Spatial variability of salt-affected soils in the middle Ebro Valley (Spain) and implications in plant breeding for increased productivity

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ABSTRACT

The assessment of the level and spatial variability of soil salinity and the knowledge of the salinity-yield response functions of crops are required to ascertain the best management strategies aimed at optimizing crop's productivity in saline environments. This work analyzed the spatial distribution of ECe in six irrigated, salt-affected fields of the middle Ebro River Valley (Spain) using electromagnetic survey and geostatistical techniques, and the implications of this salinity variability in plant breeding strategies for increased productivity. The average field ECe varied between 4.9 and 15.4 dS m^{-1}, with within-field coefficients of variation between 37 and 79%. The yield simulation analysis of 20 barley and durum wheat cultivars showed that almost 60% of the total yield came from the less saline areas (ECe < 6 dS m^{-1}). The model-estimate Ym (maximum yield under non-saline conditions) and the simulated yields were significantly correlated (P<0.01) in ten out of the twelve analysis performed. Thus, the best strategy for increasing the productivity in moderately salt-affected soils (average field ECe between 5 and 7 dS m^{-1}) of the middle Ebro Valley is to breed and grow high potential yielding barley and durum wheat cultivars. On the other hand, breeding for increased productivity in highly salinized soils (average field ECe around 15 dS m^{-1}) should be based, at least at the parental line's selection stage, on the combination index B (ECe_{50} Ym 10^{-3}) which takes into account both the potential yield and the salinity tolerance of crops.

Abbreviations: EC, electrical conductivity; ECa, apparent EC; ECe, saturation extract EC; ECe_{50}, the ECe that reduces yield by 50%; Ym, grain yield under non-saline conditions

INTRODUCTION

It is estimated that some 20-27% of the world's irrigated land is salt-affected (Shannon, 1997). Thus, in the semi-arid middle Ebro Valley (Spain), about 250.000 ha (i.e., close to 30% of the irrigated land) are saline or sodic (Herrero y Aragüés, 1988). Since salinity negatively affects crop yields (Maas, Hoffman, 1977), a strategy in these areas is to cultivate salt-tolerant crops like barley and wheat. However, depending on the salt level, the most sensitive cultivars of these crops may be severely affected, so that the choice of their most salt-tolerant cultivars is a key-issue to improve yields and farmer's incomes. Thus, Royo and Aragüés (1999) ranked the salinity tolerance of 124 barley genotypes using a Triple Line Source Sprinkler system. Although the variability in salinity tolerance among them was relatively low, for the commercial cultivars tested they found differences in the ECe_{50} (salinity at which yield decreases by 50%) between 5.5 and 9.0 dS m^{-1}.

Although the development of new salt-tolerant cultivars has received considerable attention in the last twenty years, only a few commercial grain-crop varieties have evolved and are being successfully grown by farmers (Flowers and Yeo, 1995). However, Richards (1983, 1992) questioned the utility of plant breeding for increasing salt tolerance because of the high yield contribution of the less saline areas to total yield, and Shannon (1997) indicated that breeding for salt tolerance could reduce their yield potentials (i.e., salt tolerance and maximum yield could be negatively correlated).

A typical characteristic of salt-affected soils is the inherent spatial variability at the metric scale which makes difficult its mapping at an adequate scale to assess detrimental effects on crops. The classical methodology based on soil sampling and subsequent laboratory analysis is unaffordable in large areas because of its high cost. This is one of the main reasons of the limited availability of detailed salinity maps for the major irrigated areas in the Ebro River Valley and elsewhere.

However, electromagnetic measurements of soil salinity using the portable EM38 (Geonics Ltd., Canada) allows for the rapid measurement of the apparent electrical conductivity (ECa) that can be converted to the standard soil saturation extract electrical conductivity (ECe) through calibration techniques. This methodology has been successfully used to measure soil salinity in the Ebro River Valley (López-Bruna and Herrero, 1996; Tedeschi et al., 2001; Herrero et al., 2003). Besides these rapid ECa measurements, the EM38 held in its horizontal-dipole position integrates soil-salinity within the 0-100 cm depth in a similar vertical pattern to that of crop's water uptake, so that this instrument is most appropriate in crop-salinity studies under field conditions.

The objectives of our study were (i) to describe the spatial variability of soil salinity in different salt-affected irrigated fields of the middle Ebro Valley using the EM38, (ii) to simulate in these fields the yields of ten barley and ten durum wheat cultivars with well defined salinity-yield response functions, and (iii) to discuss the implications in plant breeding strategies for increased salt tolerance.

