A paddy on sodic varved sediment and plant life constraints, NE Spain

Juan Herrero* and Carmen Castañeda

Estación Experimental de Aula Dei, CSIC, Av. Montañana 1005, 50059 Zaragoza, Spain

5

* Corresponding author. Tel.: +34 976 716 152; fax: +34 976 716 145.

E-mail address: jhi@eead.csic.es (J. Herrero)

10 **ABSTRACT**

In arid lands, irrigation is necessary for agriculture to be profitable. However, the nature of soils and parent materials is significant enough to trigger permanent management limitations and the loss of important investments, as happened in some areas of the Flumen irrigation district in the Central Ebro Basin, NE Spain. We studied the distinct soil characteristics of a salt-affected agricultural plot and its recurrent problems from the last 30 years. We describe and discuss the prominent features of this soil and their effects on plant life and agricultural management. The evidence of post-irrigation salt-related effects is documented together with the water and soil salinity monitoring records. The presence of varved Holocene sediments comprising alternating clays and carbonate-rich silt with high levels of salinity and sodicity, together with a shallow saline water table, were found to be the key unfavorable conditions. Despite a noticeable decrease in sodium adsorption ratio (SAR) from 1999 to 2015 and a reduction in soil salinity down to a steady state after rice paddy cultivation, SAR and alkalinity remained high enough to hamper irrigated agriculture. Only the native plant *Puccinellia festuciformis* thrives in the studied plot. The article presents and discusses chemical features —analytical data— and morphological features —pictures and descriptions— that are seldom reported and interpreted together in the scientific or technical literature about irrigation of sodic soils, often limited to chem data. The paddy field studied is deemed representative of the most unfavorable soils for agriculture in the irrigated districts of the Ebro valley.

30

Keywords: Ebro Basin, Holocene, irrigation, rice, salinity, sodicity, soil.

Abbreviations

35 EC, electrical conductivity reported in dS m^{-1} at 25°C ; ECe , electrical conductivity of the saturation extract; EC1:5 , electrical conductivity of the extract in a soil to water dilution with a weight ratio of 1:5; EC1:10 , electrical conductivity of the extract in a soil to water dilution with a weight ratio of 1:10; OM; organic matter; pH1:2.5 , pH measured in a 1:2.5 soil to water dilution; pHe , pH measured in the soil saturated paste
40 extract; pHp , pH measured in the soil saturated paste; SAR, sodium adsorption ratio expressed in $(\text{meq L}^{-1})^{0.5}$; SP, saturation percentage reported as cm^3 of water per 100 g of fine earth.

1. Introduction

45 Irrigation of the soil is a must for permanent agriculture in arid regions. This practice has been taking place in Spain since prehistory (Chapman, 1978), and is documented in the Ebro Valley in Roman inscriptions from more than 2100 years ago (Beltrán, 2006). A frequent drawback for irrigation is the effect of salt on the soil that occurs in many areas around the world, resulting in heavy economic losses (Qadir et al., 2014). Salt-affected soils are present in significant zones of the Ebro Valley, N.E. Spain (Alberto et al., 1986).

Herrero and Snyder (1997) provided an overview of the relationship between aridity and irrigation in the Central Ebro Valley. The new irrigation districts established since the 1940s in this semiarid region, use fresh water from the Pyrenees, stored in
55 reservoirs. This water, transported through several hundred-km-long canals is distributed by a dense network of ditches to the individual leveled plots, suited to basin and border irrigation. After the developmental years, agricultural production increased vastly, with alfalfa, corn, rice, sunflower, and winter cereals being the most extensive crops. The districts irrigated by gravity are currently adapting to pressurized
60 irrigation (Lecina et al., 2010) in order to better control the water applied and to overcome the shortage of manpower. This change has necessitated the merger of small plots and the installation of solid set sprinklers or central pivot machines, which are now popular irrigation systems.

Problems of soil salinity arose in some of the newly irrigated lands only few years after irrigation began, and was a concern from the 1940s onwards as shown by the references in Ayers et al. (1960). This insidious problem was combatted by watering the soils, with irregular results. In some cases, rice paddy cultivation using low EC, running irrigation water successfully desalinated soils, making the rice crop somewhat independent of the salinity of the soil. The technique of rice cultivation includes puddling with the rice fallow (Playán et al., 2008; Herrero and Hudnall, 2014), and careful subsequent variations of water depth, from a few mm to ~10 cm, for weed control during the flooding period from May 1st to September. This approach worked for leaching soils in areas of favorable soil textures or where gypsum in the profile impeded clay sodication and its ensuing dispersion, which can lead to soil imperviousness. However, at present, some fields are under rice monocropping as other cash crops are unfeasible, either due to the shallow saline water table or other soil constraints. When the market or subsidizing policies make rice unprofitable, these fields remain uncultivated and bare, or populated with volunteer halophytes.

The relief of the study area is a result of the Quaternary carving of horizontal Miocene saliferous strata comprising alternating sandstone and fine-grained sediments, overprinted by several periods of Holocene erosion and sedimentation. One of these Holocene sediments is a finely laminated varve-like formation of millimetric sodic clay layers, containing mica and chlorite, alternating with silt-rich layers, with a high calcium carbonate content and an elevated salinity and sodicity (Vizcayno et al., 1995).

This deposit is several meters thick and was called *hojaldre*, the Spanish word for puff pastry, due to its distinctive lamination that are visible to the naked-eye (Herrero et al., 1989; Rodríguez-Ochoa et al., 1990). The *hojaldre* material has been recorded at distinct locations separated by more than 100 km in the Central Ebro Valley (Martínez-Beltrán, 1978; Porta et al., 1992). A considerable extent of *hojaldre* sediments was destroyed by the earth movements necessary for reshaping the irrigated areas. The total coverage and location of this deposit is difficult to assess as it is not identified as a unique geological formation (or a distinct stratigraphic unit), and therefore is not shown on the geological maps.

