 DAS) and Gebeinea/Gairdner (flowering at 1126 °DAS or 91 DAS) had grain yields of 1.6 and 1.8 t ha⁻¹ respectively; these yields were lower than the highest yielding cultivars (Parent 19 and Hindmarsh) which flowered at 1165–1179 °DAS (94–95 DAS) and had grain yields of 2.6 t ha⁻¹. With wheat, the highest yielding cultivar Westonia-Nax2-5924 flowered at 1233 °DAS (99 DAS) and had a yield of 1.8 t ha⁻¹; by contrast, Endure and IGW3073 flowered at 1366 and 1381 °DAS (108 and 109 DAS), and had grain yields of 1.3 and 1.4 t ha⁻¹ respectively (Fig. 7B).

INSERT FIG. 7 NEAR HERE

4. Discussion

This paper reports the effects of variation in natural field salinity on grain production by a range of wheat and barley genotypes over two growing seasons (2009 and 2011) on rainfed land with a Mediterranean climate. This discussion focuses on three issues: (1) the influence of salt tolerance, spring rain and date of flowering as factors affecting cereal yields in saline environments, (2) the use of the EM38 to assess the severity of salinity impacts on crops in the field, and (3) assessing local adaptation and salt tolerance in cereal genotypes in the field.

4.1. Salt tolerance, spring rain and date of flowering as factors affecting cereal yields in saline environments

In this work, the key to understanding the differences in grain yield between wheat and barley in the two years lies in: (a) the differences in salt tolerance of the two crops, (b) the differences in date of flowering of the two crops species, (c) the differences in rainfall in Spring between the two years (Fig. 1), and as a consequence, (d) the differences in the salinity of the soil solution and availability of water in Spring between the two years (Fig. 2).

In 2009, the median salinity of the soil solution in late Spring was ~0.4 M (Fig. 2). Water potentials of -1500 kPa are widely regarded as being indicative of permanent wilting point for many crop plants (Slatyer, 1967) and these can be generated by a soil solution with a salinity of ~0.33 M (Lang, 1967). In 2009 in late Spring (~1900 °DAS), knowing the average EM38 reading for each plot and the equation relating EM38 readings to the salinity of the soil solution (Table 2A) we estimate that ~85% of saline plots would have had salinities of the soil solution more than 0.33 M. These salinities would not have been alleviated by late-season rainfall as only 35 mm fell after this time. Most plots were therefore affected by extreme salinities and late-season water deficits during grain fill. In this year, barley genotypes would have had two advantages over wheat genotypes. Firstly, their reputedly higher salt tolerance (Ayers et al., 1952; Rawson et al., 1988) would have ensured that they could better endure the extreme salinities of the soil solution than the wheat cultivars. Secondly, with their earlier flowering they would have escaped the extremely adverse water relations that would have impacted on the longer-season wheat cultivars in late Spring (compare bars showing timing of flowering for wheat and barley with the cumulative rainfall for 2009 – Fig. 1).

By contrast, in 2011 in late Spring (~1660 °DAS), the median salinity of the soil solution across the saline site was 0.15 M. Again using the average EM38 readings for each plot and the formula relating EM38 readings to the salinity of the soil solution (Table 2B), we estimate that only ~1% of plots would have had salinities of the soil solution greater than 0.33 M. Furthermore, the 85 mm of rain that fell after ~1900 °DAS (Fig. 1) would have ensured that the salinities of the soil solution remained relatively low. In this season, differences in salt tolerance between the crops would have had only slight to moderate effects on grain yield. However, there would have been slightly lower grain production from some of the earlier flowering barley genotypes compared with the later flowering wheat genotypes because the late Spring rain would have fallen after many of the barley genotypes had ripened but while many of the wheat genotypes were still green (compare bars showing timing of flowering for wheat and barley in 2009 with the cumulative rainfall for 2011 – Fig. 1).

4.2. Use of EM38 to assess severity of salinity in the field

In saline media, plant growth responds to the salinity of the soil solution; this can be defined as the ratio of the salt concentration in the soil to the water concentration in the soil. In irrigated environments, in which water concentrations in the soil can be maintained at relatively constant levels, there can be relatively clear relationships between measures of plant growth or yield and measures of the salt concentration of the soil like the EC_e (cf. Maas and Hoffman, 1977). However, in non-irrigated (dryland) soils, we can have no such assurance: the salt concentration in the soil

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557 solution will be highly variable over the season, responding in direct proportion to soil
558 salinity and inverse proportion to soil moisture.

