Soil salinity changes over 24 years in a Mediterranean irrigated district

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Abstract

Soil degradation from salt accumulation, sodication, or both, is a threat or a fact in many irrigated lands. Salinization has often been assessed from changing cropping patterns over time, and often the trends in salinization have not been quantified. Our objective was to identify trends in salinization or desalinization by direct measurements of soil salinity where a consistent methodology was maintained over time. The soils of the Flumen irrigation district (27,500 ha) in Aragón, Spain, were sampled in 1975. The same plots were sampled again in 1985/86 and in 1999. There were 140 sampling points in 1975, and 66 in each of the other two surveys. The mean sampling depth was 103 cm, resulting in 909 soil samples and 8603 analytical determinations. Analytical results for salinity, individual ions, and pH retrieved from the first survey are compared with the two subsequent surveys. The electrical conductivity of the saturated extract (ECe) and the sodium adsorption ratio (SAR) of the extract were determined through the soil profiles, allowing us to compare the results from the three surveys. The upper meter of the soil was less saline in 1999 than in 1975. The median ECe of non-saline soils changed only slightly, while in the saline areas the median ECe for comparable soil depths averaged over 1 m was 5.9 dS m^{-1} in 1975, 3.1 dS m^{-1} in 1985/86, and 1.9 dS m^{-1} in 1999. The median of the maximum SAR to the same depth also decreased from 22.0 $(mmol/L)^{0.5}$, to 15.1 $(mmol/L)^{0.5}$, and to 10.5 $(mmol/L)^{0.5}$ for the same three periods. Thus, soil salinity in the upper meter of soil has decreased during the last 24 years.

Keywords: Sodicity; Long-term monitoring; Soil salinity trend; Salt-affected soils

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Abbreviations: EC, electrical conductivity;
compECe, the ECe up to the comparable depth (D) for a site and date;
compmSAR, the maximum SAR determined for a site and date up to the comparable depth (D);
D, depth of sampling comparable between different years in a given site;
EC1:5, electrical conductivity of the 1:5 water to soil extract;
ECe, electrical conductivity of the saturation extract;
ET_0, reference evapotranspiration;
M.A.P.A., Spanish Ministry of Agriculture, Food, and Fisheries;
PS, percent of saturation;
SAR, sodium adsorption ratio;
UTM, universal transverse Mercator.

1. Introduction

To assess salinization or desalinization one must quantify and then monitor the changes in soil salinity over time. This is time and labor intensive at field scales and larger. The seasonal variation of soil salinity, as well as its lateral and vertical variation complicate the process of surveying. Under irrigation, movement of salts vertically and laterally through the soils is also complicated by changes in water application patterns related to crop rotation. Long-term changes in soil salinity can be qualitatively assessed by archaeological methods (Jacobsen and Adams, 1958; Siyu et al., 1996) or from historic records (Blavia, 1889). Such long-term assessments are made by comparing changes over the years either in natural vegetation or crops in cultivated regions. However, in many agriculturally advanced irrigated districts, such as those common in Spain, changes in soil salinity can not be traced from the shift to salt-tolerant crops over the years because, apart from soil limitations, the choice of crop by each farmer depends on the anticipated amount of irrigation water available, and on socio-economic factors.

Parr et al. (2002) have stressed the need for a long-term monitoring program for terrestrial systems in Europe. In some countries long-term soil studies can be based on existing soil surveys (Young, 1991, 1998). Where such maps are unavailable, other historic data about soils can be used. While the examples presented by Young (1991) are not related to salinity, most of his discussion on the objections and benefits of soil monitoring is applicable to soil salinity, as dependant on land use (Grossman et al., 2001).

Assessments of salinization in the literature are often based on indirect estimation, small-scale studies, or poorly-defined periods of time. Some studies of soil salinity change over time are based on soil sampling in agricultural trials conducted on experimental farms for five years or less. Such studies are often the only available for extensive tracts of land, being hard to extrapolate and it is questionable whether true any long-term trends that could apply to a large irrigated district under commercial management can be established.

Marshall and Palmer (1939) presented comparative measurements for three sites, measuring the soluble ions in soil irrigated for 20 years. Antipov-Karatayev (1965) monitored the ion content and exchangeable sodium from 1951 to 1960 in two soils. Ballantyne (1978) studied the temporal change in average ECe profiles at a depth of 122 cm for 64 sites, taking one sampling in the fall of each year for 11 years, from 1964 to 1975. The same author (Ballantyne, 1983) presented the soil data for five years on 12 1-ha plots. Chang and Oosterveld (1981), basing their study in part on the work of Marshall and Palmer (1939), studied ten sites under irrigation for over 60 years and three sites for 25 years. They considered the studied soils to be a representation of several thousands of square kilometers.

Electrical conductivity and pH measured in a 1:1 soil-to-water solution were two of the ten soil properties measured by De Clerck et al. (2003) in their study of the soil quality trends of California soil using paired samples from 115 locations. Their reservations about whether the samples represent the entire 400 000 km^2 that is California can be applied to the work by Lindert et al. (1996), both studies showing the difficulties of a long-term comparison of soil properties.

Other important characteristic of salt-affected soils is the level of Na^+ in the soil system, which affects the behavior of the colloidal fraction of the soil. The level of Na^+ in soil is usually quantified by the exchangeable sodium percentage (ESP) or by its estimator, the sodium adsorption ratio, or SAR (United States Salinity Laboratory Staff, 1954). In the Flumen district the high SAR values of some soils are attributed to irrigation with water of low electrical conductivity combined with the lack of gypsum in most of the region's soils. Moreover, various cultural practices like puddling or amendments, when carried out over a period of years, can modify the sodicity of the soils. The associated changes in hydraulic behavior are agriculturally and environmentally relevant and can be explained in terms of clay dispersion, which is directly related to the ratio between the ESP and the electrolyte concentration. A detailed appraisal of the effects of high SAR values on the behavior of each soil in our study area should take into account the unfavorable void pattern and the high silt content of some soils (Rodríguez et al., 1990).

In this paper, we add data for 1999 to a previous evaluation of changes in soil salinity for the Flumen irrigation district (Herrero, 1987). For a similar problem, Bitllett et al. (1988) considered two approaches. In the first, many sites are sampled and re-sampled, analyzing the results statistically. In a variation of this technique, previous sites are located, sampled, and reanalyzed. The second approach was used by Herrero (1987) in the Flumen area and is maintained in the present study, incorporating non-parametric techniques of data analysis. This approach allows the variation in soil salinity to be related to local management or other circumstances.

Our aim is to assess salinity and sodicity status and temporal changes in soils of the Flumen irrigation district based on the comparison of three data sets collected in 1975, 1985/86 and 1999.

2. Materials and methods

2.1. *Study area*

The irrigated district of Flumen is in the north central part of the Ebro basin (Fig. 1), in northeast Spain. The center of this basin is one of the most arid regions in Europe

(Herrero and Snyder, 1997). The study area (27,500 ha) is the part of the Flumen irrigation district that is east of the Flumen river, comprising land mainly with an irrigation history of 50 years and, to a lesser extent, land irrigated for at least six-hundred years. Most irrigated plots are < 1 ha, with controlled-flood irrigation. The main crops are alfalfa and forage, barley, maize, rice, sunflower, and wheat. Based on 34 years of weather records taken at the Sariñena weather station, the climate is semi-arid; the mean-annual temperature is 14.5ºC, the mean-annual precipitation is 423 mm, and the mean-annual evapotranspiration (ET_0) is 1,142 mm, calculated using the FAO Blaney-Criddle method (Doorenbos and Pruitt, 1977). Using this methodology and interpolation along with geostatistical techniques, Martínez-Cob et al. (1998) estimated that the mean monthly ET_0 that was greater than precipitation from February to October for the irrigated area.

The Flumen district straddles the border between aridic and xeric soil moisture regimes, as defined by the Soil Survey Staff (1999). Irrigation water has a low ionic content with a typical electrical conductivity < 0.4 dS m^{-1} and SAR < 1 $(mmol/L)^{0.5}$, but the saliferous horizontal strata of lutite alternating with sandstone together with the evaporative deficit both help explain the natural occurrence of saline-sodic soils (Nogués et al., 2000). After irrigation started, soil salinity became a major factor constraining agriculture. Rodríguez et al. (2000) have studied the classification and composition of these soils, which always have calcium carbonate contents greater than 25%.

2.2. Survey procedure

In 1975, the soils were surveyed for irrigation suitability by INYPSA, a consultant company contracted by the Agricultural Reform and Development Institute, or IRYDA (acronym on the Spanish name), the now defunct organization in charge of irrigation projects within the Spanish Ministry of Agriculture. The 1975 surveyors selected two sets of plots for soil sampling. In the first set they opened pits with a backhoe to draw a soil map using a legend based on the 7th Approximation to Soil Taxonomy (Soil Survey Staff, 1960). The plots in the second set were selected because they were salt-affected as indicated by irregular crop growth within the plots, with the purpose of appraising the salinity tolerance of the common crops in the area. Each of these plots was sampled by auger at three points where good, medium, and bad crop development were each attributed to salinity.

The consultant company produced an unpublished report in bound photocopies with several map sketches at a scale of 1:50000. The survey used aerial photographs. In 1985 we retrieved the 1:12000 scale contact prints on which in 1975 the surveyors had indicated with a wax pencil the location of the study sites. For the two soil salinity surveys of 1985/86 and 1999, we located in the field the points studied by the surveyors of 1975. In 1999 we recorded UTM coordinates to the identified points using a Ground Positioning System (GPS).

In our surveys of 1985/86 and 1999, the loss of some marks on the contact prints or the intensive land shaping or leveling projects in some areas between the sampling years precluded a fully confident identification of some of the points sampled in 1975, which led us to not to resample these points. In other cases, the point was located but because of faint printing or of toner detachment of the 1975 document, the soil data were unreadable and the points were not re-sampled.

Finally, of the 312 points studied in 1975, we identifed 140 points corresponding to 96 plots. In the survey of 1985/86, only 51 of the 67 plots retrieved for the 1st set and 7 from the 29 plots retrieved for the 2nd set, could be located and sampled. Herrero

(1987) presented the data from 44 sampling points. In 1999 we again searched the same plots, and located and sampled 59 plots of the 1st set of 1975, and 6 of the 2nd one. The eight first columns of Table 1 summarize all these data, including depths.

The samplings of 1985/86 were done with a custom-made auger. In 1999 we used an Edelman auger. The volume of each sample was typically > 0.9 L. The 1975 samples were obtained from June 26 through August 20. The second survey was performed during several one-day trips between 19 July 1985 and 16 June 1986 (plus the point Fl-10 sampled on 12 March 1985). Fifty three of the 66 points were sampled between October 1 and February 26, i.e. during the season without evaporative deficit. The third survey was conducted from 19 April-15 May 1999.