95 The particular field studied in this work, located on *hojaldre* material, is
representative of the most unfavorable areas for agriculture in the irrigated districts of
the Ebro Valley. One of these is the Flumen irrigation district where a soil survey
(IRYDA, 1975a) mapped 46.9% of its surface area as salt affected, i.e., $E_{ce} > 4 \text{ dS m}^{-1}$ or
ESP > 15. Rodríguez-Ochoa et al. (2012) provided a bibliography relating to salt-affected
100 soils in this area, as well as a list of the salt minerals identified and microscope images
of them. The main microscopic features of these soils were reported by García-
González et al. (1996) and Sanz et al. (1996). **An average content of the sand, silt, and
clay fractions of 18.1 %, 55.1%, and 26.8, respectively, was determined by Rodríguez-
Ochoa et al. (1998, page 50) for a profile described in August, 1990, in the studied field.**

105 The classical method of reclaiming sodic soil for agriculture is based on increasing
the Ca^{2+} in the cation exchange complex, displacing Na^+ out of the root zone through
leaching by excess irrigation (Qadir et al., 2006). The review by these authors discusses
several different specific soil conditions, and the application of mined gypsum to
increase the Ca^+ content in the soil solution. However, calcium carbonate is abundant
110 in the soils of the Flumen irrigation district, and the application of gypsum did not work
in this area (Herrero et al., 1989).

The salination/desalination vicissitudes of the Flumen irrigation district from 1975
to 1999 were studied by Herrero and Pérez-Coveta (2005) and Mora et al. (2017). The
scale at which the laminated materials and their irrigation-derived problems condition
115 not only agriculture but also landscape evolution, through the development of piping
processes in the area, was studied by Castañeda et al. (2017).

This article aims to show the analytical and visual characteristics of a soil
developed on these varved Holocene materials and the problems this substrate poses
for plant life, particularly paddy rice cropping.

120 **2. Materials and methods**

2.1. The study field and its context in the irrigation district

Our first soil data for the field date back to April 3, 1985. At that moment the field
was bare and had remained uncultivated for several years after some attempts to grow
125 paddy rice. The data on the soil salinity in April 1985 and March 1999 can be found in

Herrero and Castañeda (2013, 2015). Here we present more recent data on the chemistry of the soil solution, and photographically document both the soil and its parent material.

The field (41°59'N, 0°22'W) is located in the Plan de Callén depression, Central Ebro Valley, Spain (Fig. 1), 340 m a.s.l. This depression has difficult natural drainage into the Flumen River, a fourth order tributary of the Ebro River. The irrigation district was set out at the end of the 1940s. In the early 1950s the late Instituto Nacional de Colonización opened an outlet to the Flumen River and built the irrigation and drainage ditch network. The irrigation water coming from the Pyrenees is stored in the Sotonera reservoir and then delivered to the irrigation district through the Canal del Flumen. Four water samples taken from the Sotonera reservoir in April, May, June, and July 1975 (IRYDA, 1975b) had a mean EC of 0.37 dS m⁻¹, ranging from 0.33 dS m⁻¹ to 0.41 dS m⁻¹, and a median SAR of 0.5. These values agree with those reported by López-Bruna and Aragüés (1995), as well as the mean EC of 0.30 dS m⁻¹ and median SAR of 0.3 from our 1985 and 2015 measurements (Table 1).

After leveling and parceling the land for irrigation, the landscape was transformed in a mosaic of plots (Figs. 1 and 2). These were typically designed to be ~ 1 ha each, the optimal size for the available irrigation technology, and equipped with basin and border flood irrigation utilizing a network of concrete ditches. The present layout of the study field arose in 2006 when the owner merged two plots (Fig. 2D). Both these plots were bare in the aerial photographs taken in June and July 1957 (Herrero, 2008) and subsequent years (Fig. 2B), as were their surroundings, where bare or irregularly covered plots were common, showing symptoms of soil salinity from 1927 to 2015 (Figs. 2A to 2E). The western side of the plot is bordered by an elevated concrete irrigation ditch that delivers water by gravity to the field, while a drainage ditch runs along the northern side of the plot (Fig. 2D). The 2015 orthophoto (Fig. 2F) shows the studied plot as well as its neighbors under rice cultivation. However, poor agricultural results obtained with sprinkler irrigation can lead to the abandonment of the sprinkler infrastructure; this was the case for the plots adjacent to the study field to the NE. These were then equipped with solid set sprinklers (Fig. 3A), at least from the time of our earliest visits to the plot in 1985. None of the crops planted in different years attained full coverage. In 2009 the sprinklers were abandoned and the plots reshaped

and re-leveled to return to rice monocropping. It represented a regression in terms of the agricultural value of the land.

160 The annual temperature and precipitation means, according to the records from the Almuniente weather station (41° 56' 59" N, 0° 24' 36" W), were 13.8°C and 474.5 mm, respectively. The mean annual water deficit was 600 mm, estimated as the difference between mean precipitation and the ET_0 calculated by Martínez-Cob et al. (1998), affected by the factor 0.88 as established by Faci et al. (1994).

165 A soil profile description for this plot, made on August 1st, 1990, can be found in Rodríguez-Ochoa et al. (1998). We re-classified this soil according to the Soil Survey Staff (2014) criteria as an Oxyaquic Xerofluvent. This almost impervious plot is prone to several cm of flooding even after moderate showers, with water standing until it evaporates in the summer heat and through insolation, or due to the persistent dry
170 wind in winter. In the past, the owner unsuccessfully tried to improve the infiltration by adding rubble.

When not used for rice cultivation, the plot remains bare all year round, showing patches of both white and black alkali salts (Vizcayno et al., 1995). Over the past 30 years we have observed occasional tufts of *picutín*, the annual salt grass *Puccinellia festuciformis* (Host) Parl., occurring in erratic locations from one year to next. Stunted
175 clumps of other halophytes like *Suaeda vera* Forssk. ex J.F. Gmel. and *Salicornia ramosissima* Woods also appear within the plot, but they are better developed on the berms encircling the field.