MATERIALS AND METHODS

Soil salinity survey

Six irrigated fields of the middle Ebro River Valley (Aragón, north-east Spain) were surveyed for mapping of soil salinity using an EM38 sensor (Geonics Ltd., Canada). These fields were selected as representative of the salt-affected soils present in Aragón. Table 1 gives the surface area of each field, the survey density (grid size) and the number of EM38 readings. These fields are irrigated with good-quality waters (EC < 0.5 dS/m), but they are salt-affected due to the presence of saliferous Miocenic strata coupled to an improper soil and irrigation management.

The EM38 was held at the soil surface in its horizontal dipole position and ECa readings were taken in each node of the orthogonal grids. The survey density was very high (one reading every 11 m^2 to 100 m^2 depending on field size) in order to precisely delineate the soil salinity spatial variability within each field. Soil temperatures were measured at the same time at various depths and the ECa values were referenced at 25ºC. All the EM38 readings were performed at soil water contents close to field capacity (i.e., 2 to 4 days after irrigation).

A variable number of points covering the entire range of ECa readings were selected for calibration of the EM38 sensor. After reading the ECa at each point, the soil samples were taken with an Edelman auger and the ECe was measured in the laboratory. Table 1 gives for each field site the number of soil samples, the soil depths and the linear regression equations. All the regressions were significant at $P < 0.001$. The ECa values measured in the grid nodes of each field were converted into ECe using these equations.

Crops and cultivars

Ten barley and ten durum wheat cultivars were selected for estimating their yields in the six surveyed fields. The sigmoidal response curves (van Genuchten, 1983) of these cultivars have been previously reported in Royo et al. (2000) for barley and Royo y Abió (2003) for durum wheat, and were obtained under controlled field conditions by means of a drip-injection irrigation system (Aragüés et al., 1999). Table 2 gives the model parameters Ym (the maximum grain yield under non-saline conditions), ECe_{50} (the ECe that reduces yield by 50%) and p (a constant that determines the steepness of the curve), the coefficients of determination (R^2) between the observed and the estimated grain yields (all of them significant at $P < 0.001$), and the lumped parameters A (ECe_{50} + Ym 10^{-3}) and B (ECe_{50} Ym 10^{-3}) that integrate salt tolerance and maximum yield (Royo and Aragüés, 2002).

Analysis

An exploratory data analysis was performed on each ECe data set to characterize soil salinity at each field site. The soil-salinity spatial variability in each field was determined through a geostatistical analysis of the ECe data. The semivariances were calculated using the equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(x_i + h) - Z(x_i) \right]^2$$

where $Z(x_i)$ is the ECe estimated at the "*i*" data point and $N(h)$ is the number of data-point pairs at a distance h.

After a visual examination of the sampling semivariograms, different models were fitted to each field data set by nonlinear least squares techniques in order to obtain the semivariogram parameters (nugget, sill and range). The nugget is the value obtained in the fitted semivariogram when h equals zero. In a theoretical semivariogram, the semivariance increases as h increases till a plateau (defined as sill) is reached. The information provided by the models was used to delineate the soil salinity contour maps by kriging using the Surfer 6.0 software (Golden Software, Inc, Colorado). Kriging is an interpolation methodology that considers the modeled spatial correlation of the observed values.

RESULTS AND DISCUSSION

Distribution of soil salinity

The mean ECe of the surveyed fields varied between a relatively low value of 4.9 dS/m (Callen) and a high value of 15.4 dS/m (Tauste). In four out of the six fields the medians were lower than the means, indicating a positive skewness of ECe (Fig. 1). The normal probability plots and the Shapiro-Wilk tests (not presented) showed in all cases a significant deviation of ECe from normality. The ECe frequency histograms in Monesma, Sádaba, and Almuniente showed a predominance of relatively low ECe, with most values below 10 dS m^{-1}; ECe in Melusa and Tauste were more regularly distributed, and ECe in Callen showed a bimodal distribution (Fig. 1). The within-field ECe variability was high, with coefficients of variation of the means between 37% (Tauste) and 79% (Callen). This high variability is typical in fields where the salt sources are the saliferous geologic materials and the levelling of the land has altered the original soil.