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560 Our data show that soil salinity can be highly variable spatially, even at the scale of
561 several metres, which is consistent with the results of Rawson et al. (2013) who
562 showed great variation in salinity at the surface and at depth within small farmers'
563 fields and agricultural research stations in southern Bangladesh. At one site, EC_e
564 values near the surface varied from 1 to 12 dS m^{-1} (calculated as the $EC_{1:5} \times 10$).
565 The accompanying wheat yields on individual plots ranged from 200 to 20 g m^{-2}
566 (approximating 2 to 0.2 t ha^{-1}), falling linearly with increasing EC_e . In addition, Munns
567 et al. (2012) showed an increase in the salinity of the soil solution (0–0.8 m depth) in
568 a farmer's field in eastern Australia from ~0.04 to ~0.17 M within 100 m, and over
569 this distance the yield of durum wheat fell from 2.6 to 1.3 t ha^{-1} . Soil salinity varying
570 widely over such a short distance can be exploited to compare the relative salt
571 tolerance of genotypes, that is, in highly saline compared with less saline soils, as
572 long as plot salinity is measured (Munns et al., 2012).

573
574 We have used electromagnetic induction (i.e. the EM38) to survey spatial variation in
575 the apparent electrical conductivity of the soil. These measurements are affected by
576 soil salinity, clay content and soil moisture, so spatial variation in EM38 readings can
577 be used to estimate variation in soil salinity provided that calibration curves are
578 established between these and soil salinity using soil samples collected on the day
579 of survey. Significant correlations between EM38 values and the salinity of the soil
580 solution occurred less frequently (5 out of 9 occasions across both years) than for
581 $EC_{1:5}$ and soil moisture (6 out of 9 occasions across both years), but we were

nevertheless able to estimate salinities of the soil solution across all plots at approximately similar stages of plant development in the two years.

Our work supports the importance of establishing calibration curves in EM38 surveys as shown by James et al. (2012) and others. In the current work there were similar ranges of variation in EC_a across the saline sites in 2009 and 2011. However these sites must have differed in the influence of clay and moisture on EC_a readings, because the calibration curves revealed that the sites had very different salinities of the soil solution. On the site used in 2009, the salinity of the soil solution in Spring (1461 °DAS) varied between ~0.2 and 0.6 M NaCl (calculated from average plot EM38 values and equation in Table 2A), with a median value of ~0.42 M (Fig. 2). By contrast on the site used in 2011, the salinity of the soil solution in Spring (1297 °DAS) varied between ~0.15 and 0.35 M (calculated from average plot EM38 values and equation in Table 2B), with a median value of ~0.27 M (Fig. 2).

4.3. Assessing local adaptation and salt tolerance in cereal genotypes in the field

What strategies should plant breeders adopt to select crop plants for saline soils? A traditional approach of plant physiologists and agronomists has been to assess plant salt tolerance on the basis of growth (or grain yield) under saline conditions as a percentage of a control treatment in which plants are grown at zero or low salinity (e.g. Maas and Hoffman, 1977). The problem with this approach is that farmers do not harvest relative yield; they harvest absolute yield.

In general, we support the position of Richards (1983). In saline landscapes, severe salinity will generally only occur on part of a paddock. Crops for saline land therefore need to be selected with the combination of high productivity under both non-saline conditions (which we argue is an index of 'local adaptation') and under saline conditions (so that the gains or penalties associated with salinity) can be seen. In the context of this paper, our position can be illustrated in Fig. 5. Crop cultivars for saline land need to have high values on the x-axis of this graph and values in the direction of the y-axis as high as possible. We would argue that the grain yield of a crop under non-saline conditions will be largely affected by its local adaptation, and the grain yield of a crop under saline conditions will be affected by its local adaptation and traits associated with salt tolerance. Therefore the difference in grain yield under saline and non-saline conditions (i.e. the height of each point above or below the 1:1 line in Fig. 5) can be considered to be an index of genotype salt tolerance. This kind of analysis is worthwhile for two reasons. Firstly it clarifies the search for relevant QTLs: 'local adaptation' can be expected to be affected by hundreds of genes, whereas 'salt tolerance' will be affected by a far smaller number of additional genes. Secondly, crops for farm use on saline land will need genes for salt tolerance in cultivars with locally adapted genetic backgrounds.