2.3. Analytical determinations

The analyses in 1975 were done in the IRYDA laboratory (Madrid, Spain); the 1985/86 samples were analyzed in the laboratory of Oficina de Suelos (Huesca, Spain); and the samples from 1999 in the Unidad de Suelos y Riegos (Zaragoza, Spain), where the surplus soil samples from the two most recent surveys are stored. The soil samples were air-dried and then passed through a 2-mm sieving mill. The procedures used in 1975 were not stated, but they should comply the official method of Spanish Ministry of Agriculture, comparable to the method we have used.

Chemical determinations were performed following the official methods of the Spanish Ministry of Agriculture (M.A.P.A., 1994). These methods have undergone slight changes since 1974, but some modifications made for the 1999 analyses were due to advances in laboratory equipment. In 1985/86 chlorides were titrated potentiometrically, and the sulfates in 1985/86 were determined by turbidometry with a Beckman 24 double-beam spectrophotometer (Beckman Coulter Inc., Fullerton, CA, U.S.A.). Chlorides, sulfates and nitrates were assayed in 1999 by ionic chromatography with a Dionex 2000i/SP (Dionex Corporation, Sunnyvale, CA, USA). Flame photometry was used for Na^{+}, and EDTA titrations for Ca^{2+} and Mg^{2+} in 1985/86, whereas in 1999 these three cations were measured by atomic absorption spectrophotometry with a Perkin-Elmer 3030 (Perkin Elmer, Inc., Wellesley, MA, U.S.A.).

The study of the soil salinity and sodicity in the three surveys was based on the methodology of United States Salinity Laboratory Staff (1954), measuring the electrical conductivity (ECe) of the saturated paste extract and calculating the sodium adsorption ratio ($SAR = Na^{+} / [(Ca^{2+} + Mg^{2+}) / 2]^{0.5}$ where Na^{+}, Ca^{2+}, and Mg^{2+} refer to the ionic concentrations in $mmol_c\ L^{-1}$). The percentage of water saturation (PS) in 1975 was not recorded; moreover Ca^{2+} and Mg^{2+} were determined jointly whereas in the other two surveys they were determined separately.

The 1975 report states that the ECe of auger samples was estimated by regression with EC1:5 measured in a field laboratory, but, surprisingly, the report contains an addendum with the ECe and the ionic assays. We surmise that the central laboratory in Madrid also analyzed the auger samples, but probably the results arrived too late for their discussion in the report, as suggested by the dates printed on the laboratory sheets of water analyses photocopied at the end of the document.

Supplementary determinations in other soil solution ratios were also used. Following the method of Bower and Wilcox (1965), the electrical conductivity was measured for a 1:5 soil-to-water extract (EC1:5) in both the 1985/86 and 1999 samples. In 1975, pH was measured in soil solutions of deionized water and of KCl of unknown molarity at an unspecified ratio, whereas in the two last surveys the ratio was 1:2.5 in water and 0.1 M KCl . This ratio was chosen according to the recommendation of the

International Society of Soil Science (Peech, 1965), and of the M.A.P.A. (1974, 1994), which also recommends 0.1 M KCl. The pH was also measured for the saturated extracts taken in 1999. Soluble Cl^- was determined in 1975 at an unknown soil-solution ratio; furthermore, the report does not give the units for soluble Cl^-.

The study of the ionic speciation in the extracts is beyond the scope of this article. We use regressions between the ionic concentrations and also between these concentrations and ECe to appraise the quality of the analyses (Rhoades, 1982) and to examine relationships throughout the surveys. These verifications give robustness to the parameters used for comparisons between years and also serve as a check of the consistency of the laboratory determinations in the three surveys. All the available analytical determinations for the soil samples (Table 1) are used for this purpose, but these determinations cannot be directly used for comparison of soil salinity between years, as will be discussed below. Most analyses were done on saturated paste extracts (Table 2), but a few used other soil-to-water ratios (Table 3).

2.4. Expressing the laboratory determinations as salinity/sodicity of the profiles

At many sites, the sampling depth and/or the depth intervals were not the same in the three surveys, nor were their averages (Table 1). The part of the profile represented by each sample has to be taken into account when examining soil salinity for comparison between sites or between dates. For this purpose, we have implemented three examination procedures.

In the first procedure, the upper meter of soil is taken as the master depth. This depth is relevant in terms of agricultural salinity (i.e., soil salinity/sodicity at this depth produces effects that influence crop yields and must be managed by farmers). The top meter of soil is relevant for salinity according to the current models of water extraction by plant roots for most crops, assuming that the crop is not suffering water stress. This critical depth has been used in other studies of irrigated soils (Job et al., 1995), in the classification of Australian soils (Northcote and Skene, 1972; Isbell, 1995), and in some non-metric countries where a three-foot depth is often taken as the master depth. This figure seems reasonable based on the observations of Israelsen and Hansen (1962) with respect to the root development of irrigated crops, and is also confirmed by the model used by Ayers and Westcot (1985) to calculate the average soil salinity in the root zone.

Other depths were also considered for the present study. Shallow depths were ruled out because irrigation dates for each year and plot were unknown. The main obstacles for computing depths greater than 1 m in some sites were the limited depth reached with the auger, and a water table close to this depth.

We established a comparable sampling depth (D, cm) for each point in order to compare the soil salinity for different years. In all points where the sampling depth reached at least 100 cm in the three surveys, D equals 100 cm. For the points where samplings in the second survey were shallower than 80 cm, these samplings were disregarded in order to diminish the loss of information from the first and third surveys. Several points with some sampling depths between 80 and 100 cm in any of the surveys, or having a similar shallow depth in all three surveys, are reasonably well represented by their minimum reached depth, which was taken as D.

After establishing D for each point, we calculated the comparable ECe (compECe) defined as the ECe of the soil up to the comparable depth (D). CompECe is then calculated by weighting the ECe of each soil sample by its depth interval up to D, using the first n samples of the profile up to the depth D. The formula is:

$$compECe = D^{-1} \times \left[\sum_{i=1}^{n} ECe_i \times d_i - ECe_n \times \left(\sum_{i=1}^{n} d_i - D \right) \right]$$

where for each point and sampling date, ECe_i is the ECe of the i^{th} sample from the surface, d_i is the depth interval of the i^{th} sample, and n is the first of the successive samples whose lower depth limit is ≥ D.

In order to compare the soil sodicity for different years, we define the comparable maximum SAR (compmSAR) as the maximum SAR determined for each site to the comparable depth (D). The layer with the maximum SAR in the profile is judged to be more representative of the undesirable soil properties under flood irrigation than a computed average SAR.

In the second procedure, we calculate single average ECe values for every sampled point including deeper and the deeper layers. The computed depths were: 0-20, 0-40, 0-60, 0-80, 0-100, and 0-150 cm. These single ECe values were calculated by weighting the ECe of the soil samples according to the depth interval of each sample. For SAR, an average computed either from the SAR of the samples from each depth or from their average ionic content would not generally be meaningful, so we use the maximum SAR determined in the samples for the studied depth.

In the third procedure, we weighted the ECe in the soil samples by their depth interval. Then, we constructed synthetic profiles of ECe referring the weighted values to the depth increments of 0-20, 20-40, 40-60, 60-80, 80-100, 100-150, and 150-200 cm. The statistics of ECe of each layer is used for the joint study of the sampled points in each survey.

As much as possible, our data were studied by means of resistant measures used in the exploratory data analysis (Tukey, 1977; Chambers et al., 1983), generally presented in boxplots. The regression lines were calculated using the least squares method ($p = 0.05$). The regression lines were compared using F-tests (Snedecor and

Cochran, 1989).

3. Results and discussion

3.1. A legacy of information about soil salinity/sodicity

Table 1 summarizes the scope of each survey in terms of the total number of sampled sites, soil samples and analytical determinations. The number and kind of analytical determinations retrieved from the 1975 survey, the number of soil samples and kind of analytical determinations in the surveys of 1985/86 and 1999, and the averages for each assay are shown in Table 2 for the saturation extracts, and in Table 3 for the other extracts.

Many of the plots studied by the surveyors of 1975 were identified in the field in 1985 and in 1999. This information was improved in 1999 by finding the UTM coordinates for every identified plot and by transferring the recoverable information into an electronic format, thereby avoiding the problem of vanishing ink in the surviving documents.

The consistency of analytical methods throughout the total sampling period (Beard et al., 1999) is a major concern in this and other similar studies. The stored soil samples from the two last surveys should be a reliable witness of soil salinity, could help to overcome disparities introduced by future changes in analytical techniques, and allow the determination of other soil parameters that may be defined in the future.

3.2. The consistency and relationships of the soil salinity analyses

The soil salinity for each of the three sample periods was studied using procedures specified by the United States Salinity Laboratory Staff (1954). Thus the only methodological differences between years might be in the techniques used for the determination of ions by the different laboratories. Jacober and Sandoval (1971) studied the effects of soil grinding, suction, and extraction time on the ECe values, stressing the need for standardized conditions. These conditions were the same in the two last surveys, but unknown in 1975. However, the relationships of ECe in 1975 with the ionic determinations from the same year are consistent with these relationships in the two last surveys (Table 4) stressing the comparability of the ECe measured in this year with those of the two last surveys.

The analytical results from the soil samples and their possible errors have been assessed by establishing the relationships between the determinations for the three surveys. For this purpose we use all the available analytical results of each studied year, i.e. 909 samples (Table 1), not only those samples used for the soil salinity trend study presented later.

The potassium and nitrate ions were determined only in the last survey. As expected, their contents were very low or negligible (Table 2), except in a few samples taken immediately after the application of fertilizers. These ions are used here only to compute the sums of cations and anions in 1999.

Most of the regressions of the analytical data (Table 4) take electrical conductivity, an accurate and reproducible determination, as independent variable. These regressions allow us to check the quality of the analyses and its consistency throughout the three surveys. The estimated standard deviations from the regression line, not shown in the Table 4, were in all cases small. Five of the intercepts were not different from zero at a significance level of 95%, but the change in the estimated standard deviation was always within < 0.1 unit of the dependent variable when forcing the line to pass through the coordinate origin. A general indication of the quality of the analyses is given by the first four regressions in the two last surveys (Table 4), with R^2 > 94.2%. The only available of these regressions for the first survey was sum of cations on ECe, with $R^2 = 87.8\%$, showing a relative weakness of the chemical analyses in that year. Similar conclusions can be made from the three regressions of Na^+ on Cl^- in the last line of Table 4.

3.2.1. Sum of anions on sum of cations

The 1% deviation from a slope of unity in the second survey is acceptable as well as the difference from zero in the intercept. In the third survey, with a slope of 0.88 and an intercept of 5.7, the greater residuals from the regression occur in samples having electrical conductivities greater than 20 dS m^{-1}. This may be attributed to the several dilutions and longer storage times of these extracts, to the high sensitivity of the analytical equipment of 1999, which was calibrated with standard solutions of low concentration of Na^+, and finally to the delay of some determinations because of the design of laboratory procedures for long series of analyses.