The semivariograms obtained at each field site indicate that soil salinity was spatially correlated (Fig. 2). After a visual examination of the scatter plots, different semivariogram models were adjusted to each data set to get the best fit. Spherical semivariograms were fitted in Monesma, Sádaba, and Almuniente, whereas a gaussian model was selected in Melusa and Tauste, and a linear semivariogram was adjusted in Callen because of the absence of an apparent sill. The semivariance increased with the lag-distance until a sill was reached, and no nugget effects were detected in any of the fields. The absence of a nugget effect denotes the lack of soil-salinity variability at a lower scale than that used in the survey. A sill was evident in five fields, where the range varied between 17 m (Tauste) and 69 m (Melusa). The range obtained in salt-affected soils can be interpreted as a rough estimate of the average-size of the soil salinity patches and provides information about the steepness of soil salinity gradients. Thus, a smaller range should be interpreted as higher variability at short distances. These significant differences in range among different fields remarks the importance of adequate local geostatistical analysis to obtain realistic soil salinity maps and the advantages of using kriging instead of other interpolation methods for estimating soil salinity.

Salinity maps

Based on the ECe estimates obtained from the semivariograms, contour salinity maps were delineated for each field. As an example, Fig. 3 shows these maps for the less (Sádaba) and more (Tauste) saline fields. The contour-maps clearly show the patchy nature of soil salinity and the significant small-scale ECe variability.

The surface areas in each of three ECe selected intervals (0-6, 6-12, and > 12 dS m^{-1}) were obtained by planimetry of these maps (Table 3). These intervals were selected on the basis of the salinity tolerance of barley and wheat. Thus, yields in the 0-6 dS m^{-1} interval will be close to their potential yields, whereas substantial decreases will occur in the > 12 dS m^{-1} interval.

Averaging across the six field sites, the less saline area (ECe < 6 dS m^{-1}) comprised 51% of the total area (2% in Tauste to 82% in Sadaba), the moderately saline area (6 dS m^{-1} < ECe < 12 dS m^{-1}) comprised 33% of total (17% in Sadaba to 46% in Melusa) and the high saline area (ECe > 12 dS m^{-1}) comprised 16% of total (0% in Melusa to 76% in Tauste). These results indicate that even in fields considered saline by farmers and by the standard soil taxonomy, large proportions of the land are non-saline or moderately salt-affected.

Simulated grain-yields

Based on the salinity-grain yield response functions of the barley and durum wheat cultivars presented in Table 2 and the areas for each ECe interval presented in Table 3, we estimated the percentages of the total grain yields in each of these areas (Table 4). 56-58% of the total average barley and durum wheat yields came from the low-saline areas (ECe < 6 dS/m), whereas 10-11% came from the high-saline areas (ECe > 12 dS/m). Only in the more saline field (Tauste, mean ECe = 15.4 dS/m) the high-saline area contributed to 53% (barley) and 49% (durum wheat) of total yields, whereas in the rest of fields the contributions of the high-saline areas were always equal or lower than 5%. Thus, although the crops studied were considered tolerant to salinity (average ECe_{50} = 13.1 and 11.4 for barley and durum wheat) and the soils were classified as saline (average ECe > 4 dS/m; Soil Survey Staff, 1999), most of the yield from these soils came from the least saline areas. For this reason, the precise mapping of soil salinity spatial variability is a key issue for predicting the overall field-productivity of a given crop or cultivar.

In relation to the performance of the different cultivars, Fig. 4 shows the relationship between the simulated grain yields in the less (Callén, ECe = 4.9 dS m^{-1}) and most (Tauste, ECe = 15.4 dS m^{-1}) saline fields. The grain yields were positively and significantly ($P < 0.01$) correlated. Considering all the fields under study, the barley cultivars Alpha and Criter and the durum wheat cultivar Korifla ranked as most productive in five out of the six fields. Overall, these results indicate that the most productive cultivars in the lower saline field were also most productive in the higher saline field. Previous results reported by Isla et al. (1997) and Royo et al. (2000) showed that, for a set of barley cultivars, grain yield in non-saline experimental plots was not significantly correlated to grain yield in high-saline plots. The results presented here highlight the grain-yield contribution from the less saline areas to the total grain yield.

A key issue in plant breeding for salt-affected areas is the screening criteria for selection of the genotypes. In these programs the emphasis is generally focused on salinity tolerance, as given by the ECe_{50} or the ratio of the saline to the non-saline grain-yield. However, some studies (Shannon, 1997) have indicated the difficulty to combine high grain yield and high salt tolerance. Flowers and Yeo (1995) suggested that this difficulty arises from the need for crops to consume energy for its osmotic adjustment in saline environments at the expense of some yield costs. In order to lump together both parameters, Royo and Aragüés (2002) proposed the indices A and B (Table 2) as selection criteria for predicting maximum yields in salt-affected soils.

