Salinity-yield response functions of barley genotypes assessed with a triple line source sprinkler system

A. Royo and R. Aragüés

Unidad de Suelos y Riegos, Servicio de Investigación Agroalimentaria (D.G.A.), Laboratorio Asociado de Agronomía y Medio Ambiente (DGA-CSIC). Apartado 727, 50080 Zaragoza, Spain

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Abstract

Evaluation of the salt tolerance of crop cultivars under field conditions is greatly complicated by the typical temporal and spatial variability of soil salinity. We obtained the grain yield - salinity response functions of 124 barley genotypes by growing them in ten salinity treatments imposed by a Triple Line Source Sprinkler (TLS) system during five consecutive years. Additional objectives were to ascertain the consistency and reproducibility over years of these functions, to quantify the deleterious effects of saline sprinkling irrigations, and to assess correlations between salinity tolerance and leaf sap salt concentration. The consistency and reproducibility of the response functions within and between years were adequate (only 8% of the response functions were discarded for statistical reasons). The Y_m (grain yield without salinity) and the EC_{50} (the EC_e that reduces yield by 50%) estimates were not correlated ($P > 0.05$) suggesting that the most productive genotypes were not necessarily less salinity tolerant. Y_m was positively and significantly ($P < 0.01$) correlated with Y_6 and Y_{12} (fitted grain yields at EC_e values of 6 dS m^{-1}, and 12 dS m^{-1}, respectively), indicating that it is a useful statistic in the selection of barley genotypes most productive under medium and high salinities. Foliar salt uptake due to saline sprinkling irrigations decreased the EC_{50} by around 50% as compared with the salinity tolerance obtained with surface irrigation systems. No

consistent relationships were found between either Y_m or EC_{50} and the leaf sap osmotic potential, Cl, Ca, Na and K concentrations. They could not therefore be used in screening for salinity tolerance of barley. On the basis of the evidence from the present study, Y_m is the best statistic for predicting the most productive barley genotypes in salt-affected soils.

Introduction

By area and production barley is the fourth most important cultivated cereal in the world due to its broad adaptability to arid and semi-arid environments and, in particular, to its relatively high tolerance to water and salinity stresses (Acevedo, 1991). An increase in the salinity tolerance of barley could improve the profitability of some of the more than one billion salt-affected hectares present in the world (Szabolcs, 1989).

However, a comprehensive evaluation of the tolerance of barley genotypes under field conditions is still lacking due to the testing difficulties consequent on the typical temporal and spatial variability of soil salinity. Thus, most evaluations performed under field conditions have been limited in time (usually one-year testing) and with few saline treatments (usually no more than three or four saline treatments). Trying to circumvent these problems, we developed the Triple Line Source Sprinkler (TLS) system (Aragüés et al., 1992; Royo et al, 1991). The TLS establishes ten saline treatments with which the salinity-yield response functions may be precisely established (Royo and Aragüés, 1993).

We have been using the TLS for more than ten years for evaluations of the salinity tolerance of sets of barley, wheat, and sorghum genotypes. We present here a summary of the TLS work performed during five consecutive years where we obtained the salinity-grain yield response functions (i.e., salinity tolerance) of 124 barley genotypes. Due to the intrinsic characteristics of the TLS system, where the crops under evaluation are wetted by saline water irrigations, this tolerance should be envisioned as a combination of soil (absorption of salts by roots) and water (absorption of salts by leaves) salinity tolerance. This could be a limitation for crops irrigated by surface-irrigation

systems, when the absorption of salts occurs only by roots, but it is fully applicable to crops irrigated by above-canopy sprinkling systems. This is an important consideration, since the use of sprinkling systems and saline waters is expanding throughout the world (Hoffman et al., 1990). Although the deleterious effect of the toxic accumulation of salts absorbed by the wetted leaves is well known, its quantification in different species and, in particular, in barley genotypes is very limited (Maas, 1990).

In addition, the identification of physiological traits able to predict consistently salinity tolerance under field conditions is still lacking (Blum, 1988; Flowers and Yeo, 1995; Shannon, 1997). Isla et al. (1998) have recently concluded that none of the traits examined (carbon isotope discrimination, canopy temperature, stomatal conductance and grain ash content) were useful in screening for salinity tolerance of barley. Some authors (Gorham, 1992, 1993; Pasternak, 1987) have suggested that other characters such as leaf ion accumulation and compartmentation, ion exclusion or inclusion, osmotic adjustment, and K/Na discrimination, could be related to salt tolerance. However, an in-depth evaluation of their usefulness under field conditions has not been performed for an ample set of barley genotypes and various experimental years.

The objectives of the work described here were: (1) to ascertain the consistency and reproducibility of the salinity tolerance data obtained in different years, (2) to establish the grain yield-salinity response functions of 124 barley genotypes and to rank these genotypes based on various salinity tolerance parameters, (3) to quantify the deleterious effect from using saline sprinkling irrigations, and (4) to seek correlations between tolerance and leaf sap salt concentration (osmotic potential, Cl, Na, Ca and K ions).