The use of the grain yield under non-saline conditions as an index of local adaptation, and the difference in grain yield under saline and non-saline conditions as an index of salt tolerance can be illustrated in our data from 2009 using the Westonia lines incorporating the *Nax2* gene (see insert into Fig. 5A). *Nax2* has been previously shown to increase the yield of durum wheat on a saline soil by 25% (Munns et al., 2012). The *Nax1* and *Nax2* genes, originally sourced from the wheat

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631 ancestor *Triticum monococcum* were associated with superior Na⁺ exclusion, and
632 had been introduced into bread wheat by James et al. (2011). In 2009, the cultivars
633 Westonia-Nax2-5924 and Westonia were amongst the best locally adapted of the 89
634 wheat cultivars tested, being ranked 8th and 17th in grain yield respectively (1.58 and
635 1.52 t ha⁻¹) under non-saline conditions. However, under saline conditions,
636 Westonia-Nax2-5924 and Westonia were ranked 1st and 20th in grain yield
637 respectively (1.84 t and 1.66 ha⁻¹). Scoring salt tolerance as the difference in grain
638 yield between the saline and non-saline sites, Westonia-Nax2-5924 would have
639 been ranked 9th whereas Westonia was ranked 35th (Fig. 5A; see data for individual
640 genotypes reported in Supplementary Content – Table S1). This analysis shows that
641 there was a strong gain to grain yield through incorporation of the *Nax2* gene into
642 Westonia in this Westonia-Nax2 line. It supports the view that it is possible to breed
643 cereal cultivars with the combination of both local adaptation and genes that confer
644 enhanced salt tolerance.

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646 Another test of our use of grain yields in non-saline and saline environments to
647 determine indices of local adaptation and salt tolerance comes from the case of
648 Kharchia 65. This wheat genotype was selected on the sodic-saline soils of farmers'
649 fields in Rajasthan (Munns et al., 2006), but it appeared to be affected by cold at
650 Ballidu. In the water limited environments of 2009, Kharchia 65 had the second
651 lowest grain yield of any bread wheat under non-saline conditions (1.3 t ha⁻¹) and an
652 even lower grain yield under saline conditions (1.1 t ha⁻¹); it was therefore clearly not
653 locally adapted. However, in 2011 with more abundant water at the end of the
654 growing season Kharchia 65 had grain yields of 1.4 and 2.1 t ha⁻¹ under non-saline
655 and saline conditions respectively, and if we consider the difference in grain yield on

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2 saline and non-saline sites to be an index of salinity tolerance, then Kharchia 65
3 would have been the 2nd most salt tolerant genotype tested in this season.
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6 659 *4.4. Concluding comments*

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12 661 Our experiments at two naturally saline sites have shown that there is a wide range
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14 662 of genetic diversity within both wheat and barley for production on saline land. They
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16 663 have also highlighted the variability of salinity within a field and the importance of
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18 664 measuring the salinity under each plot, in each season, using an EM38 meter that
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20 665 has been rigorously calibrated, to reliably assess the genetic diversity. Our trials
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22 666 confirm that barley may have higher grain yields on saltland than wheat, but in areas
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24 667 with minimal rainfall, this effect may be due to both to greater salt tolerance and
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26 668 earlier flowering during grain development. Future research on traits and candidate
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28 669 genes that can be used to elevate the salt tolerance of wheat and barley should take
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30 670 into account these constraints when evaluating novel germplasm in the field. Our
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32 671 final point is that based on variation in sodicity, salinity and pH, Rengasamy (2010)
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34 672 distinguishes 9 different types of salt-affected soil in Australia. Our experiments (at
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36 673 two sites) are arguably relevant to only one of these soil types, the acidic (pH < 7)
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38 674 saline soils (c.f. Rengasamy 2010). Further cereal cultivar screening across a
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40 675 broader range of salt affected landscapes is therefore essential.
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50 676 51 677 **Acknowledgments**

52

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List of figure captions

Fig. 1. Cumulative rainfall (mm) against thermal time ($^{\circ}$ DAS) in the 2009 and 2011 growing seasons (calculated based on data from the Bureau of Meteorology, 2016). The shaded overlay bars show the flowering intervals of the barley and wheat cultivars in 2009 (c.f. Fig. 7).

Fig. 2. Changes in soil conditions with thermal time in 2009 and 2011: (A) $EC_{1:5}$, (B) soil moisture, and (C) estimated salinity of the soil solution. The data are the means of 6–9 values (2009) or 5–7 values (2011) representative of the variation in EM38 readings across each saline site at each time. Error bars indicate $\pm$ SEM.