3.2.2. ECe on EC1:5

Here, ECe is considered the master index of soil salinity. The high coefficients of determination in the regressions of ECe on EC1:5 (Table 4) verify the consistent measurement techniques for ECe for the soil samples of 1985/86 compared to 1999. The two regression lines are the same at a significance level of 95%. After merging the data of the two surveys, we propose the equation displayed in Table 5 for the area under study. This function is valid for EC1:5 over 0.07 dS m^{-1}, a value close to the practical detection limit of many garden-variety conductivimeters, and has been computed for the range of 0.33 dS m^{-1} to 81.68 dS m^{-1} for ECe and of 0.11 dS m^{-1} to 9.80 dS m^{-1} for

EC1:5.

The intercept of -0.51 dS m^{-1} is significantly different from 0, and might be due to some specific feature, mineralogical or other, of some samples, but the residues are randomly scattered throughout the study area and occur for different soil profiles in the two surveys. In both surveys the distribution of the residues is balanced, and the error of 0.5 dS m^{-1} is acceptable depending on the purpose of the determination or on the time and resources saved, a function of the available laboratory techniques.

Several of the equations given by Aragüés et al. (1986) are similar to those proposed by us (Table 5), as were the equations found by Herrero (1987) for two farms in this area. With the proposed equation, the classic soil salinity threshold of 2 dS m^{-1} of ECe (United States Salinity Laboratory Staff, 1954) is translated into 0.33 dS m^{-1} at EC1:5. The threshold of 0.3 dS m^{-1} of EC1:5 proposed for this region by Rodríguez-Ochoa (2000, personal communication) is confirmed.

Shaw (cited by Sumner et al., 1998, p.7) proposed a formula to relate ECe with EC1:5, PS, and the air-dry moisture content. This last parameter becomes impractical for samples that contain gypsum and/or hygroscopic salts, and was not calculated by us. However, the regression of ECe on the ratio EC1:5 to PS is a supplementary verification:

$$\text{ECe} = -1.14 + 7.19 \times (50 \times \text{EC1:5/PS}) \quad R^2 = 94.1\% \quad n = 422 \quad S = 1.58$$

which yields the same coefficient of determination and has a similar slope and standard error for the equation given in Table 5.

3.2.3. Sum of ions on ECe

The F-tests show significant differences between the regression equations from one year to other, especially for the slope of the regression on the ECe of both sum of anions and sum of cations (Table 4). Only a small part of the increases in slopes in 1999 could be attributed to the computing of NO_3^- and K^+, which were not analyzed in the two first surveys, thus the increase in slope with time suggests a sustained change in the ionic composition of the saturation extracts, and may be related principally to the marked decrease of Cl^- in the samples over time (Table 2). Table 4 also shows an R^2 in 1999 lower than in 1985 in the regressions of both sum of anions and sum of cations over ECe, in spite of having computed NO_3^- and K^+ in 1999, and in spite of using more advanced analytical equipment. In 1999 the ions of all the saturation extracts were analyzed as a single set with an automatic analyzer, involving different storage periods for the saturation extracts; in contrast, the extracts in 1985/86 were analyzed in a small lab fully supervised by the surveyors, with only days between extract preparation and ion determination.

3.2.4. Single ions on ECe

The closest relationship between single cations and ECe for the three surveys occurs for Na^+, where R^2 was very high for the two last surveys, again higher than in the first one (Table 4). The slopes of these regressions increase with time. The value of R^2 ranges from 62.6% to 77.8% in Ca^{2+} and in Mg^{2+}, but this relationship is better for the sum of Ca^{2+} and Mg^{2+}, which also allows us to compare with the data for 1975.

The regressions involving Cl^- from 1975 must be taken with some reservation. The 1975 study presented “Soluble Cl^-”, in a column separated from the determinations for the saturation extract. At first, we supposed that the soil-to-water ratio was 1:5, following M.A.P.A. (1974, 1994). However, after multiplying the 1975 data for Cl^- by 10^3 we obtained figures of the same order as the Cl^- in the saturation extracts in the other two surveys, and by regressing these magnitudes on ECe (Table 4) we found the slope similar to that which obtained in the other two surveys. If we accept that Cl^- was determined for the saturation extract in 1975, we could merge the 872 available cases for regressing Cl^- on ECe, provided the three equations do not have significant differences after the F-tests. Nevertheless, the relatively low R^2 in 1975 indicates that it is more reliable to use only the data from the two last surveys, with 423 available cases for Cl^- on ECe. This, then, is the equation presented in Table 5.

The R^2 for the regressions of sulfates on ECe range from 52.8% to 67.2% (Table 4). These low values are attributed to the irregular distribution of gypsum and other sulfate minerals with different saturation concentrations in the soils. Looking at the regressions of ions on ECe (Table 4), SO_4^{2-} on ECe is the only case where R^2 is much lower in 1985/86 than in 1999. This fact can be again related to the analytical method. In 1985/85 each set of about 25 extracts was titrated using a different standard curve, whereas all the extracts in 1999 were analyzed as one set. Moreover, the ionic chromatography of 1999 is more precise than the turbidometric method of 1985/86.

Given the high ionic concentrations in some samples, neutral ionic pairs are in part responsible for the low R^2 of the regressions of Ca^{2+}, Mg^{2+}, and SO_4^{2+} on ECe.

3.2.5. Na^+ on Cl^-

As in the other equations, the values of R^2 in 1975 are the lowest of the three surveys. The change in the interrelationships of the salinity determinations that were previously observed in the regressions of Cl^- on ECe also appear between Na^+ and Cl^-, with the slope increasing as the years advance for the three surveys (Table 4).

3.2.6. SAR on ECe

The regressions of SAR on ECe are not directly related to the quality of analyses, but represent changes of this relationship throughout time. The R^2 in 1985/86 is lower than those of the other two surveys (Table 4). This is in agreement with the sustained decrease of the median ECe over the three surveys, as well as the fact that the median SAR was the same for the two first surveys, decreasing in 1999. The contents of Ca^{2+}, Mg^{2+}, SO_4^{2+}, and HCO_3^- (Table 2) were quite stable throughout the three surveys. This fact together with the sustained overall decrease in Na^+ results in a decrease in median SAR of the soil samples throughout the three surveys.

3.2.7. Some general relationships between chemical determinations

The regressions on ECe of the sum of cations, the sum of ions, and all the individual ions, excepting Mg^{2+}, increase their slopes throughout the three surveys. The causes are out of the scope of this article, but are most likely related to the soil mineralogy and to the history of crops and water application for the sampled sites. This kind of information is not available, however.

After studying the regressions of Table 4, we decided to merge only the analyses of the two most recent surveys, and Table 5 shows the resulting equations ranked by their coefficient of determination. With the adopted significance threshold, only the regressions for ECe on EC1:5, and for Cl^- on ECe (Table 4) changed between 1985/86 and 1999. We consider that the differences between these two surveys in the equations of the Table are less than those produced by the possible differences in soil moisture at the time of sampling. By merging the equations we include a wider range of actual moisture conditions, crops, and management regimens for the sampled soils, obtaining a less date-dependent result. Future surveyors will have to decide if these equations can be used for their specific purposes, perhaps based on further tests of the stability of the regressions.

The first three regressions in Table 5 involve sums of ions and have coefficients of determination higher than any other regression in the Table, probably because of the compensation for laboratory errors in the individual determinations of ions; these equations give reliability to both the ECe and the ionic content determinations.

The regression lines of the ionic concentrations, cations or anions, on the ECe fit the model of Marion and Babcock (1976). By applying this model to the analyses of 1985/86 and 1999, we obtain

$\log C\ (\mathrm{mmol_c/L}) = -0.988 + 0.930 \log \mathrm{ECe} \quad R^2 = 97.6\% \quad n = 428$

for values up to log cat ≈ 3, and log ECe ≈ 2.

The regression equations are similar for cations and anions, and are also similar for the 1975 samples, but the coefficient of determination decreases to 90.7%.

The next four equations in Table 5 do not involve sums of ions and still have $R^2 >$ 90%. As well as indicating the reliability of the results, they will be interesting in the case where some of the regressed parameters need to be estimated, especially considering the stability of the regression of ECe on EC1:5 and of Cl^- on ECe (Table 4) with the passing of years. The other regressions yield coefficients of determination < 90% and have minor interest for the estimation of soil salt affection parameters from ECe. The decrease of R^2 in the four regressions of $Ca^{2+} + Mg^{2+}$, Mg^{2+}, Ca^{2+}, and SO_4^{2+} on ECe agrees with the solubilities of the salts of these ions. The regression of SAR on ECe shows high relative Na^+ concentrations in many samples.

3.3. pH measurements versus salinity

Table 3 shows the number of pH measurements made for the three surveys, and their measures of location. The means and the medians denote similar distribution shapes for the three surveys. The soil solutions used for pH analysis in 1975 were not reported. Thus, the pH values from 1975 cannot be treated together nor directly compared with the other surveys. As noted by Van Lierop (1990), this is because a consistent soil/water ratio is required for obtaining reproducible and comparable pH values. These values increase from 0.5 to 1.5 pH units as moisture content increases (Jackson, 1964), as can be seen for the average pH in water 1:2.5 in 1999 (Table 3) and the average pH in the saturation extracts of the same samples (Table 2). There is also some doubt regarding the comparability of pH between the surveys because of the differences in pH produced by the grinding intensity (Baver, 1927), unknown for the samples from the first survey.

The increase of about 0.5 units of pH from the first survey, in both water and KCl, are attributed to the change in the soil to water ratio, as discussed above. The 0.12 unit increase in the median pH in water from the second to the third survey may be due to average soil moisture differences between the two surveys, given the negligible difference of the median pH measurements in KCl (Table 3), which stands for the "potential pH" or exchange acidity of the soil. The range of the pH boxplots (not presented in this article) reduces throughout the three surveys because of a shrinking maximum value, and a simultaneous decrease in the number of outliers. The reduction is more pronounced from the second to the third surveys, and more clear for KCl because of the decrease in the number of the more alkaline samples in 1999. The range reduction of pH in water cannot be explained by a different homogeneity of the soil moisture between surveys, given that the shortening also occurs for the pH in KCl.

As expected for saline soils, the difference between the soil pH measured in water and measured in an electrolyte, KCl 0.1 M in our case, is always positive (Fig. 2). Moreover, when the difference between pH in water and pH in KCl is plotted against the ECe (Fig. 2) the shape is similar for the three soil surveys, an indication of consistency between years. As expected, most of the saline samples have small differences between both pH measurements, whereas most cases where this difference is > 1 occur for the less saline samples.

3.4. The salinity/sodicity in the soil samples

The statistics of the individual samples (Table 2) are calculated including the samples from the second set of 1975, a fact which should be borne in mind when comparing with the statistics of the other two surveys.

Table 6 shows the percent in each salinity class (Soil Survey Division Staff, 1993) of the 879 samples having ECe determinations. SAR is available for 893 samples in the three surveys. The number of samples with a SAR ≥ 13.0 was 142 (30.6%) in 1975, 59 (31.1%) in 1985/86, and 51 (21.4%) in 1999. ECe and SAR are plotted in Fig. 3 to give an overview of the salinity/sodicity of the individual soil samples for each survey.