Materials and Methods

We conducted this study on a mixed, mesic, Typic Torrifluvent soil at the SIA field experimental station located in the central part of the Ebro River Basin (0º 49’ W, 41º 44’ N). The triple-line-source sprinkler (TLS) system consists of three parallel lines of sprinklers with a lateral spacing of

15.0 m, equivalent to the sprinkler's wetted radius (Aragüés et al., 1992; Royo et a., 1991). Each line applies equal quantities of water. The two outer lines are supplied with fresh water (EC < 2 dS m^{-1}), and the central line is supplied with saline water made up of NaCl and $CaCl_2$ (1 : 1 w/w). The result is a continuous gradient of salinity between the centre (most saline) and the two outer sprinkler lines (least saline) with the same volume of applied water between each pair of lines.

Ten individual salinity treatments (as plots 1.5 x 1.2 m) were designated between each lateral pair at increasing distances from the central line. Pluviometers (0.16-m diameter) were placed in the centre of each plot to measure the volume of the irrigation water and to collect water samples for determining their electrical conductivity. Irrigations were scheduled according to evapotranspiration (ET) measurements made in a lysimeter close to the TLS that was planted with barley at the same time that in the TLS plots. At the beginning and at the end of each irrigation, plants received supplemental 3 min pre- and post-irrigations with fresh water to reduce foliar salt absorption and injury (Aragüés et al., 1994; Benes et al., 1996). Soil salinity (EC_a) in each salinity treatment was measured every three weeks with a portable electromagnetic sensor (EM-38; Geonics Limited, Ontario, Canada). The instrument was calibrated against the EC of the soil saturation extract (EC_e) and the 1:5 (soil:water) extract ($EC_{1:5}$) with soil samples taken from 0 to 0.30-m soil depth in each of the ten salinity treatments.

Table 1 gives the general characteristics of the 1990 to 1994 field trials. In 1990 and in half of the area in 1991 the experimental plots were leached with fresh water during the summer prior to sowing. In the other years the trials were carried out with the soil salinity profiles developed in the previous experimental year, although the barley was established after sprinkler irrigations with fresh water. The saline water treatments started at the dates given in Table 1 (at the 2-3 leaf stage of barley). The seasonal water applied (irrigation + rainfall) varied among years between 533 mm and 424 mm, and the calculated leaching fractions (defined as the fraction of the infiltrating water that percolates below the crop's root zone) for the control treatments varied between 0.20 and 0.46 (Table 1). The seasonal average minimum and maximum applied water EC (EC_{aw}: weighed average

of irrigation and rainfall) and EC_a values are also shown in Table 1. The seasonal EC_{aw} and EC_a gradients that developed across the laterals were linearly correlated ($P < 0.001$) and were the same ($P > 0.05$) on both sides of the centre line.

Barley (*Hordeum vulgare L.*) seeds were sown in each year on the dates given in Table 1 at a density of 270 seeds m^{-2} in rows parallel to the sprinkler laterals. The sowing dates (Table 1) were typical of the area for winter genotypes, except in 1990 where heavy rains in the fall delayed sowing until 24 January. For this reason, most of the genotypes sown in 1990 were spring types. The genotypes studied were commercial varieties and lines from the SIA collection. The total number of genotypes sown was 196. The data for 180 are presented here, based on the following criteria: (a) significant ($P < 0.05$) fitting of the yield data to the model, (b) EC_{50} (soil salinity that reduces yield by 50%) estimates significantly ($P < 0.05$) different from zero, and (c) standard errors of the EC_{50} estimates lower than 25% of the estimate. Since some genotypes were studied in several different years for comparison purposes, the salinity-grain yield response functions were determined for a total of 124 different barley genotypes.

The grain yield of each barley genotype measured in each plot at the end of the experiments (harvest dates in Table 1) was regressed against the corresponding seasonal average EC_e value (estimated from the seasonal average EC_a and the EC_e-EC_a calibration equations) with the sigmoidal growth response model (program 12 of SALT) described by van Genuchten (1983). The salinity tolerance statistics EC_{50} (the EC_e that reduces grain yield by 50 per cent), EC_t (threshold EC_e at which the yield is 95%), and Y_6 and Y_{12} (the grain yields at EC_e values of 6 dS m^{-1}, and 12 dS m^{-1}, respectively) were estimated by non-linear least-squares techniques with the maximum neighbourhood method of Marquardt (1963). In those cases where the estimated Y_m (maximum grain yield in non-saline conditions) was unrealistic, we used the program 11 of SALT, where Y_m is a user-fixed value equated in our case to the observed maximum yield. Salt tolerance, defined as the inherent ability of a plant to withstand the effects of high salts in the root zone, is commonly

equated to EC_{50} and EC_t. However, we also used Y_6 and Y_{12} as measures of salt tolerance since the actual yield under saline conditions is most important from the farmer's point of view.

The numbers of genotypes sampled for leaf analysis in three saline treatments of the 1991-1994 TLS experiments are given in Table 1. The samplings were made early in the morning at the beginning of heading. Five to ten leaves were taken from the principal tillers, brought to the laboratory, rinsed successively in each of three trays of distilled water to remove surface salts, blotted dry, placed in 5 mL plastic syringes, and frozen. After thawing, the leaf sap was extracted by applying pressure to the plunger of the syringe. The osmotic potential of the sap was measured in a Wescor 5500 osmometer. Chloride was measured in a Buchler chloridometer by adding 10 μL of the leaf sap to a dilute acid solution according to the procedure of Cotlove (1963). Na, Ca and K ions were measured in a Perkin-Elmer model 3030 atomic absorption spectrophotometer using a diluted Schinkel buffer solution (10 g L^{-1} CsCl and 100 g L^{-1} $LaCl_3$).