Table 5 presents the Spearman rank correlation coefficients (Rs) between the simulated grain yields obtained in each field site and the parameters Ym, ECe_{50}, A and B. The salinity tolerance (as given by the ECe_{50}) was inappropriate in predicting crop's productivity since the Rs values were not significant ($P > 0.05$) for the barley fields and three durum wheat fields, or slightly significant ($P < 0.05$) in the other three durum wheat fields. On the other hand, Ym was an appropriate screening parameter, since it was significantly correlated ($P < 0.01$) with crop's productivity in all fields except in two, where the Rs values were significant at $P < 0.05$. These results also suggest that, in terms of productivity, the best strategy for moderately salt-affected areas as those depicted in five out of the six field sites tested, is to grow the highest-yielding cultivars rather than the most tolerant ones. Overall, the index B was the best screening parameter since it was significantly correlated ($P < 0.01$) with crop's productivity in all the field sites and its stability was higher than that for Ym. However, in practical terms Ym is most suitable since it was almost as good as B and it is much easier and less time consuming to obtain under field conditions. Thus, the index B is not practical in breeding population, although it could be useful to select the parental lines.

Although the approach in our work was similar to that of Richards (1983), the yield-response functions used in our work were more consistent (higher R^2), and our soil salinity contour maps were more precise and reliable because of the high survey density, only affordable using electromagnetic induction techniques. Our results confirm and validate earlier observations of Richards for the salt-affected areas in the middle Ebro Valley and for moderately salt-tolerant grain crops.

CONCLUSIONS

The significant deviations from normality of the ECe values and the differences in the spatial correlation patterns among the study field sites highlight the need to perform geostatistical analysis for soil salinity mapping.

The yield simulation analysis of barley and durum wheat cultivars grown in salt-affected soils showed that a large proportion of total yields came from the less saline areas (ECe < 6 dS m^{-1}). The significant correlations found in all cultivars and field sites between Ym and the simulated yields indicate, in agreement with Richards (1983), that the best strategy for increasing the productivity in moderately (average field ECe < 7 dS m^{-1}) salt-affected soils of the middle Ebro Valley (Spain) is to grow high-yielding rather than high-tolerant barley and durum wheat cultivars.

In consequence, breeding for increased productivity in these moderate saline environments should be based on yield potential, whereas breeding for increased productivity in high-saline soils (average field ECe around 15 dS m^{-1}) should be based, at least during selection of the parental lines, in a combination of yield potential and salinity tolerance such as the B index ($B = ECe_{50}$ Ym 10^{-3}).

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Table 1. General characteristics of the surveyed fields and ECe-ECa linear regression equations obtained at each field site for the given number of soil samples and soil depths.

Field site	Field surface (m^2)	EM38 survey density (m) (grid size)	Nº of EM38 readings	Nº of soil samples	Soil depth (m)	ECe = a + b ECa		
						b	a	R^2
Almuniente	23000	10 x 10	250	40	0.4	3.82	-0.73	0.86
Callen	8536	10 x 8	141	22	0.5	6.15	-0.49	0.80
Melusa	2495	3 x 3.6	272	13	0.6	5.61	-1.74	0.89
Monesma	5692	3 x 4	555	15	0.6	10.3	-2.34	0.95
Sadaba	2184	3 x 4	184	20	0.6	7.76	-2.46	0.86
Tauste	2418	1.6 x 10	206	20	1.0	6.41	-5.00	0.78

Table 2. Salinity - grain yield response functions (Ym, ECe_{50}, p and R^2) of ten barley and ten durum wheat cultivars and "yield-salinity tolerance" indices A and B.

Cultivar	Ym Kg ha^{-1}	ECe_{50} dS m^{-1}	p	R^2	[1]A	[2]B
Barley						
Acsad-60	2840	12.2	3.7	0.85	15.04	34.6
Albacete	3830	15.6	4.4	0.77	19.43	59.7
Alpha	6080	11.0	3.1	0.82	17.08	66.9
Antequera	3430	15.1	4.5	0.60	18.53	51.8
Cameo	4090	10.4	4.0	0.89	14.49	42.5
Criter	5300	13.3	3.4	0.89	18.60	70.5
Kym	2060	11.4	4.7	0.74	13.46	23.5
Martín	4940	14.4	4.1	0.81	19.34	71.1
Orge Pays	4640	14.5	3.7	0.83	19.14	67.3
Tunis	4950	13.5	2.8	0.78	18.45	66.8
Durum wheat						
Altar-dos	4113	11.83	2.42	0.86	15.04	42.4
Aw12/Bit	4861	11.74	2.40	0.96	15.97	51.1
Bolo	3704	8.80	2.06	0.94	12.92	36.6
Jabato	4426	11.55	2.81	0.86	20.22	75.3
Korifla	6107	12.11	2.15	0.96	16.19	49.5
Lagost	4094	12.10	8.06	0.96	15.94	48.6
Mexa	4203	8.72	2.65	0.92	15.84	54.3
Omrabi	5022	10.82	2.73	0.84	12.50	32.6
Valira	3760	11.28	15.5	0.98	18.22	73.9
Vitron	4923	15.30	1.49	0.94	16.60	57.1

