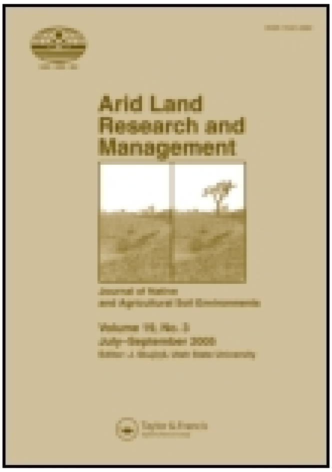

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A Soil Toposequence Characterization in the Irrigable Lands - Protected Area Contact Zone of El Basal, NE-Spain

David Badía [a] , Clara Martí [a] & Rosa M. Poch [b]
[a] High Technical School of Agrarian Engineering and Environmental Sciences , University of Zaragoza , Spain
[b] Department of Environment and Soil Sciences , University of Lleida , Spain
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David Badía[1], Clara Martí[1], and Rosa M. Poch[2]

[1]High Technical School of Agrarian Engineering and Environmental Sciences, University of Zaragoza, Spain
[2]Department of Environment and Soil Sciences, University of Lleida, Spain

The Central Ebro Valley, one of the most arid regions of Europe, has one of the longest histories of continuous and sustainable irrigation within Europe. Despite this sustainable outcome, the further expansion of irrigation into areas that have less favorable soil conditions produces unfavorable results and environmental problems. A representative soil toposequence of currently rainfed agricultural land, located very close to El Basal protected area, has been characterized in order to get information on the soils and to assess their capacity to be irrigated. The studied toposequence comprises three different landforms, a structural platform, a depression, and a step which links them; in these landforms soil profiles were described, analyzed, and classified using standard methodologies.

The soil properties and their stages of pedogenic evolution are closely related to their topographic position. Petric Calcisols on the structural platform and Leptic Regosols on the step, both with very shallow rooting depth, give way to a series of salt-affected soils in the depression, such as Hypersalic Solonchak or Salic Solonetz. These severely salt-affected soils, which are included in irrigation plans, have the severe potential to limit agricultural management and plant production; moreover, their proximity to the protected area of El Basal, which includes a saline wetland, is inadvisable due to the probable changes in water and nutrient cycles. For these reasons, a buffer zone around the protected area is proposed. Moreover, the soil toposequence shows a great pedodiversity that should be considered as adding value to the recognized biodiversity of El Basal area.

Keywords pedodiversity, irrigation, salinity, sodicity, soil, Spain, wetland

Irrigation to guarantee agricultural production has become essential in Spain, especially in the Central Ebro Basin, as it is the most arid inland region of Europe (Herrero & Snyder, 1997; Aquastat-FAO, 2010). To successfully transform arid rainfed lands into irrigated areas, knowledge of the soils is needed to carefully

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Address correspondence to David Badía, Escuela Politécnica Superior, Universidad de Zaragoza, Crta. Cuarte s/n 22071, Huesca, Spain. E-mail: badia@unizar.es

manage the water and to avoid soil and environmental degradation. This is especially true when the irrigable lands are surrounded by seasonally-flooded saline basins, which are of scientific and ecological importance in the European Natura 2000 Network (Castañeda & Herrero, 2008b). One of the longest histories of continuous and sustainable irrigation within Europe has occurred with soils developed on fluvial terraces, mainly Fluvisols and Calcisols. However, not all dry-land areas in the Ebro Valley have been transformed successfully with irrigation. Some problems have arisen, in particular, where there has been a lack of detailed information on soils and their hydrological behavior (Herrero et al., 1989; Porta & Rodríguez, 1991; Castañeda & Herrero, 2008a).

This is the case for El Basal de Ballobar, a protected saline wetland in the Bajo Cinca region (Pedrocchi, 1998; Badía, 2009a;), which is bordered to the north by dry-land areas anticipated to be irrigated in the future (Monegros V District). The protection of this saline wetland is related to its biodiversity, but we have no recorded knowledge about pedodiversity. Moreover, the limits between the future irrigated area and the protected area do not take into consideration soil properties. For these reasons, the objectives of the present work are to: (1) characterize and classify soils developed along a selected toposequence alongside the protected area of El Basal; and (2) establish relationships between the landscape soils' position, their morphological, physical, and chemical properties, and to anticipate the management practices when the area is irrigated.