Fig. 3. Relative frequency distributions of: (a) EM38 readings, and (b) salinities of the soil solution in Spring. These graphs are based on EM38 data collected in the vertical orientation 114 DAS in 2009 and 104 DAS in 2011; the salinities of the soil solution were estimated using the relevant calibration curves (see Table 2).

Fig. 4. Relative frequency distributions for grain yield in wheat and barley genotypes in four combinations of year and environment: (A) 2009 saline, (B) 2009 non-saline, (C) 2011 saline, and (D) 2011 non-saline. Relative frequencies were calculated on the basis that there were 90 and 27 wheat and barley cultivars respectively in 2009, and 320 and 14 wheat and barley cultivars in 2011. The inserts show the median grain yields for the wheat and barley cultivars in each year and environment.

Fig. 5. Scatter plots of the best linear unbiased estimates of grain yield under non-saline against saline conditions in 2009 (A) and 2011 (B). Each graph also shows the 1:1 line (dotted). The insert in Fig. 5A shows the grain yields of: 'a' Westonia, 'b' Westonia-Nax2-5924, 'c' Westonia-Nax2-5915, 'd' Westonia-Nax1-5933, 'e' Westonia-Nax1-5907, 'f' Westonia-Nax2-5912 and 'g' Mace. Data for individual genotypes are in the Supplementary Content (Tables S1, S2, S3 and S4).

Fig. 6. Scatter plots of the best linear unbiased estimates of grain yields in 2009 and 2011 for the 34 wheat cultivars and 8 barley cultivars common to trials in each year: (A) non-saline plots; (B) saline plots. The line of best fit for wheat under non-saline conditions ($y = 1.31x + 0.22$) was significant at $P = 0.004$ and accounted for 21% of the variation. The line of best fit for wheat under saline conditions ($y = 0.43x + 1.536$) was significant at $P < 0.001$ and accounted for 45% of the variation.

Fig. 7. Relationships for the saline plots in 2009 between average number of days to flowering (Zadoks scale 65) and: (A) biomass at anthesis, and (B) grain yield. Days to flowering and biomass at anthesis data for individual genotypes are in the Supplementary Content (Tables S1 and S2).

Table 1. Agronomic details of trials conducted in the 2009 and 2011 growing seasons.

Factor	2009 season	2011 season
<i>Genotypes tested</i>		
• Wheat	91 cultivars or populations	320 cultivars or populations
• Barley	27 cultivars or populations	14 cultivars or populations
<i>Plot layout</i>		
• Wheat	12 x 34 = 408 plots	12 x 67 = 804 plots
• Barley	12 x 14 = 168 plots	12 x 5 = 60 plots
<i>Critical dates</i>		
• Sowing	16 June	31 May
• Establishment counts	23 DAS* (= 275 °DAS)	31 DAS (= 410 °DAS)
• Anthesis biomass cuts	Wheat 105 DAS (= 1320 °DAS) Barley 107 DAS (= 1350 °DAS)	Not determined
• EM38 readings	10, 41, 71, 114 and 139 DAS (= 123, 480, 868, 1461, 1922 °DAS respectively)	22, 65, 104 and 129 DAS (= 297, 815, 1297, 1663 °DAS respectively)
• Development scores	76, 79, 90, 100 and 107 DAS (= 934, 973, 1114, 1247, 1351 °DAS respectively)	Not determined
• Harvest	162 DAS (= 2428 °DAS)	171 DAS (= 2458 °DAS)
<i>Planting regime</i>		
• Fertiliser at sowing	District practice	Agstar (100 kg ha ⁻¹)
• Pre emergent herbicide	District practice	SpraySeed® 1.5 L ha ⁻¹ ; Boxer Gold® 2.5 L ha ⁻¹

*DAS = days after sowing; °DAS = degree days after sowing.

Table 2. Significance of calibration curves between EM38 readings in the vertical orientation (mS/m) and other soil parameters (EC_{1:5}, soil moisture and salinity of the soil solution) on the saline plots at Ballidu in 2009 and 2011.