Results and discussion

Consistency and reproducibility of the salinity tolerance data obtained in different years

During the 5 yr. of experiments with the TLS system, 196 salinity response functions of grain yield vs. EC_e were calculated with the van Genuchten sigmoidal model. Only 2 of these 196 functions had non-significant r values at $P>0.05$ and one had an EC_{50} value not significantly different from zero ($P > 0.05$). Of the remaining 193 functions, the results for 13 were not used because the standard errors of the EC_{50} estimates were higher than $0.25 \cdot EC_{50}$. Therefore, 180 (i.e., 92% of the tested genotypes) had consistent functions and only 8% were discarded for the reasons given above. However, in 20% of these 180 functions the Y_m statistics were unrealistically high and for these, Y_m was fixed to the maximum value experimentally measured.

For the remaining 143 barley genotypes which complied with all our statistical requisites, Table 2 presents the mean EC_{50} and EC_t estimates ± SD obtained in each experimental year. The average r (coefficient of correlation) of these 143 functions was 0.91 (significant at $P < 0.001$).

Although a rigorous statistical comparison among years is not possible because most of the genotypes were different in each year, this Table shows that these estimates were quite similar among years. In fact, only the EC_{50} estimates for 1992 and 1993 and the EC_t estimates for 1990 and 1992 were significantly different ($P < 0.01$) using the SD as a measure of error for comparison among years.

The reproducibility of the salinity response functions obtained in different years was evaluated on the basis of the EC_{50} estimates obtained for 24 genotypes grown at least in two or more years. A comparison of the 95% confidence intervals (CI) of the EC_{50} estimates obtained for a given genotype grown in different years indicates that they overlapped in 59 of the 65 comparisons. For each of these genotypes, we generated a single response function by pooling the yield data expressed in relative terms (Y/Y_m), where Y_m is the model estimate obtained in each year. A comparison of the 95% CI of the pooled EC_{50} estimates of each genotype with the CI of the EC_{50} estimates obtained in each year indicated that in 60 of the 64 comparisons there was an overlapping of the CI values. In addition, in 86% of the comparisons the pooled EC_{50} values were within the CI of the corresponding annual EC_{50} values.

Based on these results, we concluded that the salinity-grain yield response functions generally gave consistent, reproducible results during the years studied, and that differences among years, if any, were small.

Ranking of the grain yield-salinity response functions of 124 barley genotypes

Table 3 summarises, in alphabetical order, the response functions of the 124 barley genotypes which comply with the statistical requisites defined in the Materials and Methods section. This Table gives, for each barley genotype, the estimated grain yields (kg ha^{-1}) in the absence of salinity (Y_m) and at EC_e values of 6 dS m^{-1} (Y_6), and 12 dS m^{-1} (Y_{12}), and the salinity tolerance parameters EC_{50} and EC_t. The numbers in parenthesis after the genotypes names indicate the number of years in which the given genotype was tested. The genotypes in italics are those where we fixed the Y_m

values (see Materials and Methods). The tolerance statistics for these genotypes should therefore be taken as approximate and they are not be used in the following discussion.

Among genotypes, the variability in the Y_m estimates was high (coefficient of variation (CV) being 37 %), a result which is not surprising since we tested many different materials (commercial varieties, breeding lines and exotic genotypes). The average EC_{50} was 7.1 dS m^{-1}, and its CV relatively low (13 %); CBC-22 was the most tolerant genotype (EC_{50} = 9.0 dS m^{-1}) and the mutant 4210 was the least tolerant (EC_{50} = 5.3 dS m^{-1}). The average EC_t was 4.0 dS m^{-1}, and its CV relatively high (26 %); The genotype Sutter had the highest EC_t (6.6 dS m^{-1}), and Athos had the lowest EC_t (1.3 dS m^{-1}). Of the commercial genotypes tested, the most tolerant were Hatif de Grignon (EC_{50} = 9.0 dS m^{-1}) and Forrest (EC_{50} = 8.8 dS m^{-1}) and the least tolerant were Astrix (EC_{50} = 5.5 dS m^{-1}) and Logra (EC_{50} = 5.8 dS m^{-1}). From an economic point of view, the most important statistics for farmers with fields with moderate and high soil salinities are, respectively, the grain yields at the EC's of 6.0 and 12.0 dS m^{-1} (Y_6 and Y_{12}, respectively). Based on their statistics, the best commercial genotypes would be Briggs and Flavia for moderate salinities and Athos and Klaxon for high salinities.

Table 4 shows the correlation coefficients among the tolerance statistics. 70% of the coefficients were significant at $P < 0.001$, although in general they were not high. The lack of a significant correlation between Y_m and EC_{50} suggests that the most productive genotypes were not necessarily the least tolerant to salinity. In contrast, Shannon (1997) noted that one difficulty in breeding for salinity tolerance is that the low-yielding varieties were less sensitive to salinity than the high-yielding varieties, and Pasternak and De Malach (1994) indicated that yields of crops with high yield potential could be more severely affected by salinity than yields of more salt tolerant crops with lower yield potential. The lack in correlation between Y_m and EC_{50} is also shown in Fig. 1, where the EC_{50} values of each genotype are plotted against their corresponding Y_m values. The dotted lines are the mean EC_{50} and Y_m values of the 103 barley genotypes. The 24 genotypes falling in the upper-right quadrant have good salinity tolerance and grain yield, since their EC_{50} and Y_m

values are higher than the means. A similar analysis performed for each individual year (i.e., correlation coefficients among genotypes within a year) indicates that the EC_{50}-Y_m correlations, although negative, were generally low and only significant ($P < 0.05$) for the 1990 and 1991s years.