Study Area

The study area is located in the Central Ebro Basin, Spain (Figure 1) where annual rainfall is scarce and very irregular, ranging from less than 200 mm to more than 550 mm, with an average of 350 mm per year. The mean annual temperature is 15.2°C, and the mean annual reference evapo-transpiration (by the Hargreaves method) is 1240 mm (Badía, 2009b). Additionally, there is relatively high windiness, which increases the water deficit, one of the highest in Europe (Herrero & Snyder,

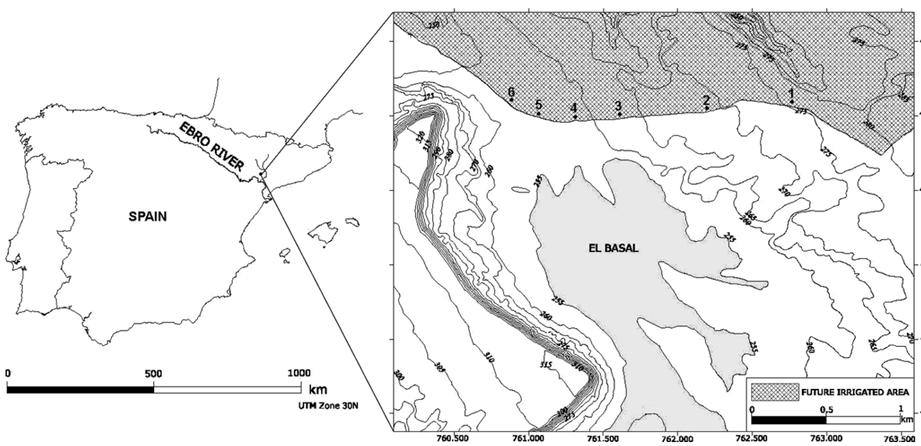


Figure 1. Location of the soil toposequence, in the contact zone between the future irrigated area (weave) and El Basal protected zone with the seasonally flooded basin (in gray).

1997). With these weather conditions, the soil temperature regime (SSS, 2010) is thermic, and the soil moisture regime ranges between aridic and xeric, depending on the specific soil properties (Jarauta, 1989).

Geologically, the Ebro Basin is one of the largest Tertiary basins in the Iberian Peninsula. The central part of the Ebro basin consists of carbonate sediments formed in lacustrine systems during the Oligocene and Miocene epochs (Arenas & Pardo, 1999). Specifically, in the studied area of El Basal, subhorizontal structural platforms have developed on thin layers of limestone alternated with grey, ochre, and reddish marl (some of it saline) from the Aquitanian age (Galocha-Ontiñena Tecto-Sedimentary Unit; Lower Miocene, 20–23 Millions of years). The limestone is mainly composed of biomicrite with small amounts of quartz and clays, while the marl is a mixture of micrite and clays (illites with occasional chlorites and smectites) with small amounts of quartz and feldspars (ITGE, 1998). Thin Holocene deposits have accumulated at the bottom of these layers. These deposits are made of fine detrital sediments, yellowish pale brown, eroded, and transported from the surrounding slopes where there are marl and limestone outcrops.

The soil toposequence studied here is located in rainfed agricultural land close to the protected area of El Basal (U.T.M. 31T BF 4612400/0261000). El Basal forms part of the Natura 2000 Network of Aragon (Spain) as a Zone of Special Protection for Birds and as a Place of European Natural Interest (Badía, 2009a). It consists of a basin, only seasonally flooded during wet years, located at around an elevation of 250 meters above sea level, and surrounded by a subhorizontal structural platform located at 275 meters above sea level.

Although more than a hundred isolated saline wetlands located in depressions were inventoried in the region (Castañeda & Herrero, 2008b), El Basal has many differences from the others: it is located the furthest east, on carbonate rather than evaporite lithofacies; and when it occasionally floods, the water salinity is lower compared with the other wetlands. On the other hand, water inputs to the wetland can be by water runoff or by groundwater, supply systems of unknown importance.