Table 2 shows measures of location of the distributions for the soil salinity/sodicity parameters of the samples for the three surveys. The differences between the mean and the median show the asymmetry of all the distributions. Carbonate ion concentrations in the saturation extract, not analyzed in 1975, were unappreciable in the last two surveys for all samples, except for three cases which correspond to two of the points of the second set of 1975 which were re-sampled in 1985. These results are consistent with the pH < 9 in all the extracts of 1999, except for one. The decrease over time of the medians of ECe, Na^+ and Cl^- shows the general decrease in salinity of the soil samples (Table 2). These decreases are greater when passing between the second and the third survey. The other analyzed ions are relevant for sodicity, and the decrease of $Ca^{2+} + Mg^{2+}$ combined with the decrease in Na^+ produces a substantial reduction of the SAR of the samples between 1975 and 1999

(Fig. 4), a change which is more marked from the second to the third survey. The boxplots in Figs. 5 and 6 allow us to compare the distributions of ECe, Na^+ and Cl^- with time.

The decrease of the median, range, quartiles, and upper adjacent values of the salinity/sodicity of the soil samples from 1975 to 1999 (Figs. 4 to 6) gives a preview of the overall trend at the sampled sites. The only exception are the upper value and the third quartile of Na^+ in the second survey, accompanied by a confidence interval for the median that is wider than that of the two other surveys (Fig. 6). This exception could be due to inferior analytical technique in 1975, given that the regressions of Na^+ and Cl^- on ECe, and Na^+ on Cl^- are better in the last two surveys (Table 4). Another reason for this exception could be the vertical distribution of salinity combined with the mean depth attained by the sampling in 1985/86 which was only 71 cm against 112 cm in 1975, and 116 cm in 1999, and the thinner layers sampled in the second survey (Table 1). Both characteristics of the 1985/86 sampling operations cause increased ionic content measurements. In general, unequal depth intervals when sampling also diminish the value of the statistics of salinity in the samples when comparing the degree of salinity/sodicity over time.

The SAR data should not be treated in the same way as electrical conductivity or ionic content data. First, as noted in Table 2, the mean SAR is chemically unsound, as is the case for the mean pH. Second, electrical conductivity measurements are closely related to the ionic content, and can be translated into ionic mass, with the appropriate equation. SAR cannot be translated into mass; its main pedological sense it is quantitative and is related to the structural stability of the soil.

In the following three sections we present and discuss the results of the three procedures used to overcome the obstacles for comparing the salt-affection of the soil over time.

3.5. Comparison point by point

Table 7 sows soil salt-affection as calculated using the first procedure, the common sampling points shared by the three surveys and the depths used for computing compECe and compmSAR. This Table allows us to express the salinity/sodicity trend for each sampling point by means of a vector whose two components are compECe and compmSAR. This Table shows separately the points assigned to the saline class (compECe > 2 dS m^{-1} in 1975) and to the non-saline class (compECe ≤ 2 dS m^{-1} in 1975).

In the non-saline class the only relevant changes in compECe occur for points 29, 38, and 62; these were the only points exceeding 2 dS m^{-1} of compECe for any of the surveys. Herrero (1987) attributed the salinization of points 38 and 62 to seepage related to their location on a slope under generalized flood irrigation. The two points became non-saline after the 1999 survey. The time trend of the compECe of these points corresponds in each case with the appearance of the crop planted in each survey year, except for the poor development of wheat in 1999 for point 62, with a compECe of 0.80 dS m^{-1} (Table 7). Similarly, the temporal changes in SAR were negligible except for points 29, 50 and 53, whose compmSAR for 1999 surpass the classical threshold of 13 for sodic soils. We could not identify a reason for this change, except in the case of point 29. Here, the farmer adapted to increases in compECe and in compmSAR by planting maize in 1975, alfalfa in 1985, and forage in 1999, indirect evidence of a change to a saline-sodic soil, which could be related to its location under a Miocene materials escarpment.

From the twenty-seven points included in the saline class (Table 7), eighteen diminished in salinity from 1975 to 1999, even though four of them (6, 7, 10 and 66) were still saline in 1999. For three points (15, 18 and 76) salinity did not change. The remaining six points (5, 12, 13, 17, 57 and 63b) increased in salinity throughout the three surveys. Points 12 and 57 were puddled for rice production in 1985 whereas in 1999 they were cropped with winter cereal and alfalfa. This crop change could account for the increased salt content, previously impeded by puddling. Point 63b was the most saline in 1999, and shows its greatest increase in salinity from 1975 to 1999. This plot was uncropped in 1985, and already occupied by halophytes (*Suaeda vera* Forsk. ex J.F. Gmel.). The increase in salinity of points 5, 13 and 17 was moderate.

The compmSAR of the points in the saline class does not show any clear general time trend. However, three point classes can be established by combining compmSAR with compECe. For the first group, points 5, 13, 17, 18, 57 and 63b, both quantities increase for the three surveys.

The second group of points are 6, 9, 26, 30, 31, 32, 33, 35, 54, 56, and 65; here both indicators decreased for the three surveys, and in 1999 reached values under the thresholds of salinity and sodicity for salt-affected soils, except for point 6, which was puddled in 1998. We also include point 58 in this group, which had a slight increase in compmSAR, and a decrease in compECe that was under the threshold of 2 dS m^{-1}.

In the third group we include the nine points where the behavior of compmSAR, compECe, or both was irregular. Points 7, 12, 51, 66, and 76 registered strong increases in their compmSAR in 1985/86, then decreased in 1999 to values similar to those of 1975. Meanwhile, the compECe behaved irregularly: there was a decrease for three points, an increase for one point, and a negligible increase for another point. Point 10 increased its compmSAR and compECe in 1985, then descending in 1999 to values lower than for 1975. This behavior agrees with: the presence of *Suaeda vera* in 1975, the land leveling before the 1985 survey, the continuous puddling until 1999, and the good wheat crop in 1999. For point 15, both the compECe and the compmSAR decreased sharply from 1975 to 1985/86 because of the construction of a drainage ditch, but in 1999 both quantities increased, probably related to the fact that the ditch became clogged. Point 59 passes from the saline class in 1975 to non-saline in 1999; however, the cause of its irregular behavior in 1985/86 is not clear because the sampling depth reached was less than for the other two surveys. Point 36 changes from saline non-sodic in 1975 to non-saline sodic in 1999.

The mechanistic interpretation of the evolution of each point is hampered by the lack of information about its management history in terms of crops, amendments, fertilization, various agricultural practices, and leveling and drainage works.

A matter of concern when comparing the salinity measurements for the three surveys in a saline point is the high lateral variability of salinity, a classical feature well established for this irrigated district (Lesch et al., 1998; Herrero et al., 2003). Since the sampling site localization is merely the plot, the re-sampling within a saline plot might be measuring more the lateral variation than the temporal. Our statistical study shows that we have overcome the difficulties of within-plot lateral variability. This permits us to make conclusions regarding the temporal trends for the population of studied plots. The medians of ECe and compmSAR in Table 7 show a negligible change in the salinity/sodicity of the non-saline class while in the saline class, compECe decreases 4 dS m^{-1}, and compmSAR decreases 12 $(mmol/L)^{0.5}$ from 1975 to 1999. These trends are supported by the intermediate figures from the 1985/86 survey.

3.6. Soil salinity as deeper and the deeper layers are computed

The second procedure shows a decrease of the median ECe from 1975 to 1999 for all the computed depths (Fig. 7). The values of the median ECe in 1985/86 for the 80 and 100 cm depths support this trend, and though the median ECe for the upper layers does not follow the trend, this can be attributed to the greater temporal variability in salinity for shallow soils; exacerbated by the fact that the 1985/86 survey was carried out over a longer period than the other two surveys. The trend of decreasing salinity can be accepted as a fact, even though the 95% confidence intervals of the medians slightly overlap, and that for the greater depths (Fig. 7). This behavior of the distributions is produced by the inertial effect of the many non-saline soils, as shown by the separate boxplots of compECe for the saline and for the non-saline classes (Fig. 8). The changes in salinity for the non-saline class are irrelevant, with all soils but one maintaining good conditions for irrigated agriculture, while the saline class undergoes a decrease in salinity.

The generalized increase of the median ECe when increasing the computed depth (Fig. 7) in the three surveys indicates that salinity is greater for deep layers than shallow ones. Moreover, at greater computed depths maximum values are lower and outliers become scarcer, showing again that the shallow soil ECe was more variable than that of deep soil.

The exploratory data analysis has also been applied to compmSAR. This index is plotted separately for the non-saline and saline classes in Fig. 9. The non-saline class shows a stable compmSAR during the period studied, despite increases in the number of outliers in 1999. In the saline class, the median compmSAR decreases with time, reaching values under the commonly accepted threshold of 13 for SAR. The broadening of the range with time is due to both a temporal decrease in minimums and an increase in maximums, confirming the existence of groups of points with contrasting compmSAR evolutions, as mentioned in the section *Comparison point by point*.

The boxplots in Fig. 9 show the association between salinity and sodicity, confirming the presence of saline-sodic soils in the Flumen district, with only small areas of sodic soils. From the twenty-two non-saline soils (Table 7), only three (29, 50, and 53) surpass the threshold of SAR = 13, whereas twelve of the twenty seven soils in the saline class surpass this threshold. However, a prognosis for the potential for land reclamation cannot be made based only on this information.

3.7. The synthetic profile

Finally, we computed synthetic profiles in the third procedure for analyzing soil salinity evolution. For this computation we used the points included in Tables 7, i.e., 59 points for 1975, 49 for 1985/86, and 59 for 1999. The synthetic profiles of pH have been discarded because the averaging of a logarithmic parameter is objectionable. SAR is also discarded, as previously discussed.

Fig. 10 shows the boxplots of the weighted ECe for each of the first five 20 cm layers down to one meter, and for two more layers: 100 cm to 150 cm, and 150 cm to 200 cm. These boxplots illustrate the evolution of the salinity distribution in the soils during the three surveys. Comparing the boxplot profiles of 1975 and 1985/86, there are small decreases in the medians for every layer except for the 100 cm to 150 cm layer. The shortening of the boxes, the shrinking of the first and the third quartiles and that of the upper adjacent values all accompany the decreasing medians. The number of outliers decreased from 1975, but remained evident in 1985/86. This agrees with the conclusions made by Herrero (1987) regarding the general reduction of soil salt affection, except for the strongly salt-affected sites of 1975 whose salinity/sodicity increased until 1985/86. The overall picture is clearer when comparing the survey of 1999 with each of the two previous surveys (Fig. 10). All parameters of the boxplots show a decrease in salinity, especially for soil layers up to one meter deep. Moreover, the number of outliers is greater in 1999 than in the two previous surveys.