The correlation coefficients between Y_m, Y_6 and Y_{12} were positive and significant ($P < 0.001$). Thus, the most productive genotypes under saline conditions were those which yielded most under control conditions. Y_m may therefore be a good indicator in screening of barley for high yield under both moderate and high salinity values. We concluded that, in the absence of genotypes specifically bred for salinity tolerance, it is best to use those with the greatest Y_m. Richards (1983) came to the same conclusion, although based on a different argument: in fields where there is a high spatial variability in salinity, most of the yield comes from the least saline areas, where varieties with the greatest Y_m will do best.

The EC_{50} salinity tolerance parameter is significantly correlated with Y_6 ($P < 0.001$) and Y_{12} ($P < 0.05$), whereas the EC_t parameter is not correlated with Y_6 ($P > 0.05$) and is negatively correlated with Y_{12} ($P < 0.001$). This result suggests that screening of barley for high EC_t could be detrimental since it will select for low-yielding barley genotypes under high soil salinity conditions. We therefore concluded that EC_{50} is preferred over EC_t as predictor of high yields in salt-affected soils.

Effect of saline sprinkling irrigations on the tolerance of barley genotypes

Sprinkler-irrigated crops are potentially subject to additional damage caused by foliar salt uptake from spray contact of the foliage. The information available for predicting yield losses from saline sprinkler irrigation is quite limited, and has not yet been quantified in terms of the EC_t or EC_{50} tolerance parameters. Since the TLS system integrates the effects of the absorption of salts by leaves and roots, a comparison of the mean EC_{50} (7.1 dS m^{-1}) and EC_t (4.0 dS m^{-1}) values obtained with the TLS with those reported for barley in the literature for surface irrigation systems (EC_{50} = 18 dS m^{-1} and EC_t = 8 dS m^{-1}; FAO, 1985) could give an indication of the negative effects of sprinkling with saline waters. Although this comparison is not strictly valid as it will also be

influenced by the different environmental conditions under which the assessments were made, it suggests that the salinity tolerance of barley under saline sprinkling irrigations was 60 % (EC_{50} basis) and 50% (EC_t basis) lower than that obtained with surface irrigation systems. According to the results of Fowler and Hamm (1980), McKenzie et al (1983), Royo et al (1991b) and other unpublished results obtained by us, the EC_{50} estimates for saline field conditions with surface irrigation systems are around 14 dS m^{-1} (i.e. 22 % lower than the value reported by FAO, 1985). Based on this value, the tolerance of barley under sprinkling irrigation was around 50 % lower than that obtained under surface irrigation.

Based on the EC of the applied water (EC_{aw}), the established EC_{aw}-grain yield response functions (data not given) had average estimates of 5.8 dS m^{-1} for EC_{awt} and 11.6 dS m^{-1} for EC_{aw50}. These results suggest that, with our irrigation strategy of short pre-wettings and post-washings of the foliage with fresh water (see Materials and Methods section), barley could withstand saline waters of around 60 meq Cl L^{-1} without a substantial yield loss. This value is much higher than the 10-20 meq Cl L^{-1} reported by Maas (1990) as causing foliar injury in barley in conventional sprinkler irrigation systems (i.e., without pre- and post-irrigations with fresh water) indicating that, as demonstrated by Benes et al. (1996), these treatments considerably reduced foliar salt uptake and damage to the plants.

Although saline sprinkling irrigations have an important additional deleterious effect on the salinity tolerance of barley compared to surface irrigation systems, the rank order of the salinity tolerance of barley genotypes is similar among both systems, as demonstrated by Ortiz (1997) and Isla et al (1998). This result implies that the TLS is a convenient system to rank and screen barley genotypes for salinity tolerance as well as for quantifying tolerance to saline sprinklings (i.e., leaf + root salt absorption), although not for quantifying tolerance to saline surface irrigations (i. e., only root salt absorption).

Leaf salt accumulation and relationships with salinity tolerance

Table 5 summarises the leaf sap analyses performed on various leaves of barley genotypes sown in treatments 1 (control), 5 (intermediate salinity) and 9 (high salinity) of the 1991 to 1994 TLS experiments. As expected, leaf sap osmotic potential (OP) and the concentrations of Cl, Ca and Na increased with increasing salinities, whereas leaf sap K remained relatively constant. Similar results were reported by Isla et al. (1997, 1998). The OP measured in 1991ns was much lower than in the other years, probably due to the initial absence of salts in the soil profile. The leaf sap OP measured in the three treatments each year were significantly different ($P < 0.05$), except in 1993 where $OP_1 = OP_5$. The variability of the OP among genotypes was relatively low, as indicated by the CV of the mean OP, which was, in general, lower than 19 %.

Leaf sap Cl concentrations measured in the three treatments each year were also different, except in 1994 ($Cl_1 = Cl_5$), and the CV of the mean Cl values were greater than those for the OP. The results of the leaf sap Cl and Na analyses performed on different leaves in 1993 indicated that, in the three treatments, their concentrations increased with leaf age (i.e., leaf sap Cl and Na flag leaf (Fl) < Fl-1 < Fl-2 < Fl-3). As indicated by Grattan et al. (1994) and Isla et al. (1997) these results may reflect the longer time of exposure of the older leaves to the saline sprinklings and/or by the translocation of salts from younger to older tissues.