180 2.2. Water and soil sampling and lab determinations

We determined the EC and major ions in the water of the irrigation ditch in June, 1985, and then again in April and June of 2015 (Table 1). Table 1 also provides the data for the samples taken from the phreatic water and the drainage ditch bordering the northern side of the field.

185 A failed attempt to grow Bermuda grass, var. Coastcross-1, i.e., *Cynodon dactylon* L. (Pers.), was conducted in 1985 on an experimental area of 30 m × 52 m within the study field, first using drip irrigation and then sprinkling. This experiment provided the opportunity to study the soil solution in the upper soil layer using eight vertical ceramic probes installed within a 6-m radius inside the experimental area. The probes worked

190 during 103 days, from May 29th to September 19th, 1985. Their distribution and other details, like the dates of the 25 days of the 115 suction probe extracts, plus EC, pH and major ions determinations were reported by Herrero (2008, pages 137-139). Not all determinations were made for all samples due to the different volumes of the extracts and to the availability of lab facilities. The columns 2 to 5 of Table 2 show the number
195 of determinations and other statistics. The probes reached a depth of 20 cm, with the exception of probes 4 and 5, which reached 10 cm and 15 cm, respectively, due to the lengths of the available probes. On June 5th, 1985, the soil in the probe area was spread with 1.5 kg m⁻² of gyprock milled to < 5 mm diameter, with a gypsum richness of 85.5%.

Table 3 shows the dates and other details of the soil sampling. The rationale for
200 soil sampling in 1985 was to look for differences in salinity between two sites within the plot and their relationship with the occurrence of halophytes. For this purpose we took soil samples with a hand auger. The first site (PC1) was in the bare area and the other (PC2) was located close to clumps of *P. festuciformis*. On April 3rd, 1985, we installed a perforated PVC pipe into this second hole to further sample the phreatic
205 water and record its level.

Over the following years, we realized the erratic nature of the *P. festuciformis* clumps, but we maintained the location of the PC1 and PC2 augering sites for sampling in 1999 and 2015. The plot was already inundated for rice cultivation when we visited it on May, 2006, so we augered in two neighboring plots (Fig. 2D). PC3 was bare, while
210 PC4 was located in an area covered by almost dry clumps of *P. festuciformis* and some *S. vera*. Both the PC3 and PC4 plots had just been plowed in April 2015, and we were able to sample the surface soil from 0 to 20 cm.

The EC of all the water samples (irrigation, drainage, phreatic, and ceramic cup probes) was determined. Depending on the volume of water extracted by the ceramic
215 probes and the lab availability, some of the following were also measured: pH, Ca²⁺, Mg²⁺, Na⁺, CO₃²⁻, HCO₃⁻, SO₄²⁻, and Cl⁻. The water sampled in 2015, in the irrigation channel and drainage ditch, were also analyzed for K⁺, showing a negligible content of ≤ 0.03 meq L⁻¹. The measurements were made only a few hours after the sampling to avoid microbial growth or other alterations.

220 Soil salinity was assessed by measuring the EC of aqueous soil extracts (United States Salinity Laboratory Staff, 1954; Herrero et al., 2015). EC1:5 was measured in all

of the 62 soil samples taken (Table 3). Different supplementary lab determinations were made depending on the lab facilities available at the time of each sampling campaign. EC1:10 was measured in the 30 samples from 2006 and 2015. Saturated
225 pastes were prepared, their saturation percentage (SP) recorded and E_{Ce} measured for the 44 saturation extracts from 1985, 1999, and 2015. The major ions (Ca^{2+} , Mg^{2+} , Na^{+} , CO_3^{2-} , HCO_3^{-} , SO_4^{2-} , and Cl^{-}) from the 32 saturation extracts from 1985 and 1999 were titrated. K^{+} was assumed to be negligible in non-fertilized saline soils (Hernández et al., 2002; Herrero and Castañeda, 2013). Moreover, Ca^{2+} , Mg^{2+} , and Na^{+} content was
230 determined for the saturation extracts of 11 of the 12 samples taken in 2015.

Depending on the lab facilities available, the soil reaction was appraised using pH determined by potentiometry in: (i) a soil to water ratio of 1:2.5 (pH1:2.5) for the 45 samples from 1985, 2006 and 2015; (ii) the saturated paste (pHp) of the 27 samples taken in 1985 and 2015; and (iii) the saturation extract of the 17 samples from 1999.
235 Organic matter (OM) was titrated in the 12 samples from 2015 using chromic-acid digestion (Heanes, 1984) and spectrophotometry. The calcium carbonate equivalent was measured by gasometry in the soil samples from 2006 and 2015. The gypsum content was determined by thermogravimetry (Artieda et al., 2006) in the 2015 soil samples.

240 2.4. Data analysis and representation

The data were analyzed with MINITAB® using resistant measures from exploratory data analysis (Tukey, 1977; Chambers et al., 1983). Boxplots were drawn following Chambers et al. (1983) and included 95% confidence intervals (CI) for the medians,
245 which were estimated according to Hettmansperger and Sheather (1986). The regression lines were calculated using the Ordinary Least Squares method ($p = 0.05$).

The multitemporal comparison and graphic representation of the vertical distribution of salinity were undertaken using synthetic profiles (Herrero and Pérez-Coveta, 2005) consisting of 20 cm-depth-weighted averages of soil attributes
250 generated using the Slices software v.2 (<http://hdl.handle.net/10261/60892>).