The seasonal dry-wet cycles of these saline wetlands are of particular interest for their biodiversity and for their endemic organisms that have adapted to the extreme fluctuations of water level and chemistry (Pedrocchi, 1998). If the land is undisturbed, these endemic plants, which are poorly represented in inland Europe, appear in concentric fringes according to water and nitrogen availability and salinity tolerance. The traditional agricultural fields form an irregular mosaic adapted to the relief, and native plants have found a refuge on the borders of fields and roads; xerophytic shrubs (*Rosmarinus officinalis* L., *Thymus vulgaris* L.) exist on the platform, nitrohalophilous plants (*Artemisia herba-alba* Asso, *Salsola vermiculata* L.) are found at the borders of the depression, and halophilous plants (*Suaeda vera* Forsk. ex J.F. Gmelin in L., *Atriplex halimus* L., *Aizoon hispanicum* L.) are found in the lowest parts of the depression. The agricultural fields recently have become square-shaped due to land consolidation in anticipation of the transformation to irrigation; this change has reduced the presence of native plants.

Materials and Methods

The soil toposequence comprises a transect 2 km long from the platform, at the East, to the depression at the West, with a drop of 20 meters. From an extensive series of observations, six representative soil profiles were selected and sampled

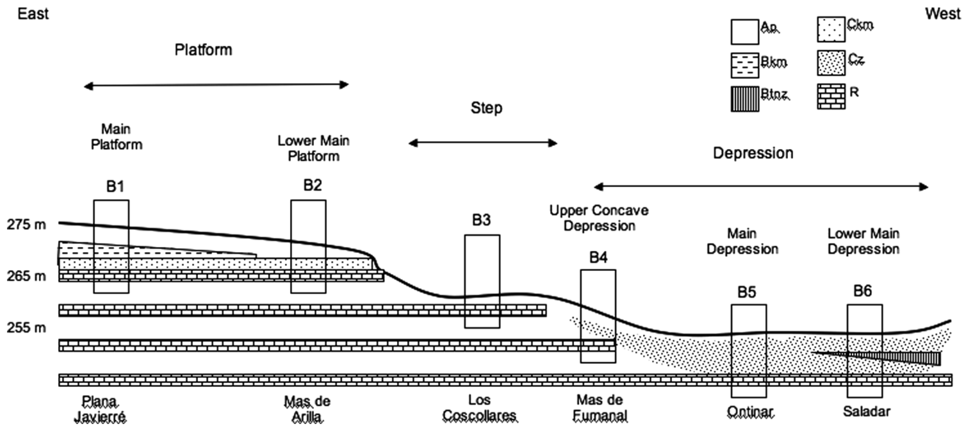


Figure 2. Soil profile locations in different geomorphic units in El Basal.

in three different geomorphic units along a toposequence. These units include a subhorizontal structural platform, a step, and a depression (Figure 2).

Profiles were described (FAO, 2006) and soil samples were collected for physical and chemical analyses, conducted according to standard methods. All the samples were air-dried and screened to 2 mm, and the percentages of gravels (>2 mm) and fine earth (<2 mm) were determined. The laboratory analysis was made using the fine-earth fraction. Air-dried samples of the soils were gently sieved to separate 1–2 mm macro-aggregates. Stability of these aggregates was assayed by wet-sieving with the single sieve method (Kemper & Koch, 1966). The particle size distribution was determined using the pipette method, after the removal of organic matter using H_2O_2 and with Na-hexametaphosphate used as a dispersing agent (Gee & Bauder, 1986). The water availability at a permanent wilting point (−1500 kPa) and at field capacity (−33 kPa) was measured using a volumetric pressure plate extractor (Richards, 1947). The water holding capacity (WHC, as mm/profile) was calculated as the difference of water retention between field capacity and permanent wilting point (USDA, 1980), by means of the equation:

$$\mathrm{WHC} = \sum_{i=1}^{n} \lfloor (\mathrm{FC} - \mathrm{PWP})_{\mathrm{i}} \times (1 - \mathrm{G})_{\mathrm{i}} \times \mathrm{Bd}_{\mathrm{i}} \times \mathrm{T}_{\mathrm{i}} \rfloor$$

where:

WHC = Water Holding Capacity (L/m^2 = mm) per profile;
FC = Field Capacity; water retention to 33 kPa (L/100 kg of soil);
PWP = Permanent Wilting Point; water retention to 1500 kPa (L/100 kg of soil);
G = Gravels (Kg gravels/100 Kg soil);
Bd = Bulk density (kg/m^3), estimated from textural class (Saña et al. 1996);
T = Thickness of the horizon (meters); and
i = Horizon, to petrocalcic horizon or lithic contact.