The leaf sap K concentrations measured in the different treatments of the TLS system were quite constant and, in general, did not decrease with salinity as it has been reported by others (Cramer et al., 1991 and Gorham et al., 1994 in barley; Johnson, 1991, Schachtman et al., 1991 and Weinberg, 1987 in wheat). The reason for this apparent discrepancy may be that we used relatively high Ca concentrations in the saline sprinkling waters. Cramer et al. (1991) and Huang and Redmann (1995) concluded that the addition of Ca prevents the nutritional disorders caused by high Na concentrations. Under these circumstances, plants are able to discriminate in favour of K and against Na, so that whereas the Na/K ratio in the soil solution is very high (up to 50-60 according to Isla et al., 1997), this ratio is in general lower than unity in the leaf sap (Table 6). Also Gorham (1993) concluded that K/Na discrimination as a mechanism of salt tolerance was operative in wheat

but not in barley, which suggests that other salt tolerance mechanisms, such as salt compartmentation to the vacuoles or to old leaves, could be responsible for the greater salt tolerance of barley than wheat.

Table 6 gives the correlation coefficients obtained among the various salinity tolerance parameters and the leaf sap OP, Cl, Ca, Na and K values measured in the saline treatments 5 and 9 and normalised to the corresponding values measured in the control (treatment 1). These coefficients, obtained with a large number of barley genotypes, show the lack of consistent relationships between salinity tolerance and the sap concentrations of any of the ions we analysed. Similar results were obtained by Isla et al (1997) with 18 barley genotypes and by Rawson et al. (1988) with 8 barley genotypes, 10 wheat genotypes and 2 triticale genotypes. We therefore concluded that these leaf ion concentrations cannot be used in screening for increased salinity tolerance in barley.

Conclusions

In five years of experiments with the Triple Line Source Sprinkler (TLS) system, 196 grain yield-salinity response functions were calculated with the van Genuchten sigmoidal model. Of these functions, 180 (i.e., 92% of total) gave r (correlation coefficient) and EC_{50} (the EC_e that reduces yield by 50%) estimates which were significant at $P < 0.05$, and the SE's (standard error) of the EC_{50} estimates were lower than 25% of the EC_{50}. The response functions of 24 genotypes grown at least in two or more years generally gave consistent and reproducible results and differences among years, if any, were small. We therefore concluded that the consistency and reproducibility of the salinity tolerance data obtained with the TLS within and between years was adequate.

The response functions of 124 barley genotypes were reported on the basis of their estimated grain yields in the absence of salinity (Y_m) and at EC_e values of 6 (Y_6), and 12 (Y_{12}) dS m^{-1}, as well as on the basis of the salinity tolerance statistics EC_{50} and EC_t (threshold EC_e). The lack of a significant ($P > 0.05$) correlation between Y_m and EC_{50} suggests that the most productive genotypes were not

necessarily the least tolerant to salinity. In fact, the correlation coefficients obtained between Y_m, Y_6 and Y_{12} were positive and significant ($P < 0.01$), indicating that those genotypes with the highest yield potential were also the most productive at the medium and high salinity values. We therefore concluded that, in the absence of genotypes specifically bred for salinity tolerance, those with the greatest Y_m should be used.

Foliar salt uptake due to saline sprinkling irrigations decreased the salinity tolerance of barley by around 50% as compared with the tolerance obtained for surface irrigation systems. Nevertheless, our irrigation strategy of short pre-wettings and post-washings of the foliage with fresh water was effective in reducing foliar salt uptake. Thus, barley could withstand saline waters of around 60 meq Cl L^{-1} without a substantial yield loss, as compared to the 10-20 meq Cl L^{-1} reported in the literature as causing foliar injury in conventional (i.e., without pre- and post-irrigations with fresh water) sprinkler irrigation systems.

Leaf sap osmotic potential (OP), Cl, Ca and Na increased with increasing salinity values, whereas leaf sap K remained relatively constant. However, no consistent relationships were found among the salinity tolerance parameters and the leaf sap analyses. We therefore conclude that leaf sap OP and leaf sap ion concentrations may not be used as screening tools in breeding programs for increasing the salinity tolerance in barley.

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Table 1. Principal characteristics of the triple-line-source (TLS) experiments

	experimental year					
	1990	1991ns	1991s	1992	1993	1994
Initial salinity in soil profile	no	no	yes	yes	yes	yes
Number of tested genotypes	40	30	14	38	55	19
Number of selected genotypes	33	23	14	38	53	19
Sowing date	24/01/90	19/10/90	19/11/90	21/11/91	27/11/92	19/11/93
Harvest date	28/6/90	1/7/91	1/7/91	30/6/92	2/7/93	22/6/94
Rows $plot^{-1}$	2	2	6	2	2	6
First saline irrigation	23/02/90	31/01/91	31/01/91	21/01/92	3/02/93	31/01/94
Last saline irrigation	4/06/90	7/06/91	7/06/91	1/06/92	31/05/93	31/05/94
Number of irrigations	29	31	31	22	31	28
Irrigation time, min	36	33	33	37	37	34
Seasonal saline irrigation, mm	417	406	406	365	399	351
Seasonal rain plus non-saline irrigation, mm	102	127	127	59	128	118
Seasonal applied water, mm	519	533	533	424	527	469
Seasonal evapotranspiration, mm	301	303	303	337	283	339
Estimated leaching fraction (LF)	0.42	0.43	0.43	0.20	0.46	0.30
Seasonal EC applied water interval, dS m^{-1}	2.5-17.2	1.6-14.7	1.6-14.7	2.2-12.7	1.9-16.2	1.5-16.7
Seasonal EC_a EM-sensor interval, dS m^{-1}	0.8-2.1	0.8-1.9	1.0-2.6	0.8-2.6	0.7-2.4	0.8-2.1
Number of genotypes sampled for leaf analysis	---	15	---	30	74	18