2.5. Observations of soil and parent material morphology

Visual soil assessment has been used since at least the 1990s (Murphy et al., 2013) to evaluate surface structure, a key feature conditioning the hydrological functions of soil. The visual observations made in the study plot and in the nearby undisturbed parent material are here illustrated using previously unpublished field pictures taken over the last 30 years. The alkalinity is easy to appreciate either due to the frequent black coatings of humates on the soil surface (Fig. 3B) or the extraction of OM from manure (Fig. 3C). A symptom of the high SAR and the mild salinity is the dispersion of the fine soil materials and the consequent imperviousness of the soil.

3. Results and discussion

3.1. Calcium carbonate, gypsum, and organic matter

The calcium carbonate equivalent in the soil, measured in a total of 30 samples taken in 2006 and 2015, ranged from 21.1% to 31.7%, with a mean of 25.9%, a median of 26.2%, and a coefficient of variation of 0.09. A calcium carbonate equivalent content of about 30% is common in many soils and fine-grained sediments in the area (Herrero et al., 1989; Rodríguez-Ochoa et al., 1998; Herrero, 2008). In addition, the almost uniform calcium carbonate equivalent in the 2-m deep soil profile explored is similar to that reported by Herrero et al. (1989) in nearby *hojaldre* materials.

In the 12 soil samples from 2015 the gypsum content was determined to be < 0.6%. Following the negative results of the qualitative test for sulfates in these samples, these figures are attributed (Herrero et al., 2016) to the release of residual water from the soil samples. The gypsum content is therefore assumed to be nil, as expected for this alkaline, sodic soil.

The uniform composition through the profile is supported by the SP of the 44 pastes prepared, which showed a mean of 31.1 SP with a low coefficient of variation (CV = 0.22). The SP showed a relationship with the OM content, where $R^2 = 89.4\%$, calculated for the 12 samples in which both were tested for.

The mean content of OM in our sampling of 2015 was 0.54 %, and it falls to 0.36% if the depth 0-20 cm is not accounted for. These values are similar to those in the profile described in this field by Rodríguez-Ochoa et al. (1998). The vertical distribution of the OM in the sampled sites is shown in Fig. 4. The almost two fold contents of OM

in the upper horizons of PC2 against PC1 might be related to the occurrence of a clump of *P. festuciformis* in this site.

3.2. Soil water

The water table depth ranged from 138 cm to 147 cm with a mean of 142 cm after our observations on 11 different days between April 16th, 1985, and July 8th, 1985. The EC measured on five different days between April and October 1985 ranged from 8.12 dS m⁻¹ to 8.95 dS m⁻¹, with a mean of 8.54 dS m⁻¹. The pH of the phreatic was 8.1 in 18 June 1985, very similar to water pH 8.2 in the irrigation ditch in 5 June 1985.

The results of the chemical determinations for the 115 suction extracts collected in 1985 is given in Herrero (2008, pages 137-139). Table 2 shows that the soil water from the ceramic probes and the saturation extracts from the same year show similar composition patterns, with a predominance of Na⁺ > Cl⁻ > SO₄²⁺ in both extracts.

The extreme EC fluctuations in the soil solutions extracted using eight ceramic suction probes (Fig. 5) illustrate the practical limitations of this device in the field. The probe limitations reported by Aragüés (1986), and Grossmann and Udluft (1991) suggest that the sharp increases and decreases in EC were caused by accidental openings of the stoppers in some probes. If rain or water from the sprinkler entered the probe, the extract would become diluted, while in others, if no water entered, it would become concentrated due to evaporation. The extreme fluctuations seem not related to weather because they do not have a common pattern for the probes.

The EC in the soil solution from the eight probes (Fig. 5) ranged from 5.1 dS m⁻¹ to 29.6 dS m⁻¹, with the latter value disregarded as discussed below. The limitations of the probes technology for field research are illustrated by the erratic records of probes 4 and 6 and the final rise of EC in probe 9, attributable to unnoticed openings of the probes stoppers or other accidents. The EC measurements from probe 5 were quite stable around 22 dS m⁻¹, and were highest than the remaining probes (2, 3, 7, 8, and 9), probably due to his shallower insertion of only 10 cm. Then, the probe 8 is deemed representative of the highest EC values in the upper 20 cm soil layer. The successive extracts of this probe decreased from 19 dS m⁻¹ until a stable value of 16 dS m⁻¹ in the last four measurements. These values denote the high salinity of the soil solution that *P. festuciformis* deals with in the study plot.

The variability of EC between the probes in the upper soil horizon was probably intensified by soil surface characteristics, such as the centimetric relief in the soil surface, with shallow cracks promoting water flow before they become filled by fine materials transported even by the modest amount of water applied by drip irrigation as shown in Fig. 6A where the salt efflorescence standing on the top of the microreliefs between cracks denotes that no rain happened to transport the fines. These materials are swept away by showers or drip irrigation from the ephemeral, millimeter-scale puffed crust (Fig. 6B), locally known as *coscarana*, whose materials are loose. This crust is formed during the dry period following either a rain shower, or a sprinkler or drip irrigation with the non-saline irrigation water. The anecdotal but eloquent effect of spreading gypsum, still visible on the plastic drip emitter, is the transparency of the water in the ponds (Fig. 6C). No noticeable effect on SAR was detected, the SAR values in most extractions being much higher than the threshold for sodic soils.

In the period of experimental irrigation in 1985, the soil solution extractions by ceramic suction probes confirmed the E_{Ce} and SAR values, as well as the high sodium content and pH of this soil (Tables 2 and 4). The sum of the concentrations of Ca²⁺ and Mg²⁺ in the samples collected by the probes ranged from 1.5 to 10 meq L⁻¹, and 70% of the samples had ≤ 5 meq L⁻¹. With this composition, slight differences in the titrated amounts of Ca²⁺ plus Mg²⁺ within the allowable accuracy of the analytical methods, or caused by changes in the labs through time, might lead to substantial differences in SAR values, compromising the comparison of individual values. That said, the comparisons of the median SAR in our plot are reliable, as these come from batches of samples (Table 2).