Table 2A – 2009

DAS (°DAS)*	Measurement	Equations for 0-25 cm soil depth
10 (123)	EC _{1:5} (dS/m)	$y = 0.0059 \text{ EM38} - 0.7439$ ($r^2 = 0.755$, $n = 9$; $P = 0.001$)
	Moisture (% DM)	$y = 0.0418 \text{ EM38} - 2.9865$ ($r^2 = 0.800$; $n = 9$, $P < 0.001$)
	Salinity of soil solution (M)	NS**
41 (480)	EC _{1:5} (dS/m)	$y = 0.0091 \text{ EM38} - 1.4788$ ($r^2 = 0.705$; $n = 9$; $P = 0.003$)
	Moisture (% DM)	$y = 0.0312 \text{ EM38} + 2.7809$ ($r^2 = 0.574$; $n = 9$; $P = 0.011$)
	Salinity of soil solution (M)	$y = 0.0028 \text{ EM38} - 0.3484$ ($r^2 = 0.687$; $n = 9$; $P = 0.004$)
71 (868)	EC _{1:5} (dS/m)	$y = 0.0025 \text{ EM38} - 0.4144$ ($r^2 = 0.547$; $n = 9$; $P = 0.014$)
	Moisture (% DM)	$y = 0.0439 \text{ EM38} - 1.8299$ ($r^2 = 0.653$; $n = 9$; $P = 0.005$)
	Salinity of soil solution (M)	$y = 0.0008 \text{ EM38} - 0.0959$ ($r^2 = 0.465$; $n = 9$; $P = 0.026$)
114 (1461)	EC _{1:5} (dS/m)	$y = 0.005 \text{ EM38} - 0.8182$ ($r^2 = 0.635$; $n = 9$; $P = 0.006$)
	Moisture (% DM)	$y = 0.0407 \text{ EM38} - 5.6202$ ($r^2 = 0.614$; $n = 9$; $P = 0.008$)
	Salinity of soil solution (M)	$y = 0.0018 \text{ EM38} - 0.0335$ ($r^2 = 0.718$; $n = 9$; $P = 0.002$)
139 (1922)	EC _{1:5} (dS/m)	NS
	Moisture (% DM)	$y = 0.0211 \text{ EM38} - 1.2825$ ($r^2 = 0.792$; $n = 6$; $P = 0.011$)
	Salinity of soil solution (M)	NS

Table 2B – 2010

DAS (°DAS)*	Measurement	Equations for 0-25 cm soil depth
22 (297)	EC _{1:5} (dS/m)	$y = 0.00878 \text{ EM38} - 1.285$ ($r^2 = 0.839$, $n = 7$; $P = 0.002$)
	Moisture (% DM)	NS
	Salinity of soil solution (M)	$y = 0.00678 \text{ EM38} - 0.938$ ($r^2 = 0.779$, $n = 7$; $P = 0.005$)
65 (815)	EC _{1:5} (dS/m)	NS
	Moisture (% DM)	$y = 0.02185 \text{ EM38} + 3.94$ ($r^2 = 0.52$, $n = 7$; $P = 0.041$)
	Salinity of soil solution (M)	NS
104 (1297)	EC _{1:5} (dS/m)	$y = 0.00177 \text{ EM38} - 0.198$ ($r^2 = 0.75$, $n = 5$; $P = 0.037$)
	Moisture (% DM)	NS
	Salinity of soil solution (M)	$y = 0.000778 \text{ EM38} + 0.0762$ ($r^2 = 0.707$, $n = 5$; $P = 0.047$)
129 (1663)	EC _{1:5} (dS/m)	NS
	Moisture (% DM)	NS
	Salinity of soil solution (M)	NS

*DAS = Days after sowing; °DAS = Degree days after sowing

**NS = not significant.

Table 3. Significance (*P*-value) of the fixed terms used in the models to account for variation in grain yield and biomass production.

Salinity	Crop	Year	Genotype	Emergence	EM38 (June)	lin(row)	lin(col)
<i>Grain yield</i>							
Non-saline	Wheat	2009	<0.001	NS*	ND**	-.***	-
		2011	<0.001	NS	ND	<0.001	-
	Barley	2009	<0.001	NS	ND	<0.001	-
		2011	<0.001	NS	ND	-	-
Saline	Wheat	2009	<0.001	0.0076	<0.001	0.0418	<0.001
		2011	<0.001	<0.001	NS	<0.001	0.0141
	Barley	2009	<0.001	NS	<0.001	0.0062	0.0036
		2011	<0.001	<0.001	<0.001	-	-
<i>Biomass production</i>							
Saline	Wheat	2009	<0.001	NS	<0.001	0.0164	-
	Barley	2009	<0.001	0.0229	<0.001	<0.001	0.0016

*NS = not significant.

**ND = not determined. The use of EM38 readings was not included in these models.

***- = trend not present.

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