Table 2. Mean ± standard deviation (SD) of the EC_{50} and EC_t estimates obtained in each of the TLS experimental years using the sigmoidal model of van Genuchten (1983).

TLS year	Number of selected barley genotypes	Mean EC_{50} ± SD ($dS\ m^{-1}$)	Mean EC_t ± SD ($dS\ m^{-1}$)
1990	21	7.35 ± 1.10	3.63 ± 1.39
1991 ns[a]	15	7.53 ± 0.99	3.58 ± 1.57
1991 s[a]	13	7.00 ± 1.03	3.85 ± 0.92
1992	38	7.50 ± 0.93	4.51 ± 1.01
1993	39	6.80 ± 0.91	3.93 ± 0.95
1994	17	7.07 ± 0.66	4.00 ± 0.69
Total	143	7.19 ± 0.97	4.00 ± 1.12

[a]: ns = no salts initially in the soil profile; s = salts initially in the soil profile

Table 3. Salinity-grain yield response functions of 124 barley genotypes computed from data obtained with the TLS system. Y_m, Y_6 and Y_{12} are the grain yields estimated for the control, the EC_e = 6 and the EC_e = 12 dS m^{-1} saline treatments, respectively. EC_{50} and EC_t are salinity tolerance statistics defined in Materials and Methods. All the EC values are on a saturation extract basis (EC_e).

#	Genotype	Y_m Kg ha^{-1}	EC_{50} dS m^{-1}	EC_t dS m^{-1}	Y_6 Kg ha^{-1}	Y_{12} Kg ha^{-1}
1	ACSAD 60	1970	7.58	4.06	1479	202
2	ACSAD 176	2950	6.73	3.46	1841	214
3	AGLOU	1640	8.10	5.63	1507	65
4	ALBACETE (5)[a]	3830	8.28	3.81	2957	754
5	ALMUDENA	3860	8.51	4.41	3193	682
6	ALPHA (4)	4580	7.29	4.66	3585	166
7	AMALTEA	3940	8.20	5.56	3602	209
8	ANNOCEUR	3150	6.46	3.01	1798	264
9	ANTEQUERA-2	2530	7.51	4.66	2023	133
10	ANTEQUERA-3 (2)	3820	8.06	4.10	2992	575
11	ARABI ABYAD	3240	6.75	3.77	2089	167
12	ARAYA (2)	5020	8.21	5.40	4521	726
13	*ARCADIL*[b]	*5450*	*6.79*	*2.72*	*3261*	*751*
14	ARIG	3390	7.24	4.28	2513	189
15	ARIVAT	5110	8.15	4.92	4376	485
16	ASNI (2)	2170	7.54	4.63	1733	124
17	ASTRIX	6030	5.52	2.05	2645	550
18	ATHOS	7110	6.16	1.34	3645	1538
19	ATLAS 57	4260	6.50	3.60	2549	192
20	ATLAS 65	4600	5.95	3.39	2250	114
21	ATLAS 66	3310	5.71	3.41	1422	47
22	BARBARROSA (3)	5610	6.00	2.71	2805	398
23	BARI 1	3640	5.71	4.65	1198	0
24	*BARI 2*	*3640*	*6.62*	*2.08*	*2046*	*658*
25	BARI 3	3410	5.49	4.08	1001	2
26	BARI 4	3640	6.38	3.87	2145	87
27	BARI 5	2700	6.13	4.62	1500	3
28	BARI 6	3170	6.93	4.94	2648	26
29	BARI 7	2910	6.51	4.07	1819	62
30	*BARI 8*	*4540*	*5.98*	*2.13*	*2259*	*552*
31	BEGOÑA (2)	3710	7.53	4.83	3035	162
32	*BERTA*	*6820*	*7.74*	*1.40*	*4145*	*2182*
33	BRIGGS	7220	8.43	5.66	6680	493
34	CALIFORNIA	4120	7.78	5.11	3545	189
35	CAMEO	2370	6.24	3.81	1323	47
36	*CAPRI*	*4540*	*7.44*	*1.42*	*2699*	*1352*
37	CARAVELA	4640	6.59	3.77	2882	189
38	CBC-22	3670	9.04	4.28	3061	906
39	CE8402	6050	7.13	4.23	4389	306
40	CE8901	6260	7.33	3.52	4323	762

Table 3. (Cont.)