3.3. Salinity, sodicity and alkalinity in the soil samples

In the saturation extracts, the regressions of each of the two major plant-stressor ions —chloride and sodium— on E_{Ce}, as well as the regression between these two ions, are compared in Table 5 against the same regressions for the whole district (Herrero and Pérez-Coveta, 2005). The regressions show high coefficients of determination (R²) for the 43 soil samples from the study plot that have these determinations in the saturation extracts. The equations are quite similar to those obtained for the whole district in spite of the extremely high sodicity in the study plot,

which agrees with the higher intercept values for the plot compared with the entire district.

One concern when using EC as bulk measure of soil salinity is the occurrence of neutral pairs or other ion associations that can weaken the value of EC as an indicator of the stock of salts present in the soil (Herrero et al., 2015). In our case, no ion pairing was present, as shown by the linearity of the relationships between EC1:5 and EC1:10 (Eqs. 1 to 3, Table 6) for the determinations grouped by sampling years. EC1:5 for all 62 soil samples ranged from 0.45 to 3.11 dS m⁻¹, with a mean of 0.97 dS m⁻¹ and a median of 0.75 dS m⁻¹.

The linear adjustments of the regressions of E_{Ce} over EC1:5 (Eqs. 4, 6, 8, and 10 in Table 6) suggest that EC1:5 works well as a proxy for E_{Ce}. This is confirmed by the improvements (Eqs. 5, 7, 9, and 11 in Table 6) when corrected for the dilution ratios in the extracts (Abrisqueta et al., 1962; Sumner et al., 1998).

In order to qualify the salinity of the soil samples with the Soil Survey Division Staff (1993) criteria, adapted by Nogués et al. (2006), we estimated the E_{Ce} for all samples from EC1:5 using Eq. 4. According to this estimation, 24 samples are “non-saline”, 24 samples are “slightly saline”, 9 samples are “strongly saline”, and the remaining 5 samples are “very strongly saline”. All the “very strongly saline” samples come from the upper meter of site PC2, four collected in 1985 and one in 1999. This is in agreement with the supposed water flux towards the drainage ditch close to PC2 (Figs. 1B, C, and 2D).

The E_{Ce} in the Plan de Callén study area was much lower than that recorded in other saline soils studied in the Ebro Valley by Herrero and Castañeda (2013, 2015) although the SAR and alkalinity were much higher. The SAR for the 43 soil samples with Na⁺, Ca²⁺ and Mg²⁺ determinations ranged from 17 to 311, with a median of 100. All the samples were classified as sodic as their SAR was higher than the classic threshold of 13. The Ca²⁺ plus Mg²⁺ contents were ≤ 3 meq L⁻¹ in 35 samples, most having a SAR > 100; the sensitivity of SAR to slight variations in Ca²⁺ plus Mg²⁺ determination discussed in the last paragraph of section 3.2 must be taken in to account.

Table 4 summarizes the soil reaction with data on the pH of the water extracted using ceramic probes, as well as the soil pH measured in different years at the 1:2.5 dilution (pH1:2.5), the saturated paste (pHp), and the saturation extract (pHe).

Alkalinity, occurring along the entire profile and dates (Fig. 7), is a prominent feature at the surface as shown in Fig. 6D by the very basic pH recorded by litmus paper and the dispersed state of the sodic clay, which does not settle in the pond. The median pH of the soil extracts was “very strongly alkaline” whereas in the suction probes it is “strongly alkaline”. As expected, the median pH_{1:2.5} was higher than the pH_p within the same batch of samples, as shown in Table 4. In addition, the samples from the upper layer are less alkaline than the deeper samples, illustrating the vertical distribution of the soil properties discussed in the next section and in previous works (Herrero, 2008; Herrero and Castañeda, 2015). Using the terms provided by the Soil Survey Division Staff (1993), the water from the ceramic probes can be classified as “strongly alkaline” and the soils as “very strongly alkaline”.

3.4. Temporal and vertical changes in soil chemistry

A significant decrease in the median soil salinity from 1985 to 1999, expressed as EC_{1:5}, is illustrated by the boxplots in Fig. 8. The lowest median and mean were recorded in 2006, with no significant difference between the years 1999 and 2015. The median SAR in the soil samples (Fig. 9) showed no significant differences between pairs in the augering campaigns (1985, 1999, and 2015) in spite of the noticeable decrease in SAR from 1999 to 2015. Similar considerations apply to the SAR determined in 1985 for the ceramic probes.

Irrespective of the lack of statistical significance of this decrease, all the samples taken in 2015 exceeded the classical SAR threshold of 13, i.e., they are sodic. The evolution of the alkalinity is illustrated by the pH_{1:2.5} and pH_p statistics shown in Table 4. From 1985 to 2015, pH_{1:2.5} decreased 0.88 pH units, and pH_p decreased 0.18 units. Fig. 7 shows that the alkalinity of the soil profiles PC1 and PC2 decreased from 1985 to 2015, with a more pronounced decrease at the upper layers.

The synthetic profiles of EC_{1:5} (Fig. 10) provide an overview of the vertical salt distribution at the various sites and on different dates (Fig. 10A), as well as the mean for each year (Fig. 10B). The outlier value of 3.03 dS m⁻¹ in the upper layer of PC2 in 1999 (Fig. 10A) is attributable to transient surficial efflorescence at the time of sampling. A strong decrease in EC_{1:5} occurred between 1985 and 1999 in the first 140 cm depth, in addition to a less important decrease in deeper layers, due to the saline

water table (Table 1). Subsequent to 1999, the EC1:5 values are almost constant, with slight or negligible decreases (Fig. 10).

415 The changes discussed in the preceding two paragraphs suggest that the chemistry of the soil solution in this plot reached a steady state sometime after 1985, at least for soil salinity (Fig. 8). This state can be attributed to the continuous management of the plot as a paddy from at least 1999, involving yearly flooding from May 1st to the end of September with a continuously flowing fresh water table. Steady state is also surmised
420 from the farmer perception of substantially constant agricultural results in this plot in the last years.