[1]A = ECe_{50} + Ym 10^{-3}

[2]B = ECe_{50} Ym 10^{-3}

Table 3. Surface areas (in % of total area) in each of the ECe intervals given in the first column obtained by planimetry of the contour maps delineated in each field site.

ECe interval	Almuniente	Callén	Melusa	Monesma	Sádaba	Tauste
$dS\ m^{-1}$	% of total surface area					
0-6	44.7	71.0	53.6	51.5	82.3	2.0
6-12	45.3	26.0	46.4	38.3	17.5	22.4
>12	10.0	3.1	0.0	10.2	0.2	75.7

Table 4. Grain yield contributions in each of the ECe intervals obtained by planimetry of the contour maps delineated in each field site. Each value is the average of the ten cultivars.

ECe interval dS m^{-1}	Almuniente	Callén	Melusa	Monesma	Sádaba	Tauste	Avg.
			% of total grain yield				
			Barley (n = 10)				
0-6	52	77	56	59	84	5	56
6-12	42	21	44	36	16	43	34
>12	5	2	-	5	0	53	11
			Durum wheat (n = 10)				
0-6	55	80	58	62	86	5	58
6-12	40	19	42	34	14	45	32
>12	5	1	-	4	0	49	10

Table 5. Spearman rank correlation coefficients between the simulated average grain yields of the ten barley and the ten durum wheat cultivars in each field site and the parameters Ym, ECe_{50}, A and B. (^{NS}Non significant at P>0.05; *,**: significant at P<0.05 and P<0.01, respectively)

Barley (n=10)					
Field site	Avg. yield (Kg/ha)	Ym	ECe_{50}	A	B
Sádaba	4073	0.99**	-0.10^{NS}	0.37^{NS}	0.85**
Melusa	3946	0.98**	0.01^{NS}	0.47^{NS}	0.88**
Callen	3847	0.71*	0.01^{NS}	0.47^{NS}	0.88**
Monesma	3602	0.98**	0.01^{NS}	0.47^{NS}	0.88**
Almuniente	3518	0.93**	0.13^{NS}	0.55^{NS}	0.92**
Tauste	1732	0.71*	0.47^{NS}	0.81**	0.96**
Average		0.88	0.09	0.52	0.89
Durum wheat (n=10)					
Field site	Avg. yield (Kg/ha)	Ym	ECe_{50}	A	B
Sadaba	4148	0.90**	0.53^{NS}	0.76*	0.92**
Melusa	3888	0.84**	0.54^{NS}	0.75*	0.89**
Callen	3874	0.90**	0.53^{NS}	0.76*	0.92**
Monesma	3513	0.84**	0.67*	0.84**	0.95**
Almuniente	3376	0.84**	0.67*	0.84**	0.95**
Tauste	1567	0.82**	0.68*	0.83**	0.92**
Average		0.86	0.60	0.80	0.92