#	Genotype	Y_m Kg ha^{-1}	EC_{50} dS m^{-1}	EC_t dS m^{-1}	Y_6 Kg ha^{-1}	Y_{12} Kg ha^{-1}
41	CE8903	5620	6.92	3.55	3668	453
42	CE8904	7740	6.34	3.18	4323	476
43	CE8905	8250	5.63	2.47	3658	519
44	CE9001	6010	6.72	4.00	3940	215
45	CE9002	3940	7.79	5.03	3359	205
46	CEBADA CAPA	3240	6.57	2.81	1872	358
47	CERRO PRIETO	3240	6.75	5.08	2500	8
48	*CLARET*	*7270*	*5.50*	*2.27*	*3112*	*504*
49	CM-67 (4)	4060	7.40	4.07	2995	343
50	CM-72	6600	7.03	3.90	4540	428
51	COMPOSITE 29	2970	6.54	4.38	1939	34
52	CRITER (3)	3310	8.04	4.72	2762	326
53	DACIL (2)	4520	7.95	4.81	3790	373
54	DEIR ALLA	3010	6.23	2.72	1606	266
55	DESNUDA 4500	1240	6.65	5.11	942	2
56	*DOBLA*	*4540*	*7.72*	*2.74*	*3049*	*1009*
57	DPCHE-18 (2)	2180	5.69	2.32	995	174
58	ESPERANCE	2500	6.04	3.90	1278	25
59	FLAVIA	7000	8.33	5.43	6337	525
60	FLIKA	4010	8.13	5.01	3464	344
61	FORREST	4240	8.78	6.33	4106	241
62	GABRIELA	4860	7.23	2.32	3006	1031
63	GEORGIE	4420	6.92	3.44	2856	394
64	GERBEL (2)	6470	7.20	3.50	4386	716
65	GIZZA 119	3420	6.14	3.45	1810	109
66	HASSAN	5750	7.25	2.87	3715	964
67	HATIF GRIGNON	4960	8.97	3.41	3832	1449
68	*IBON3/56*	*6360*	*7.84*	*1.95*	*4058*	*1835*
69	IBON3/95	6850	6.83	1.50	3853	1719
70	IBON3/193 (2)	3050	6.49	4.16	1913	51
71	*IBYT3/49*	*6360*	*7.63*	*1.55*	*3876*	*1921*
72	IGRI (5)	3690	8.11	4.04	2884	591
73	*JET * AGER*	*1360*	*4.53*	*0.69*	*532*	*242*
74	KLAXON	7840	6.70	2.03	4451	1502
75	KORU	7840	6.34	1.73	4165	1492
76	KVL468	1270	7.53	5.00	1062	43
77	KYM (2)	5050	7.29	4.75	3999	160
78	LECHTALER	2460	6.75	4.66	1767	25
79	LOGRA	7160	5.77	2.02	3384	811
80	LOS RODEOS	4130	8.25	5.89	3889	151

Table 3 (Cont.)

#	Genotype	Y_m Kg ha^{-1}	EC_{50} dS m^{-1}	EC_t dS m^{-1}	Y_6 Kg ha^{-1}	Y_{12} Kg ha^{-1}
81	LUCENA 3	5030	8.19	3.73	3836	969
82	MALTA (2)	2360	8.11	4.26	1885	337
83	MARTA (2)	4560	7.78	4.69	3736	339
84	MARTIN	3090	8.18	4.46	2529	415
85	*MARROQUI*	*7270*	*9.07*	*1.22*	*4706*	*2897*
86	MERZAGA	2450	7.10	3.90	1705	172
87	MINAK	4480	5.99	4.00	2226	28
88	MOGADOR (4)	5320	7.25	3.97	3810	417
89	*MOTAN*	*6360*	*7.36*	*2.11*	*3932*	*1525*
90	MUTANTE 4210	1930	5.33	3.47	594	7
91	MUTANTE 4211	1940	6.34	2.97	1074	150
92	O'CONNOR	4970	7.26	4.37	3734	256
93	*OLIVIA*	*3940*	*6.05*	*2.40*	*1996*	*401*
94	*ORGE PAYS*	*4090*	*7.89*	*2.08*	*2646*	*1160*
95	OSA	6810	6.05	2.30	3448	755
96	PALLAS	6150	6.10	4.95	3432	0
97	*PANE*	*6670*	*6.93*	*0.94*	*3687*	*2058*
98	*PATTY*	*5450*	*6.50*	*1.56*	*2949*	*1201*
99	PEN (2)	2600	8.24	5.02	2257	252
100	PLAISSANT	3510	8.09	5.18	3082	241
101	RABAT	2550	8.30	5.81	2387	115
102	RCB 92 (2)	5480	6.30	2.85	2987	460
103	*RCB 188*	*5450*	*7.95*	*1.73*	*3447*	*1696*
104	REINETTE (3)	3530	7.92	4.96	3007	240
105	RIBEKA	5250	6.00	3.53	2625	109
106	ROBUR	5670	6.65	2.40	3253	871
107	*RPB7078*	*5450*	*5.70*	*2.21*	*2508*	*490*
108	SEKAL	3670	7.04	3.93	2538	233
109	SEREIA	6870	6.76	4.24	4671	179
110	SINNIS 27	6570	7.20	3.12	4304	933
111	SOLEDAD	6940	7.44	4.78	5598	279
112	STEPTOE (3)	5470	8.14	4.75	4600	587
113	SUTTER	6110	8.53	6.56	5994	130
114	TABAIVA	5100	6.92	4.06	3505	233
115	TAGIDE	6240	6.86	3.98	4202	290
116	TATIANA (2)	5670	7.19	4.24	4156	308
117	*TECLA*	*3640*	*6.97*	*1.82*	*2116*	*849*
118	TISSA	5780	6.33	3.70	3311	169
119	*TRAIT UNION*	*5450*	*7.29*	*1.28*	*3169*	*1641*

Table 3 (Cont.)