3.5. The visual features of soil and parent material versus rice cultivation

The soil cracks are only about 10 cm deep. These cracks quickly become clogged
425 by the particles mobilized at the soil surface following a light rain shower, or even drip irrigation (Fig. 6A). The movement of water within the soil profile is hampered by the low vertical transmissivity resulting from the stacking of alternating layers. Moreover, the water circulation through the cracks stops because their rapid infilling. In addition, surface sealing constrains surficial water loss through evaporation (Galizzi and
430 Peinemann, 1989). In the summer, the alkaline stagnant water (Fig. 6D), become warm, and anoxic. These conditions impede the installation of most plants, including the common halophytes in the area, with the exception of *P. festuciformis*, probably due to its ability to limit Na⁺ influx into the roots (Peng et al., 2004).

Hojaldre is recognizable in the metric escarpments at the drainage trench of the
435 study plot (Fig. 3A) and in natural escarpments of many nearby non-irrigated sites (Figs. 11A and B) where this material is easily eroded. The reorganization of this material can be observed at the toe of the slopes. The abraded material is transported and deposited in the ponds where the silt-sized and larger particles quickly settle making a millimetric sediment layer. In contrast, the sodic clays do not settle and can
440 remain in suspension for months. It was checked with a simple indoor experiment consisting in several lab cylinders containing 10 g of fine earth from the studied plot and 1 L of water, after dispersing were maintained in our lab for 90 days. Cylinders with distilled water were still turbid, while in the cylinders with tap water (EC = 0.37 dS m⁻¹) and with water containing 10 g of dissolved NaCl water was transparent in < 20

445 hours. In the field, only after complete desiccation by evaporation the abraded material produces a new millimeter-scale sediment layer (Fig. 11C). In this way, successive episodes of ponding followed by desiccation generate a varved material. This present-day process producing fine lamination very probably represents the genetic model through which the abovementioned *hojaldre* sediments formed earlier
450 during the Holocene. The clayey layers are often convoluted, i.e., they form “clayey shavings” (Fig. 11D), that may be preserved as new sediment is deposited on them following episodes of rain. The features illustrated by the photographs in Fig. 11 are in agreement with the chemical characteristics of the soil in the study plot, as well as its hydric behavior, resulting in harsh conditions for plant life.

455 The consolidated knowledge on soil sodicity applied to agriculture has been associated to soils where the displacement of Na^+ from the exchange complex allows clay flocculation and, in consequence, the soil structure and porosity become more favorable for plant life. However, we show that this approach is insufficient to understand the behavior of the sodic soils of Flumen irrigation district where neither
460 the abundance of calcium carbonate nor the addition of gypsum succeeded in changing the soil behavior, it remaining unfavorable for agriculture.

The paddies show that flood water remains turbid for months, hampering photosynthesis by the submerged rice seedlings and causing them to die. Many plantlets cannot develop roots; others cannot secure themselves to the paddy bed
465 because of its loose paste-like consistency. Often the plantlets accumulate on the leeward side of the plot due to the dominant wind, resulting in an irregular cover of adult rice plants with reduced grain production that can make harvesting unprofitable.

A noticeable and non-minor problem involves the instability of the berms and ditches. Piping frequently develops, related to the lack of cohesion of *hojaldre*
470 sediments when moist, e.g., under sprinkler irrigation (Fig. 3A). This soil behavior is often perceived during sampling when the auger suddenly penetrates the sediment due to the dispersed state of the moist *hojaldre* material.

In the digital era, the visual study of soils is a powerful tool because observational pictures and their interpretations can be easily shared and discussed helping to fill the
475 gap between scientists and farmers or other people interested on soils.

3.6. *Puccinellia festuciformis*, a suitable plant

In many irrigated districts, such as the Flumen area, a common practice in reclaiming salt-affected soils for agriculture is the installation of plant cover to create soil porosity, accumulate OM, and avoid the capillary rise of the saline groundwater. One wild plant suitable for this purpose is *P. festuciformis*, shown in Fig. 12 benefiting from an irrigation pipe leak. In June 1986, this volunteer plant covered the experimental area watered in the summer of 1985, while all the stolons of Bermuda grass, var. Coastcross-1, died. Moreover, some farmers in nearby areas favor *P. festuciformis* for grazing sheep because the spring buds are palatable. Now, some sodic plots covered by volunteer *P. festuciformis* are annually plowed to earn subsidies for non-cultivation from the European Union.

4. Conclusions

The use of a battery of ceramic probes in the field for soil salinity monitoring allowed obtaining information on the salt-affected of the studied plot in agreement with comparable data gathered through soil sampling and analysis.

The salinity of studied soils was much lower than in other saline soils of the Ebro Valley, although the SAR and alkalinity were much higher. These chemical characteristics plus the silt and sodic clay varved structure of the parent material, the absence of gypsum, and the low EC of the irrigation water, converge in causing soil particle dispersion and substrate imperviousness that hamper plant life.

The classical agricultural approach to soil sodicity remediation is the displacement of Na^+ from the exchange complex to improve the soil structure. This approach does not work in the sodic soils studied. The integration of field observations (photographs) and lab analyses allowed the interpretation of the actual process that recurrently organizes the material into a multilayered structure, which is observable in the Holocene soil parent materials.

Leaching, caused by the annual high doses of fresh irrigation water needed for rice growing under the semiarid climate, succeeded in decreasing the degree of soil salinity, while the drop in alkalinity was less than one pH unit and the sodicity remained. Paddies developed on these kinds of soils present an extra problem for rice cultivation due to the dispersion of the sodic clays.