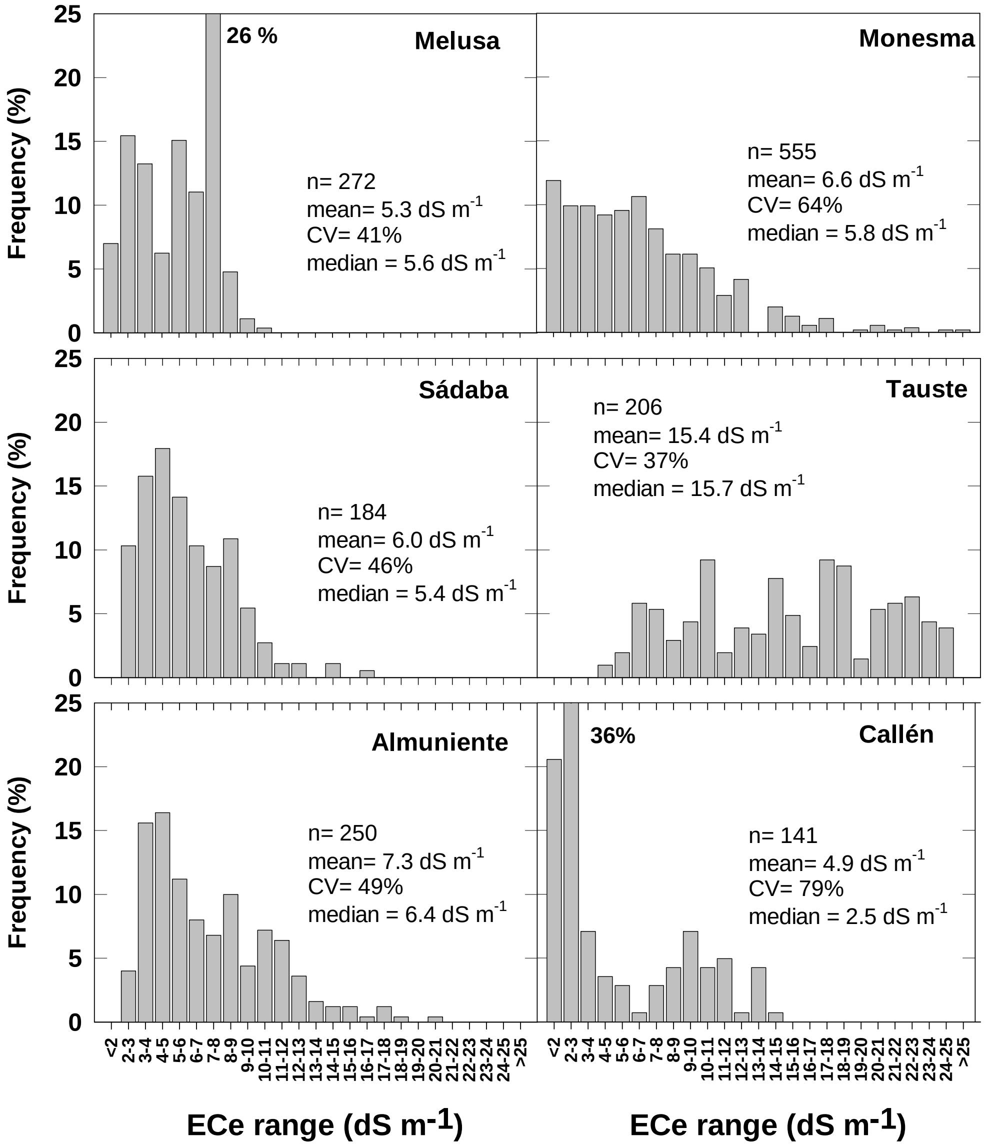

Figure 1. Frequency histograms and basic statistics of ECe in the surveyed field sites.