#	Genotype	Y_m Kg ha^{-1}	EC_{50} dS m^{-1}	EC_t dS m^{-1}	Y_6 Kg ha^{-1}	Y_{12} Kg ha^{-1}
120	TUNIS	2330	8.51	4.88	2013	325
121	VARUNDE	3160	6.90	3.80	2105	193
122	VIVA	5770	8.26	4.55	4784	787
123	*WELLAM*	*4540*	*5.45*	*1.76*	*1989*	*520*
124	ZAIDA (2)	4570	7.57	4.47	3591	323
MEAN[c]		4412	7.12	4.04	3019	371
SD[c]		1662	0.90	1.04	1224	367
MAXIMUM		8250	9.04	6.56	6680	1719
MINIMUM		1240	5.33	1.34	594	0

[a] In parenthesis: number of years evaluated with the TLS system

[b] In italics: genotypes where Y_m is fixed by the user to the maximum experimental value

[c] Mean and standard deviation of the genotypes with Y_m values calculated by the program

Table 4. Correlation coefficients obtained among the model statistics. The number of genotypes used in these calculations was 103 (those with Y_m values calculated by the program).

	Y_m	EC_{50}	EC_t	Y_6
EC_{50}	-0.084			
EC_t	-0.342***	0.620***		
Y_6	0.820***	0.428***	0.147	
Y_{12}	0.586***	0.193	-0.545***	0.466***

*** Significant at the 0.001 probability level.

Table 5. Mean values of leaf sap osmotic potential (OP), Cl, Ca, Na and K ions measured in the indicated leaves sampled in various genotypes grown in treatments 1 (control), 5 (intermediate salinity) and 9 (high salinity) of the 1991 to 1994 TLS experimental years.

Year	Nº of genot.	leaf sampled	OP_1	OP_5	OP_9	Cl_1	Cl_5	Cl_9	Ca_1	Ca_5	Ca_9	Na_1	Na_5	Na_9	K_1	K_5	K_9
			———	kPa	———	———	———	———	———	———	mmol L^{-1}	———	———	———	———		
1991ns	15	Fl	1294	1451	1641												
1992	30	Fl	1552	1790	2233												
1993	24	Fl	2051	2233	2635	94	150	240	45	77	119	35	61	85	180	187	175
1993	13	Fl-1	1958	2041	2657	185	251	342	40	60	93	58	81	112	204	205	190
1993	24	Fl-2	1785	2100	2660	223	300	412	40	71	115	71	112	145	177	172	207
1993	13	Fl-3	1751	2085	2673	259	356	482	45	76	124	95	165	206	168	141	145
1994	18	Fl-1	1810	2026	2782	206	216	386	44	61	98	69	85	108	192	194	239

Table 6. Correlation coefficients obtained between the salinity tolerance statistics (first row) and the normalised leaf sap OP, Cl, Ca, Na and K values measured in the saline treatments 5 (intermediate salinity) and 9 (high salinity) (first column); n is the number of genotypes used in each analysis.

	n	EC_{50}	EC_t	Y_6 / Y_m	Y_{12} / Y_m
OP_5 / OP_1	93	0.152	0.115	0.188	0.023
OP_9 / OP_1	93	-0.110	0.005	-0.083	-0.154
Cl_5 / Cl_1	60	0.087	-0.080	0.096	0.151
Cl_9 / Cl_1	60	0.074	0.013	0.064	0.055
Ca_5 / Ca_1	53	0.022	0.039	0.026	0.023
Ca_9 / Ca_1	53	-0.154	0.036	-0.119	-0.194
Na_5 / Na_1	52	0.288*	0.089	0.299*	0.268
Na_9 / Na_1	52	0.200	0.050	0.164	0.228
K_5 / K_1	52	-0.159	0.055	-0.137	-0.201
K_9 / K_1	52	-0.019	0.026	-0.017	-0.059

*,** Significant at the 0.05 and 0.01 probability levels, respectively.

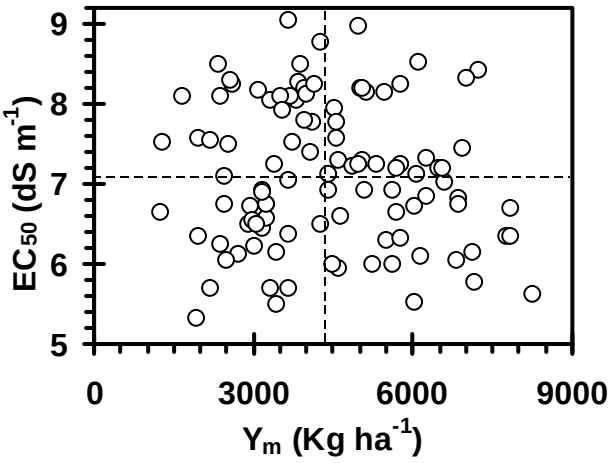

Fig. 1. Relationship between EC_{50} and Y_m for 103 barley genotypes grown in the 1991 - 1994 TLS experiments. EC_{50} is the estimated electrical conductivity of the soil saturation extract (EC_e) that reduces yield by 50%. Y_m is the estimated grain yield under non-saline conditions. The dotted lines are the mean EC_{50} and Y_m values for the 103 barley genotypes.