3.8. The value of available data in establishing soil salinity/sodicity trends

There are many factors to be taken into account for appraising how well the soil salinity in the irrigated district is represented in our study, and to judge whether a salinity trend can be inferred. Of all these, we would like consider the sampling density and strategy, and the season when the soil samples were obtained.

Table 1 shows the number of sampled sites, soil samples, and analytical determinations studied in each survey. By current standards, the resulting density of sampling seems adequate. The numbers in Table 1 are similar or greater than for other studies of time or use-dependent soil properties, even for areas larger than ours. The adequacy of the 1975 sampling strategy for representing the soil salinity of the whole irrigation district can only be assessed when a detailed soil map becomes available. In the surveys of 1985/86 and 1999 we sampled the same plots sampled in 1975 for soil mapping, thus whether or not they are representative of the irrigated district, we have three survey snapshots of soil salinity that can be legitimately compared either by their statistics or point by point.

The first sampling set of 1975 should represent all soil units, though some bias could be supposed because the field operations of 1975 were conducted in summer, when rice paddies are flooded, hindering the soil sampling in those soils used for rice. The plots of the second set of 1975 were excluded from our trend study because they could have strongly biased the evaluation of the salt content of the entire irrigated district. Moreover, the analytical data from most of these plots were unreadable in the copy of the I.R.Y.D.A. report available in 1985, and so they were not selected for sampling in 1999. Even if more readable copies of the report appear, uncertainty about the analytical methods used on these samples would hamper the use of the second data set of 1975.

The time of year samples were taken modulates the signification of each of the three snapshots of soil salinity. There may be objections to the temporal desalinization demonstrated in Figs. 7 to 10, based on arguments regarding seasonal changes in the vertical distribution of the soluble salts. This problem has been overcome by comparing profiles of equal depth, instead of layers, given that the average salt content is constant throughout the same year if at least a 100 cm depth is computed, according to observations made in this irrigated district (Herrero, 1987). The field measurements of 1975 were completed in two summer months, whereas in 1999 the sampling lasted only one spring month. In contrast, the sampling of 1985/86 lasted for almost one year, and 80% of the studied points were sampled during the season without water evaporative deficit. Since the water deficit is much greater than the precipitation, seasonal sampling differences for the three surveys are superseded by unknown irrigation dates and doses in sampled plots, and in many cases also in conterminous upper plots.

4. Conclusions

Three distinct surveys –spanning 24 years–, the number of soil profiles –58 or more in each survey–, the number of soil samples – 909 in the three surveys–, the analytical determinations – totaling 8603 assays –, all contribute to the robustness of the three soil ‘snapshots’ presented here. A comparison of the bulk data allows us to identify a salinity trend from 1975 to 1999, however the lack of information about the crops and management history of each sampled plot precludes any definitive deterministic interpretations.

The poor legibility of the 1975 report and the poor field identification of the points sampled for that same year restricted the re-sampling in 1985/86 and 1999. The georeferentiation in 1999 of the sampled points has improved both the value of the surveys as ‘snapshots’ of soil salinity and their utility as base data.

Some of the soil analyses retrieved from the early survey are rejected because of flaws in the description of methods. The regressions between the salinity determinations in the soil samples, their statistics, and their links with the pH determinations, all give proof of the quality and consistency of the data. The relationships established between the analytical determinations could be useful in future surveys of soil salinity in the area.

The 24 years that bridge the first and third survey provide a reasonable period for detecting changes in soil salinity for lands irrigated for over 50 years. The statistics of ECe, SAR, ionic content, and pH in the soil samples reveal an overall desalinization trend.

An accurate evaluation of trends in soil salinity requires the comparison of profiles, not samples. For this purpose we implement three procedures. In the first, we consider the upper 100 cm of the soil, or other comparable, shallower depths from each survey, for computing the comparable weighted ECe (compECe) and the comparable maximum SAR (compmSAR) to this depth for each point. The median compECe of the profiles that are classified as non-saline in 1975 underwent a negligible increase in ECe, whereas ECe decreased from 5.93 dS m^{-1} to 1.94 dS m^{-1} in 24 years for the saline soils. The time trend of the median mcompSAR in 24 years was similar, dropping from 22.0 $(mmol/L)^{0.5}$ in 1975 to 10.5 $(mmol/L)^{0.5}$ in 1999 for the saline class. These results are in accord with the degree of intermediary degree of salinity/sodicity found in the second survey.

Of the 22 soils from the non-saline class in 1975, only one became saline-sodic in 1999, and two become sodic. For the same period, the 27 soils of the saline class in 1975 changed in several ways: for 16 soils both compECe and compmSAR reduced, for 8 soils both parameters increased, and for 3 soils the compECe reduced while compmSAR increased. In 1999, 14 of the 27 soils classified in 1975 as saline became non saline and non sodic. The most striking changes in salinity/sodicity occurred for three points which underwent a SAR increase of around 65 $(mmol/L)^{0.5}$.

The second procedure compares the statistics of profiles at various soil depths, made at common depth intervals. If an ECe weighted by the sample depth interval is computed for several soil depths, the soil salinity in the shallow soil is found to be negligible. A desalinization trend is observed that increased with the computed soil depth. Here the median ECe decreased by 1.3 dS m^{-1} for 0-80 cm, 1.5 dS m^{-1} for 0-100 cm, and 1.6 dS m^{-1} for 0-150 cm between 1975 and 1999. The number of the profiles available for these comparisons decreases as the depth increases, but the consistency of the desalinization figures with the computed depth make these results reliable.

The third procedure consisted in constructing a synthetic profile for each survey, representing the salinity status of the district on each date. The statistics in these profiles also reveal a desalinization trend.

Together, the three procedures that were implemented to examine soil salinity overcome the problems produced by the unavoidable differences in the soil sampling techniques used in the surveys. The procedures yield consistent results in our study and improve the simple direct comparison of the salinity of the samples. The procedures described can be easily adapted to past or future surveys in this or other irrigated districts using simple calculations that can be fully monitored by the surveyors.

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Table 1. Characteristics of the three soil salinity samplings taken in 1975, 1985/86, and 1999.

Survey year	First set of 1975			Second set of 1975		Total sampled				Soil samples			Number of analytical determinations
	Pits	Auger holes	Plots	Auger holes	Plots	Points	Plots	Deep, cm		Number	Thickness, cm		
								Mean	Median		Mean	Median	
1975	67	0	67	73	29	140	96	112	100	472	32.9	34.5	2791
1985/86	0	51	51	15	7	66	58	71	67	197	23.8	23.0	2282
1999	0	59	59	7	6	66	65	116	125	240	31.8	28.0	3530
Whole study										909	30.7	28.0	8603

Table 2. Analytical determinations for the saturation extract and the derived magnitude SAR, with their mean and median values for each survey. Ionic concentrations are in $mmol_c/L$, and SAR is in $(mmol/L)^{1/2}$.

	1975			1985/86			1999		
	N	Mean	Median	N	Mean	Median	N	Mean	Median
Percentage of saturation water	0			192	40.98	39.90	240	37.96	36.67
pHe	0			0			183	‡8.25	8.24
ECe, dS m^{-1} at 25ºC	449	3.74	2.30	190	4.64	1.89	240	2.93	1.1
Ca^{2+}	0			192	9.33	6.00	240	8.66	5.14
Mg^{2+}	0			192	6.65	3.45	238	4.36	1.70
Ca^{2+} + Mg^{2+}	464	13.50	9.00	-	15.97	8.75	-	13.01	6.82
Na^{+}	464	27.02	12.15	192	39.99	11.00	240	29.03	3.79
K^{+}	0			0			238	0.51	0.18
CO_3^{2-}	0			192	0.08	0.00	240	0.00	0.00
HCO_3^{-}	0			189	4.3	3.7	240	3.37	3.00
SO_4^{2-}	0			192	20.31	10.75	237	17.81	7.11
Cl^{-}	†472	41.37	19.97	188	30.97	6.00	237	20.08	3.00
NO_3^{-}	0			0			237	1.35	0.72
SAR	464	‡10.75	4.87	190	‡13.41	4.74	238	‡10.04	1.87

† soil to water ratio surmised, not given by surveyors; ‡ chemically unsound, but useful for distribution shape appraisal.

Table 3. Other analytical determinations for each of the three surveys.

	1975			1985/86			1999		
	Number	Mean	Median	Number	Mean	Median	Number	Mean	Median
EC1:5, dS m^{-1} at 25ºC	0			184	0.63	0.32	240	0.46	0.23
pH in water	† 472	‡ 8.34	8.12	§ 189	‡ 8.72	8.53	§ 240	‡ 8.73	8.64
pH in KCl	† 470	‡ 7.55	7.50	§ 190	‡ 8.08	7.98	§ 240	‡ 8.06	8.03

† unknown soil solution ratio and molarity of solvent; ‡ chemically unsound, but useful for distribution shape appraisal; § soil solution ratio 1:2.5 KCl 0.1M.

Table 4. Regression between several chemical parameters for the soil samples from the surveys of 1975, 1985/86, and 1999.

y = a + bx		Samples of 1975				Samples of 1985/86				Samples of 1999			
y	**x**	**a**	**b**	**R^2**	**n**	**a**	**b**	**R^2**	**n**	**a**	**b**	**R^2**	**n**
ECe	EC1:5	-	-	-	-	-0.40	7.57	94.2	182	-0.61	7.73	94.2	240
Σanions	Σcations	-	-	-	-	-1.53	1.01	99.7	185	5.66	0.88	98.3	237
Σanions	ECe	-	-	-	-	-4.56	12.84	99.2	183	*0.48	14.50	96.6	237
Σcations	ECe	2.44	10.14	87.8	448	-2.88	12.71	99.5	190	-5.47	16.40	96.2	238
SAR	ECe	3.28	2.04	47.9	448	6.03	1.58	44.1	188	2.87	2.45	49.4	238
Na^+	ECe	-3.76	8.25	82.9	448	-7.40	10.22	98.5	190	-9.86	13.29	93.2	240
$Ca^{2+} + Mg^{2+}$	ECe	6.21	1.89	43.9	448	4.52	2.49	77.0	190	4.24	2.99	73.2	238
Ca^{2+}	ECe	-	-	-	-	4.38	1.07	62.6	190	3.59	1.73	66.3	240
Mg^{2+}	ECe	-	-	-	-	*0.14	1.42	77.8	190	*0.65	1.26	62.5	238
SO_4^{2-}	ECe	-	-	-	-	9.58	2.31	52.8	190	7.01	3.71	67.2	237
Cl^-	ECe	*2.95	10.19	76.3	449	-18.74	10.56	94.4	186	-11.13	10.74	93.1	237
Na^+	Cl^-	*-1.67	0.69	80.9	464	12.71	0.91	91.5	188	4.68	1.20	93.8	237

* not significantly different from 0.