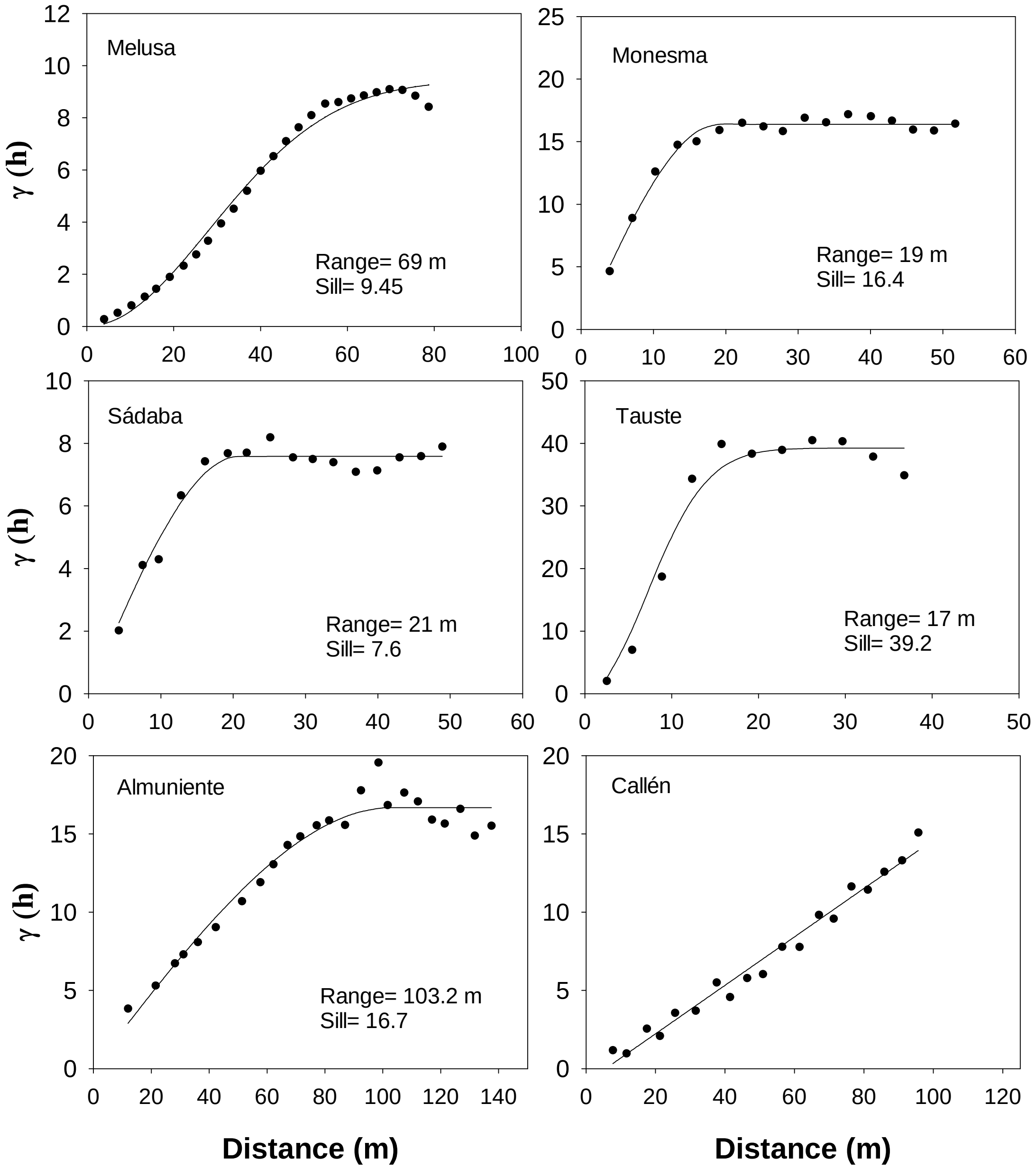

Figure 2. Semivariograms obtained in each surveyed field site. The model fitted and their parameters (range and sill) are also presented.