Research into saline-sodic soils was incipient when the field system in the study
510 area was established and not accessible to the designers of the irrigation district. This,
however, was not the case in the 1980s when sprinklers were first installed on a large
scale, with no prior study of the soils. One clear conclusion is that simple observations
by experts and a few analyses of the soils could have avoided the loss of investment.

515 **Acknowledgments**

This work was financed by the project PCIN-2014-106 funded by the Ministry of
Economy, Industry and Competitiveness of Spain through APCIN. We also acknowledge
the project Icoop-2016SU0015 granted by the Spanish National Research Council
520 (CSIC), and several previous Spanish Government projects.

References

Abrisqueta, C., Guillén, M.G., Fernández, M.G., Caro, M., 1962. Contribución al estudio
de la determinación de salinidad en suelos. *Anales de Edafología y Agrobiología*
525 21(7-12), 545-554.

Alberto, F., Machín, J., Aragüés, R., 1986. La problemática general de la salinidad en la
cuenca del Ebro. Pages 221-236 in Mariño (Ed.), *Sistema integrado del Ebro*. 728
pages + index. <http://hdl.handle.net/10261/112730>.

Aragüés, R., 1986. Métodos de medida de la salinidad del suelo. *Comunicaciones*
530 I.N.I.A., Ministerio de Agricultura, Madrid.

Artieda, O., Herrero, J., Drohan, P.J., 2006. A refinement of the differential water loss
method for gypsum determination in soils. *Soil Science Society of America Journal*
70(6), 1932-1935.

Ayers, A.D., Vázquez, A., de la Rubia, J., Blasco, F., Samplón, S., 1960. Saline and sodic
535 soils of Spain. *Soil Science* 90(2), 133-138.

Beltrán, F., 2006. An irrigation decree from Roman Spain: The 'Lex Rivi Hiberiensis'.
Journal of Roman Studies 96, 147-197.

Castañeda, C., Gracia, F.J., Rodríguez-Ochoa, R., Zarroca, M., Roqué, C., Linares, R.,
Desir, G., 2017. Origin and evolution of Sariñena Lake (central Ebro Basin): a
540 piping-based model. *Geomorphology* 290, 164-183.

- Chambers, J.M., Cleveland, W.S., Kleiner, B., Tukey, P.A., 1983. Graphical methods for data analysis. Chapman and Hall, New York.
- Chapman, R.W., 1978. The evidence for prehistoric water control in south-east Spain. *Journal of Arid Environments* 1, 261-274.
- 545 Faci, J.M., Martínez Cob, A., Cabezas, A., 1994. Agroclimatología de los regadíos del Bajo Gállego. Doce años de observaciones diarias en Montañana (Zaragoza). Departamento de Agricultura. Diputación General de Aragón. Zaragoza. 231págs.
- Galizzi, F.A., Peinemann, N., 1989. Soil surface salty crusts and water loss by evaporation. *Soil Science Society of America Journal* 53, 1605-1607.
- 550 García-González, M.T., Wierzechos, J., Vizcayno, C., Rodríguez-Ochoa, R., 1996. Fine-grained laminated Quaternary sediments in the Ebro Valley (Spain): Characteristics and formation. *Clay Minerals* 31(2), 173-181.
- Grossmann, J., Udluft, P., 1991. The extraction of soil-water by the suction-cup method - a review. *Journal of Soil Science* 42, 83-93.
- 555 Heanes, D.L., 1984. Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotometric procedure. *Communications in Soil Science & Plant Analysis* 15, 1191-1213.
- Hernández-Bastida, J., Faz-Cano, A., Marín-Sanleandro, P., Vela de Oro, N., Ortiz-Silla, R., 2002. Salt affected fluvisols in the Guadalentín Valley, Spain. In: J.L. Rubio, R.P.C. Morgan, S. Asins, V. Andreu (Eds.), *Proceedings of the 3rd International Congress Man and Soil at the Third Millennium*. Geoforma Ediciones, Logroño, Spain, pp. 1573-1584.
- 560 Herrero, J., 2008. Salinidad edáfica en varios salobres de Aragón. *Memorias de la Real Sociedad Española de Historia Natural*. Tomo IV. Madrid, 164 pp. ISSN: 1132-0869. <http://hdl.handle.net/10261/61398>
- 565 Herrero, J., Castañeda, C., 2013. Changes in soil salinity in the habitats of five halophytes after 20 years. *Catena* 109, 58-71.
- Herrero, J., Castañeda, C., 2015. Temporal changes in soil salinity at four saline wetlands in NE Spain. *Catena* 133, 145-156.
- 570 Herrero, J., Hudnall, W.H., 2014. Measurement of soil salinity using electromagnetic induction in a paddy with a densic pan and shallow water table. *Paddy and Water Environment* 12(1), 263-274.