Table 5. Regressions, after merging the soil samples of 1985/86 and 1999, ranked by their coefficients of determination.

y = a + bx		a	b	R^2	n
y	x				
Σanions	Σcations	2.30	0.95	98.7	422
Σanions	ECe	*-0.58	13.26	97.6	420
Σcations	ECe	-2.37	13.79	96.3	428
Na^+	ECe	-7.12	11.13	94.3	430
ECe	EC1:5	-0.51	7.63	94.2	422
Cl^-	ECe	-14.09	10.53	93.7	423
Na^+	Cl^-	9.08	1.01	90.9	425
Ca^{2+} + Mg^{2+}	ECe	4.64	2.64	74.8	428
Mg^{2+}	ECe	*0.36	1.37	73.0	428
Ca^{2+}	ECe	4.28	1.27	60.7	430
SO_4^{2-}	ECe	8.84	2.74	56.6	427
SAR	ECe	4.65	1.86	45.1	426

* not significantly different from 0.

Table 6. Percent of the soil samples with ECe studied in this article for each survey in the saline phases established by the Soil Survey Division Staff (1993).

Survey year	Salinity (ECe) intervals in dS m^{-1} at 25ºC				
	< 2 Non saline	≥ 2 to 4 Very slightly saline	≥ 4 to 8 Slightly saline	≥ 8 to 16 Moderately saline	≥ 16 Strongly saline
1975	45.7	23.2	18.3	11.1	1.8
1985/86	52.6	16.3	16.8	9.5	4.7
1999	65.0	16.3	12.5	3.3	2.9
Total	52.4	19.8	16.4	8.6	2.7

Table 7. CompECe (dS m^{-1}) and compmSAR (mmol/L)$^{1/2}$, depth of averaging, and depths reached in the three surveys for each comparable sampling point.

Soils considered non-saline in the survey of 1975

Sampling point	1975		1985/86		1999		Depth (cm)			
	ECe	SAR	ECe	SAR	ECe	SAR	of averaging	of pit 1975	of drilling 1985/86	of drilling 1999
16	0.63	1.5			1.24	5.5	60	70		60
25	1.11	1.1	1.74	1.6	1.08	2.7	100	149	70	149
27	0.64	2.3	0.83	1.3	0.66	1.6	100	160	50	160
28	0.73	0.6	1.01	1.3	0.53	0.5	100	168	120	168
29	1.08	2.5			5.91	43.7	100	151		151
37	0.87	3.2	1.04	1.0	0.87	1.1	80	130	82	80
38	0.77	6.1	2.76	6.3	0.94	1.4	100	117	101	117
41	1.13	2.5	1.07	1.9	1.42	1.9	100	105	60	105
50	0.65	1.1	1.56	7.3	1.12	20.4	100	126	55	126
52	0.70	0.7	0.69	1.3	1.02	1.0	64	64	65	64
53	1.69	7.1	0.98	3.1	1.53	14.5	100	125	62	125
61	1.16	2.6	0.45	0.5	0.66	0.6	100	149	31	149
62	1.33	6.5	5.19	11.8	0.80	1.6	100	162	92	162
63	0.78	2.0	1.67	5.0	1.82	6.7	100	114	118	100
64	1.05	2.2	1.74	9.4	0.61	0.7	100	160	137	160
67	0.66	1.9	0.85	0.0	1.15	0.6	98	98	45	98
68	0.30	0.5	0.58	1.2	0.85	0.3	20	40	33	20
69	0.70	0.7	0.78	1.0	0.87	1.1	61	61	61	61
71	1.04	1.3			0.71	1.5	100	157		157
78	0.66	0.6	1.00	1.6	0.92	1.3	100	144	51	144
81	1.45	2.6			0.63	0.6	64	64		64
84	0.70	0.8			0.77	0.8	40	40		55
Median	0.78	1.95	1.01	1.58	0.90	1.36				

Table 7. (*continued*).

Soils considered saline in the survey of 1975										
Sampling point	1975		1985/86		1999		Depth (cm)			
	ECe	SAR	ECe	SAR	ECe	SAR	of averaging	of pit 1975	of drilling 1985/86	of drilling 1999
5	2.89	11.7			4.05	29.6	85	85		85
6	13.33	50.1			2.88	28.7	100	165		165
7	14.14	41.6	9.40	69.4	8.94	46.4	100	178	145	178
9	6.37	22.0	1.23	0.9	0.95	4.4	100	150	35	150
10	11.85	28.7	15.24	65.7	4.13	9.7	100	168	105	150
12	5.95	40.1	7.60	87.8	8.39	46.7	84	109	84	109
13	4.05	20.4	5.71	15.8	6.54	51.3	100	136	52	136
15	24.54	83.2	7.71	26.3	20.34	46.1	100	134	97	134
17	3.37	12.5	6.39	14.4	6.77	24.8	100	141	59	141
18	3.08	20.0	3.71	28.6	3.29	88.1	100	152	70	152
26	7.59	27.1	1.75	8.6	0.90	1.5	100	152	38	152
30	2.76	17.7	0.67	0.6	1.08	0.9	100	159	98	159
31	7.44	25.4	1.12	1.6	0.89	1.3	100	142	71	142
32	7.26	5.2	1.02	1.6	0.94	2.4	100	163	64	163
33	3.63	11.0	3.15	8.6	1.64	8.9	100	140	92	140
35	6.24	11.3	1.25	1.2	0.68	0.6	100	130	114	130
36	4.77	9.1	4.47	24.1	1.94	19.7	100	161	71	161
51	2.88	14.8	3.74	42.1	1.09	10.5	100	150	138	150
54	9.24	22.7	0.79	1.7	0.97	1.0	90	90	105	200
56	3.16	35.4	0.92	4.5	0.75	2.2	100	125	46	125
57	5.93	34.6	3.15	44.5	8.52	97.6	100	120	118	120
58	2.67	2.7	2.38	3.6	1.77	5.3	100	140	60	140
59	3.85	16.6	1.59	2.7	1.49	12.0	100	152	76	152
63b	8.83	23.1	36.49	74.8	28.60	93.7	100	170	68	114
65	3.05	49.8	2.42	28.9	0.96	1.1	80	170	80	170
66	12.72	36.3	34.1	63.3	4.51	20.5	90	90	20	90
76	2.39	4.2	10.34	15.8	2.84	7.1	100	140	46	140
Median	5.93	22.0	3.15	15.1	1.94	10.5				

Table 7. *(continued)*

Points discarded for their individual study, because of the shallow sampling										
Sampling point	1975		1985/86		1999		Depth (cm)			
	ECe	SAR	ECe	SAR	ECe	SAR	of averaging	of pit 1975	of drilling 1985/86	of drilling 1999
8	0.60	0.6			5.50	17.8	62	117		62
11	1.27	1.5	1.92	2.6			36	145	36	
11b			2.08	2.7	2.23	3.7	43		43	150
14	0.40	0.5			0.60	0.6	25	25		25
34	0.61	0.7			0.74	0.7	65	152		65
40	0.90	4.1	0.58	0.6	0.72	1.1	40	140	40	71
70	0.53	0.5	1.37	0.7	0.64	0.7	26	81	26	40
75	2.00	17.8	2.60	3.1	1.30	4.0	44	136	44	70
77	0.50	0.5	0.80	0.3	0.64	0.8	20	80	20	50
79	0.50	0.6	0.44	0.6	0.52	0.5	36	77	55	36
83	0.70	0.6			0.61	0.4	50	80		50

Non compared points	Main reasons for no comparison
1, 3, 4, 60, 80, 82	Sampled only in 1975.
2	Non-irrigated in 1999.
39	Data from the horizon 0-21 cm were unreadable. Only 40 cm were drilled in 1985/86, and was not sampled in 1999.

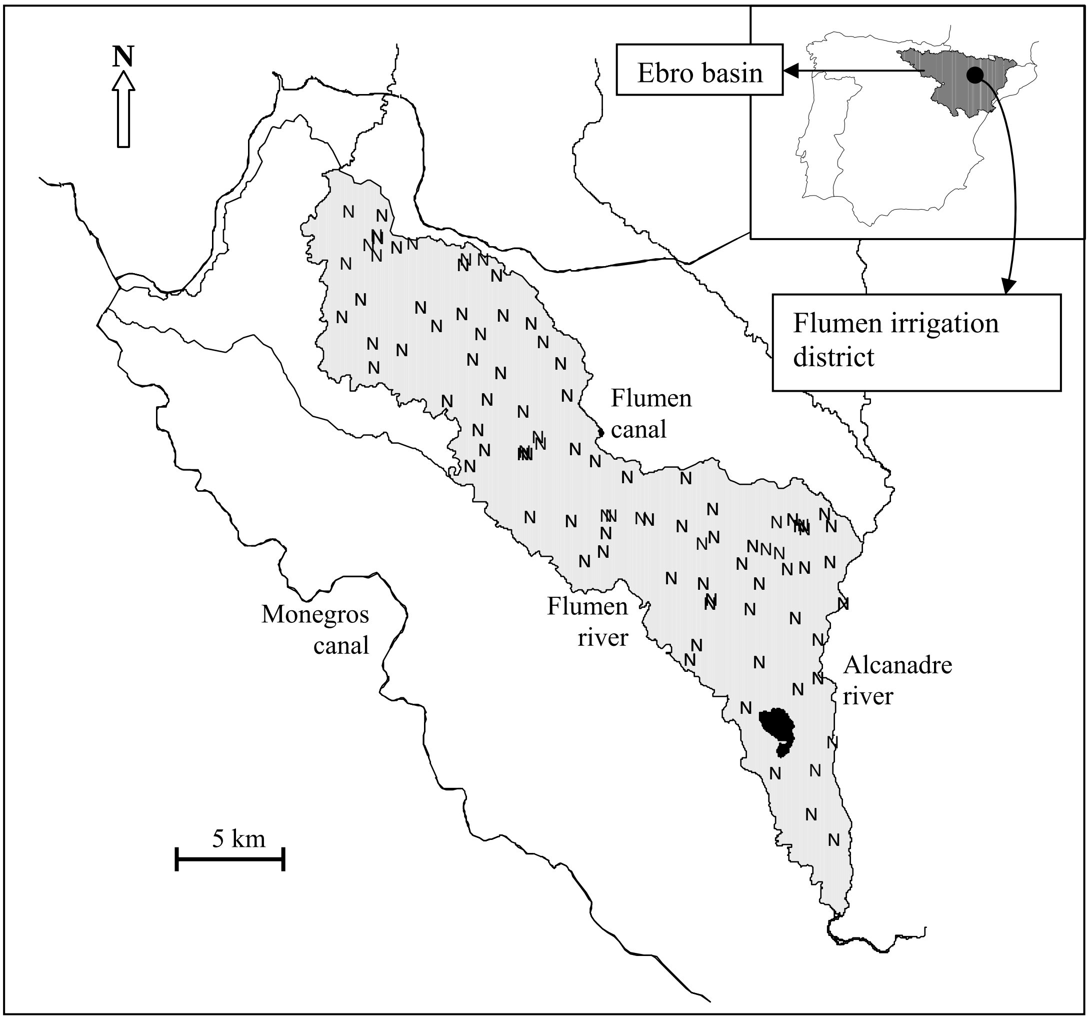

Fig. 1. Site map of the Flumen irrigation district within the Ebro basin (NE Spain) and location of the soil sampling points in the studied area (shaded) of the district.