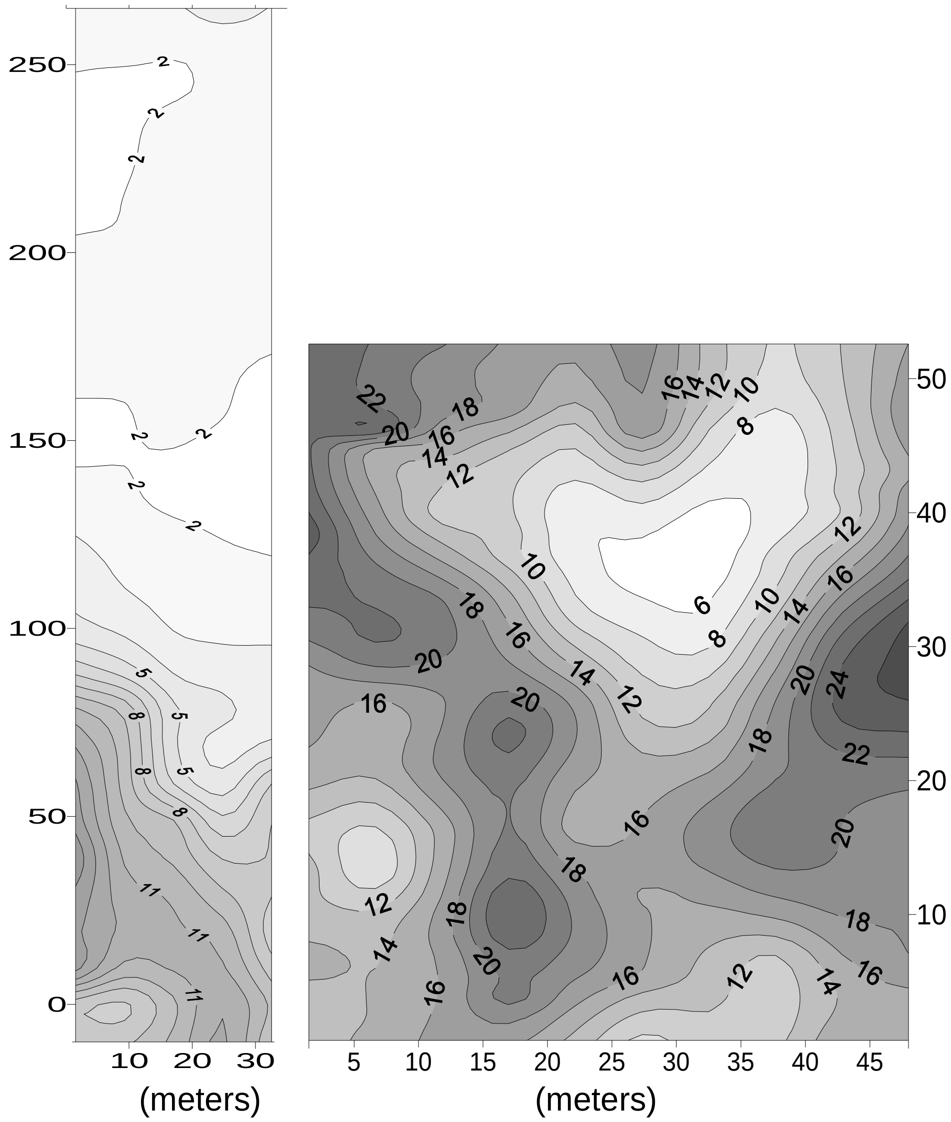

Figure 3. ECe (dS m^{-1}) contour maps of Callén (left side, avg. ECe = 4.9 dS m^{-1}) and Tauste (right side, avg. ECe = 15.4 dS m^{-1}) field sites.

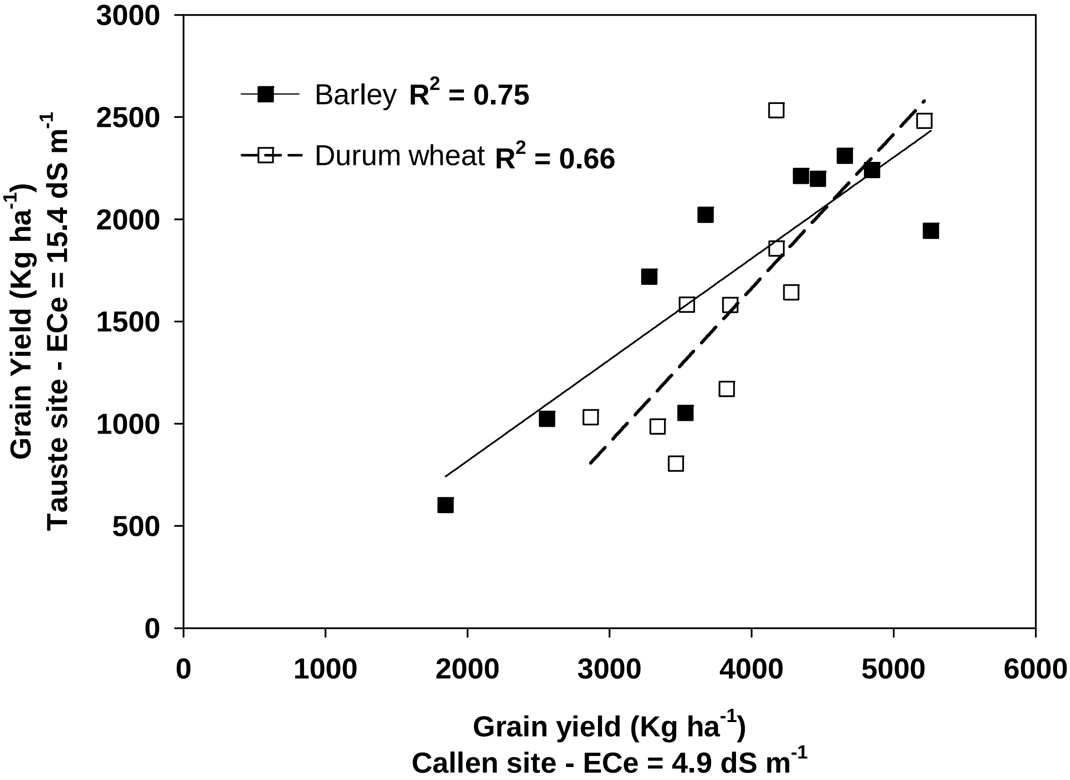

Figure 4. Relationship between the simulated grain-yield in the less saline field (Callén), and the most saline field (Tauste) for the ten barley and ten durum wheat cultivars. The linear regression and the R^2 are presented.