- Herrero, J., Pérez-Coveta, O., 2005. Soil salinity changes over 24 years in a Mediterranean irrigated district. *Geoderma* 125(3-4), 287-308.
- 575 Herrero, J., Snyder, R.L., 1997. Aridity and irrigation in Aragon, Spain. *Journal of Arid Environments* 35, 535-547.
- Herrero, J., Rodríguez-Ochoa, R., Porta, J., 1989. Colmatación de drenes en suelos afectados por salinidad. Institución Fernando el Católico. Zaragoza, 134 pp.
ifc.dpz.es/recursos/publicaciones/15/82/_ebook.pdf
- 580 Herrero, J., Artieda, O., Weindorf, D.C., 2016. Soil Gypsum Determination. *Methods of Soil Analysis*. Vol. 1. Soil Science Society of America. Madison, WI. DOI: 10.2136/methods-soil.2016.0037.
- Herrero, J., Weindorf, D.C., Castañeda, C., 2015. Two fixed ratio dilutions for soil salinity monitoring in hypersaline wetlands. *PLoS ONE* 10(5), e0126493.
- 585 Hettmansperger, T., Sheather, S.J., 1986. Confidence intervals based on interpolated order statistics. *Statistics & Probability Letters* 4, 75–79.
- IRYDA, 1975a. Estudio de suelos de la 1ª y 2ª partes de la zona regable de Flumen (Huesca). Instituto Nacional de Reforma y Desarrollo Agrario. Ministerio de Agricultura. Inypsa, Madrid.
- 590 IRYDA, 1975b. Estudio de suelos del 2º y 3er tramo de la zona regable de los Monegros (Huesca). Instituto Nacional de Reforma y Desarrollo Agrario. Ministerio de Agricultura. Intecsa, Madrid. 2 tomos.
- Lecina, S., Isidoro, D., Playán, E., Aragüés, R., 2010. Irrigation modernization and water conservation in Spain: The case of Riegos del Alto Aragón. *Agricultural Water Management* 97, 1663-1675.
- 595 López-Bruna, D., Aragüés, R., 1995. Estabilidad estructural de cinco suelos de Monegros II regados con un simulador de lluvia: efecto de la calidad del agua y del acolchado. *Investigación Agraria. Producción y Protección Vegetales* 10(3), 441-462.
- 600 Martínez-Beltrán J., 1978. Drainage and reclamation of salt-affected soils. Bardenas area, Spain. Publication 24. International Institute for Land Reclamation and Improvement/ILRI, Wageningen, Netherlands, 322 pp.

- Martínez-Cob, A., Faci, J.M., Bercero, A., 1998. Evapotranspiración y necesidades de riego de los principales cultivos en las comarcas de Aragón. 223 págs. Institución Fernando el Católico. Zaragoza.
- Mora, J.L., Herrero, J., Weindorf, D.C., 2017. Multivariate analysis of soil salination-desalination in a semi-arid irrigated district of Spain. *Geoderma* 291, 1-10.
- Murphy, B.W., Crawford, M.H., Duncan, D.A., McKenzie, D.C., Koen, T.B., 2013. The use of visual soil assessment schemes to evaluate surface structure in a soil monitoring program. *Soil & Tillage Research* 127, 3-12.
- Nogués, J., Robinson, D.A., Herrero, J., 2006. Incorporating electromagnetic induction methods into regional soil salinity survey of irrigation districts. *Soil Science Society of America Journal* 70, 2075-2085.
- Peng, Y.H., Zhu, Y.F., Mao, Y.Q., Wang, S.M, Su, W.A., Tang, Z.C., 2004. Alkali grass resists salt stress through high $[K^+]$ and an endodermis barrier to Na^+ . *Journal of Experimental Botany* 55(398), 939-949.
- Playán, E., Pérez-Coveta, O., Martínez-Cob, A., Herrero, J., García-Navarro, P., Latorre, B., Brufau, P., Garcés, J., 2008. Overland water and salt flows in a set of rice paddies. *Agricultural Water Management* 95(6), 645-658.
- Porta, J., Rodríguez-Ochoa, R. García-González, M.T., Vizcayno, M.C., 1992. Material originario laminado de suelos afectados por sales en el valle del Ebro: Implicaciones tecnológicas y de uso. Pages 305-310, in: III Congreso Nacional de la Ciencia del Suelo. Pamplona, España. <http://hdl.handle.net/10261/65815>
- Qadir, M., Noble, A.D., Schubert, S., Thomas, R.J., Arslan, A., 2006. Sodicty-induced land degradation and its sustainable management: problems and prospects. *Land Degradation and Development* 17, 661-676.
- Qadir, M., Quillérrou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R.J., Drechsel, P., Noble, A.D., 2014. Economics of salt-induced land degradation and restoration. *Natural Resources Forum* 38, 282-295.
- Rodríguez-Ochoa, R., Herrero, J., Porta, J., 1990. Micromorphological assessment of drain siltation risk indexes in a saline sodic soil in Monegros irrigation district (Spain). In: L.A. Douglas (Ed.), *Soil Micromorphology: A basic and applied science. Developments in Soil Science* 19, 41-52. Elsevier. Amsterdam.

- Rodríguez-Ochoa, R., Olarieta, J.R., Castañeda, C., 2012. Micromorphology of salt
635 accumulations in soils of north Monegros, Spain: optical microscopy and SEM.
Proceedings of the 14th International Working Meeting on Soil Micromorphology.
Lleida, Spain. <http://hdl.handle.net/10261/91794>.
- Rodríguez-Ochoa, R., Usón, A., Olarieta, J.R., Herrero, J., Porta, J., 1998. Irrigation from
the sixties: Flumen-Monegros. pages 3.3: 1-51. In: J. Boixadera, R.M. Poch, C.
640 Herrero (Eds.), Soil information for sustainable development. Guidebook for field
trip B8. 16th World Congress of Soil Science. International Union of Soil Sciences.
<http://hdl.handle.net/10261/130156>
- Sanz, A., García-González, M.T., Vizcayno, C., Rodríguez-Ochoa, R., 1996. Iron-
manganese nodules in a semi-arid environment. Australian Journal of Soil
645 Research 34(5), 623-634.
- Soil Survey Division Staff, 1993. Soil Survey Manual. Natural Resources Conservation
Service, Handbook 18. USDA. Washington, DC.
- Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA, Natural Resources
Conservation Service. Washington, DC.
- 650 Sumner, M.E., Rengasamy, P., Naidu, R., 1998. Sodic soils: a reappraisal. In M.E.
Sumner and R. Naidu (Eds.), Sodic soils: distribution, properties, management, and
environmental consequences. Oxford University Press, New York, pp 3-17.
- Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley, Mass.
- United States Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and
655 alkali soils. Agriculture Handbook No. 60. USDA (Reprinted 1969).
- Vizcayno, C., García-González, M.T., Gutiérrez, M., Rodríguez-Ochoa, R., 1995.
Mineralogical, chemical and morphological features of salt accumulations in the
Flumen-Monegros district, NE Spain. Geoderma 68, 193-210.