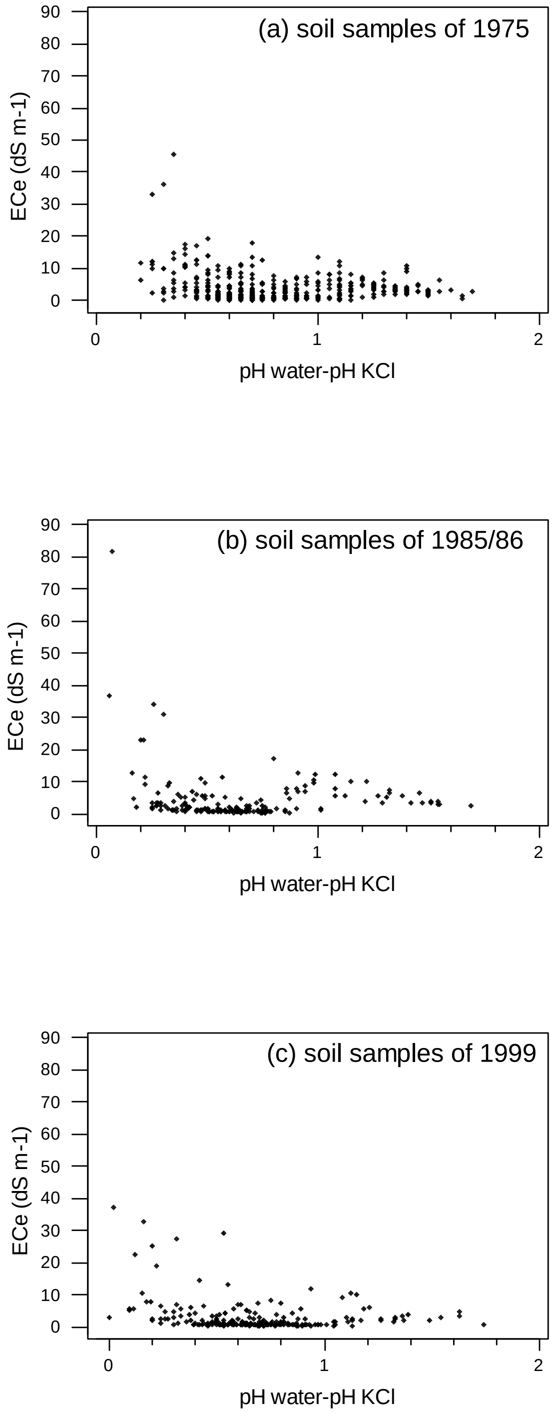

Fig. 2. ECe (dS m^{-1}) against the difference between the pH measured in water and the pH measured in KCl 0.1 M, both in a 1:2.5 soil to solvent ratio: (a) 1975, (b) 1985/86, and (c) 1999.

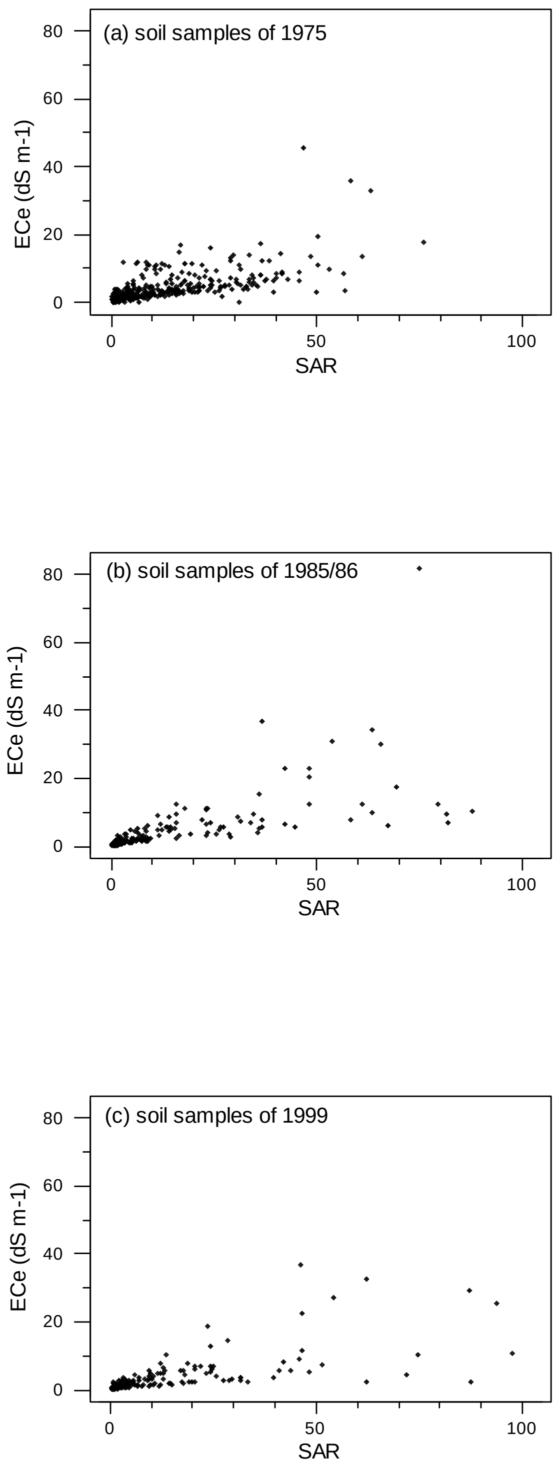

Fig. 3. The salt-affection of the individual soil samples in the surveys of (a) 1975, (b) 1985/86, and (c) 1999.

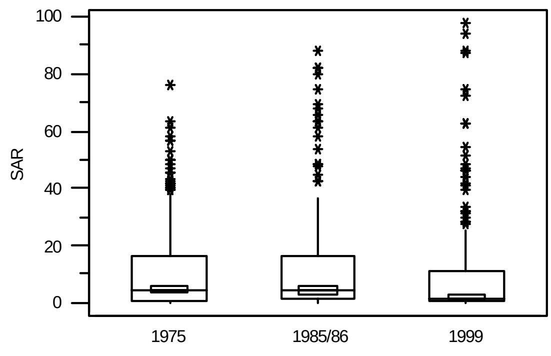

Fig. 4. Boxplots of SAR in the soil samples of the three surveys.

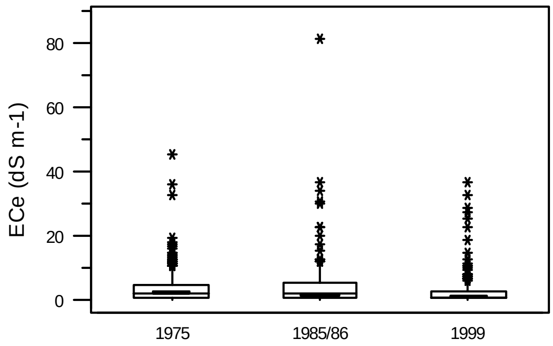

Fig. 5. Boxplot of ECe in the soil samples of the three surveys.

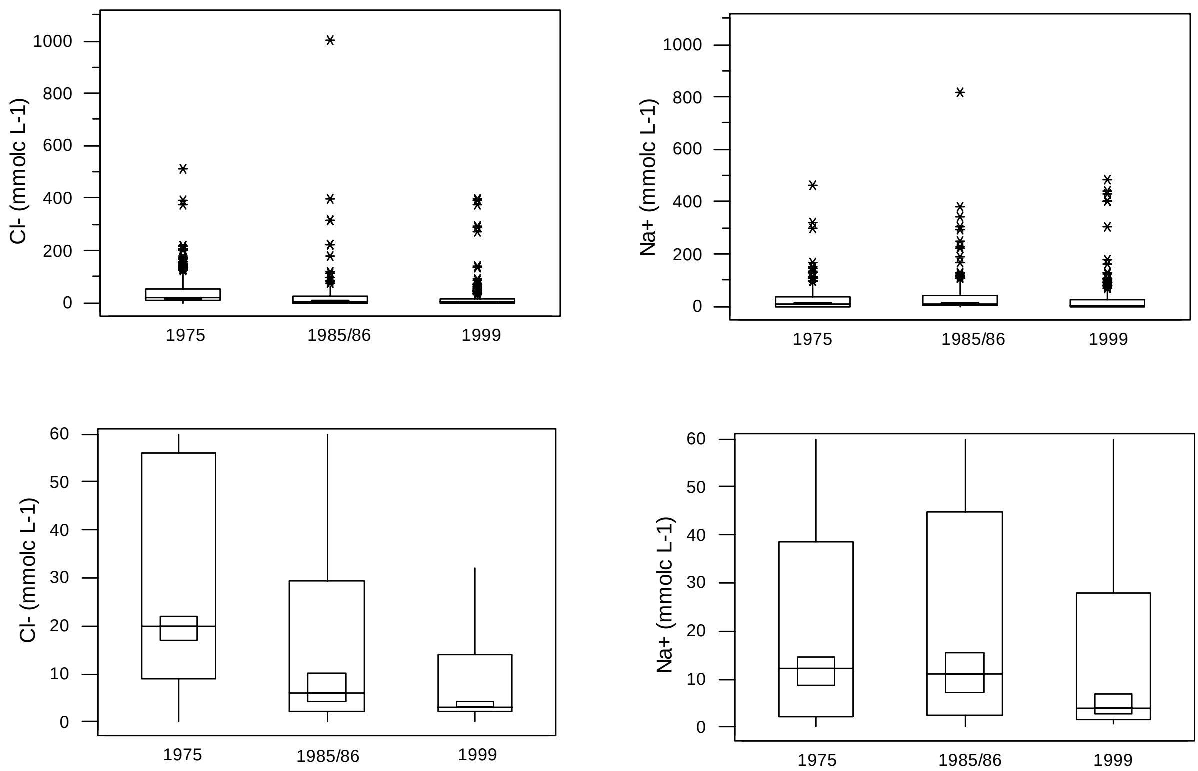

Fig. 6. Boxplots of the Cl^- and Na^+ contents in the soil samples of the three surveys. Bottom boxplots are enlargements, with outliers not drawn.