Soil pH was determined potentiometrically in a 1:2.5 ratio in H_2O (McLean, 1982). Total carbonate content was measured volumetrically (with a calcimeter) after treating with 6N hydrochloric acid (Nelson, 1982). Total soil organic C was determined by the method of wet oxidation (Nelson & Sommers, 1982); organic matter was estimated using the van Bemmelen factor (1.724). The cation exchange capacity (CEC) was determined by NH_4^+ retention after leaching with a solution (pH 7) of 1N NH_4OAc (Rhoades, 1982a).

Soil salinity was evaluated measuring the electrolytic conductivity (ECe) of the saturation paste extract at 25°C, from which also soluble ions were measured (Rhoades, 1982b). Mineral N (N-NO_3 and N-NH_4), from this extract (mmol L^{-1}), was obtained for each horizon and also for each profile, as a weighted average of their horizons (as kg N ha^{-1}). Soil sodicity was measured as the sodium adsorption ratio (SAR), the soluble Na^+ concentration relative to the soluble divalent cation concentration in a soil solution of the saturation paste extract, according the US Salinity Laboratory Staff (1954). SAR were initially calculated individually for each horizon and finally for the whole profile, taking into account its thickness (cm) to a R-layer:

$$SAR_{profile} = \frac{\left[\sum_{i=1}^{n} (SAR \times \text{horizon thickness})\right]}{\text{Profile thickness}}$$

Regressions and correlations between the measured parameters were obtained ($P < 0.05$ and $P < 0.01$) using the SPSS package.

The soils were classified according the World Reference Base (WRB) system (IUSS Working group WRB, 2007) and the USDA Soil Taxonomy system (Soil Survey Staff, 2010).

Soil thin sections of selected horizons were prepared using standard techniques (Benyarku & Stoops, 2005). Their micromorphological study was done according to Stoops (2003) using a polarizing microscope.

Results and Discussion

Morphological and Physical Properties

The surface horizons of the soils that developed on the structural platform and the step over limestone have a brown color (7.5YR 5/4, in dry); conversely, the soils that developed on the depression have a light yellowish brown color (10YR 6/4, in dry). Soil redness is due to an increase of hematites, which is considered an index of soil age (Badía et al., 2009). Some profiles have a very shallow rooting depth (<35 cm depth), either due to the development of a petrocalcic horizon (Bkm and/or Ckm) on the platform, or due to the presence of a lithic contact (R layer) in the step geomorphic unit. In the depression, the rooting depth is slightly deeper (60 to 80 cm depth) than it is in the other geomorphic units.

The soil structure types are crumbly and fine on the surface soil horizons of both the platform and step geomorphic units. However, in the bottom of the depression, the soil structure in the surface horizons is mainly platy and slightly hard, and a surface crust, covered with salts, appears frequently. Below the surface, peds morphology changes from strongly prismatic forms to weakly developed coarse subangular blocky or structureless horizons. Under dry conditions, cracks can produce a mixing of the surface horizon, in a kind of pedoturbation, called churning (Table 1).

Table 1. Morphological properties of the soil profiles

Geoform	Profile	Horizon	Depth (cm)	Color (dry)	Color (wet)	Structure (grade, kind)*	Dry consistence**	Pedofeatures
Main platform	B1	Ap1	15	7.5YR 5/4	7.5YR 4/3	m, CR	SO	
		Ap2	30	7.5YR 5/4	7.5YR 4/4	m, CR	SHA	
		Bkm	60			MA	EHA	Cemented carbonates
		Ckm	90			MA	EHA	Cemented carbonates
		R	160			RS	–	
Lower Main Platform	B2	Ap1	10	7.5YR 5/4	7.5YR 4/3	m, CR	SO	
		Ap2	30	7.5YR 5/4	7.5YR 4/4	m, SB	SHA	
		Ckm	60			MA	EHA	
		R	150			RS	–	Cemented carbonates
Step	B3	Ap	30	7.5YR 6/4	7.5YR 4/4	m, CR	SHA	
		C	35	7.5YR 7/3	7.5YR 5/4	MA	HA	
		R	50			RS	–	
Upper Concave Depression	B4	Ap1	10	10YR 6/4	10YR 4/3	w, SB	SHA	Thin salt cover in Ap
		Ap2	40	10YR 6/3	10YR 4/4	w, SB	HA	
		C	60	10YR 7/4	10YR 5/4	MA	HA	
		R	80			RS	–	