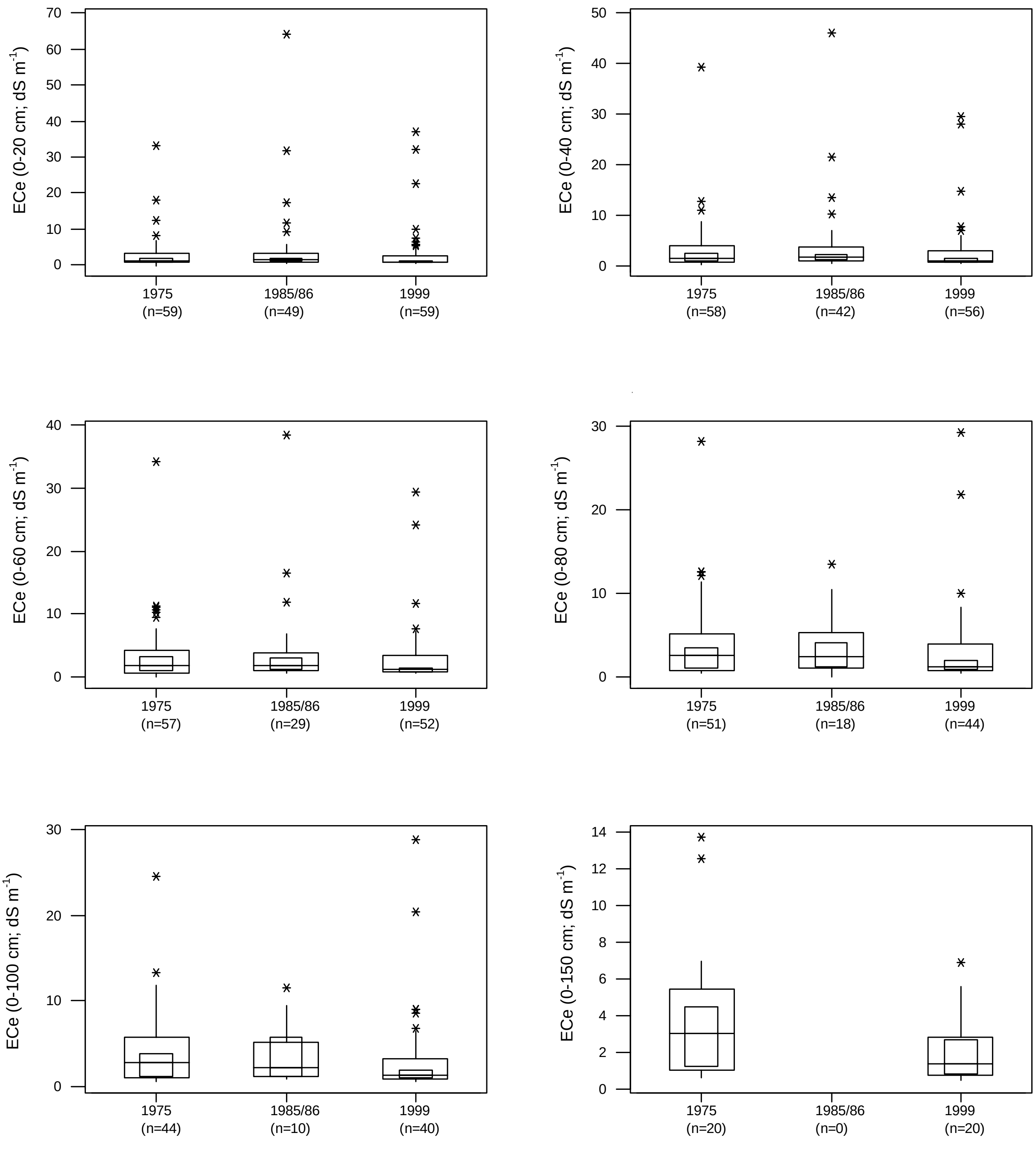

Fig. 7. Boxplot of ECe (dS m^{-1}) of 0-20, 0-40, 0-60, 0-80, 0-100, and 0-150 cm depth in the three surveys.

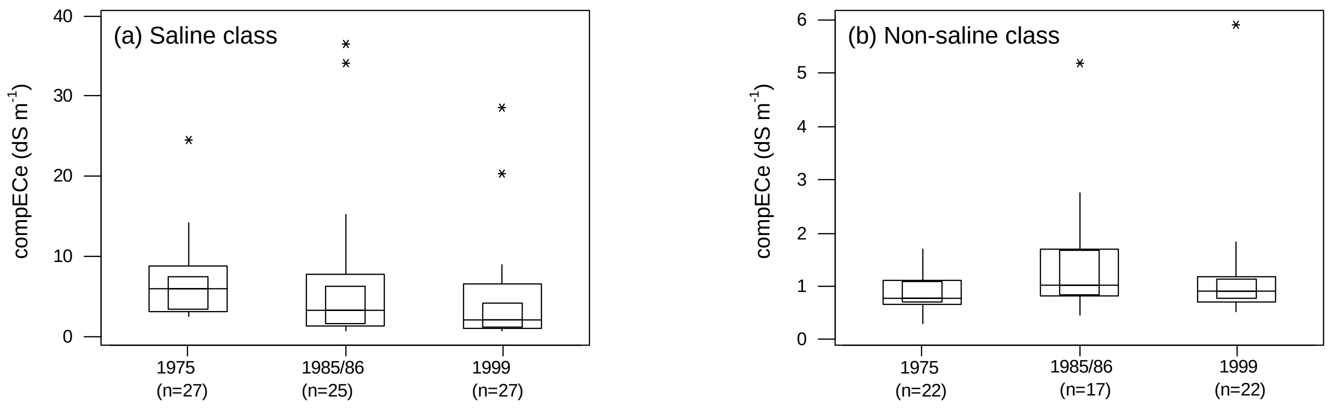

Fig. 8. Boxplot of compECe (dS m^{-1}) for the soils of the (a) saline and (b) non-saline classes.

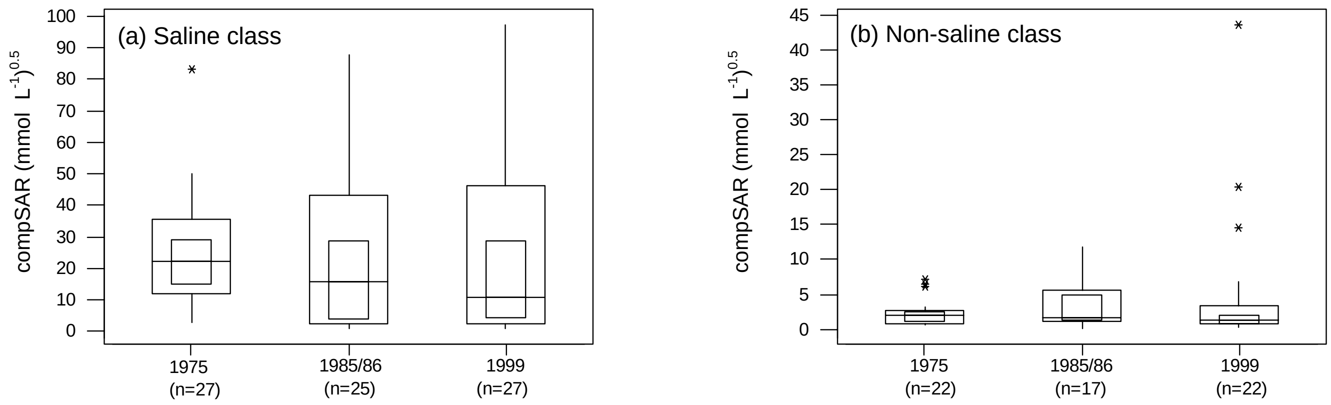

Fig. 9. Boxplot of compmSAR (mmol L^{-1})$^{0.5}$ for the soils of the (a) saline and the (b) non-saline classes.

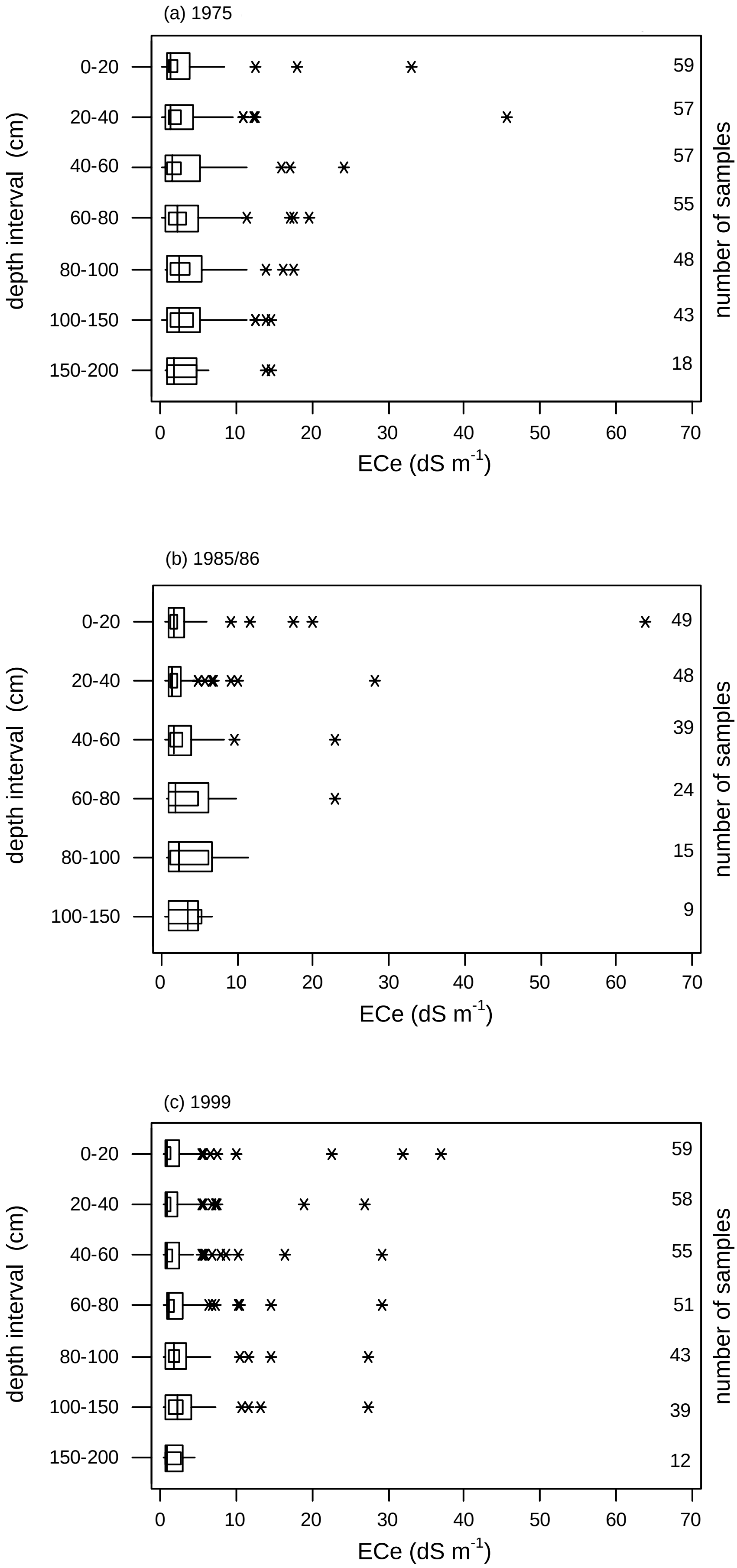

Fig. 10. Synthetic profiles of ECe (dS m^{-1}) in (a) 1975, (b) 1985/86, and (c) 1999.