Main Depression	B5	Apz1	15	10YR 6/6	10YR 5/4	m, PL	SHA	Surface crust: thin and slightly hard
		Apz2	35	10YR 6/4	10YR 5/4	w, SB	HA	Thin salt cover in Ap
		Cz	75	10YR 6/4	10YR 5/4	w, SB	HA	
		R	90			RS	–	
Lower Main Depression	B6	Ahz	26	10YR 6/4	10YR 5/3,5	m, PL	HA	Surface crust: thick and hard
		Btnz	50	5YR 6/6	5YR 5/6	s, PR	VHA	Surface cracks: fine and deep
		Cyz	80	10YR 7/4	10YR 5/4	MA	HA	Thin salt cover in Ah (puffy)
		R	120			RS	–	Clayskins, slickensides in A and B

*Structure grade: W = weak; m = medium; s = strong. Structure kind: CR = crumbly; SB = subangular blocky; AB = angular blocky; PL = platy; PR = prismatic; MA = massive; RS = Rock structure.

**Dry consistence: LO = loose or non-coherent; SO = soft; SHA = slightly hard; HA = hard; VHA = very hard; EHA = extremely hard.

The soil aggregate stability (SAS) is moderate (about 30%) in the surface soil horizons of the platform and step geomorphic units, but it is drastically reduced (SAS <10%) in the soils of the depression (Table 2). The aggregation is positively and significantly correlated with the organic matter content ($R = 0.91$; $p < 0.01$), and negatively correlated with the sodium adsorption rate ($R = -0.88$; $p < 0.01$), fine silt particles ($r = -0.64$; $p < 0.01$), and clays ($r = -0.56$; $p < 0.05$).

The texture class is loam on the horizons of the platform and step, but in the depression it is silty loam or silty clay loam. Within each profile, the texture is quite similar, with the exception of the soil profile in the lower depression unit where a clay translocation under saline-sodic conditions occurs.

The plant available water holding capacity is low in the soils that developed on the platform and step (<40 mm/profile), due to their thinness and high stoniness. The soils of the depression have an increased water holding capacity (to 170 mm/profile), but because of their platy structure, low soil aggregate stability, and high sodium levels, their permeability will be low. With these properties, if the soils on upper landform units are to be irrigated, the sprinkler or drop systems should supply small amounts of water at frequent intervals. However, in the soils of the depression unit, amendments and high leaching fractions with drainage systems should be provided.

Chemical Properties

Relative to their chemical properties (Table 3), all of the soil horizons have high pH values (from 8.0 to 8.5 in surface horizons) and high total calcium carbonate content (among 20 to 40% in surface horizons). Both of these parameters normally increase with depth; occasionally the pH values are around 9.0 in subsurface horizons of some of the depression soils, which can be related to the presence of sodium carbonate (Porta et al., 2003). There is normally no gypsum in the soil profiles, with the exception of the deepest horizon of the profile developed on the lower main depression (Cyz-horizon of profile B6). On the platform (profiles B1 and B2), thick and hard horizons of pedogenic calcium carbonate accumulation have developed. The organic matter content is low in the A horizons of the soils described on the platform (1.5 to 2.8%), and even lower in the depression unit (<1.2%).

Mineral soluble N occurs mainly in the NO_3^- form (from 1 to 10 mmol L^{-1}) being NH_4^+ 100-times less abundant (from 0.01 to 0.1 mmol L^{-1}), probably due to NH_3 volatilization, the major pathway of N loss in most calcareous sodic soils (Qadir et al., 2007). Mineral N has a maximum value in the soil profiles of the border of the main depression, where nitrohalophilous plants such as *Artemisia herba-alba* are dominant. Hyperhalophilous plants, such as *Suaeda vera,* substitute for these plants, in the lower main depression where mineral nitrogen decreases and chlorides increase.

The predominant ions of paste saturated soil extracts are sodium and chloride within the soils of the depression unit, while calcium and bicarbonates are the main ions in the soils of the platform (data not shown). We found a positive and significant correlation ($p < 0.01$) between ECe and the soluble ions of soil solution, especially chloride ($r = 0.99$). PO_4^{2-} soil content is found in low concentrations (from 0.02 to 0.1 m mol L^{-1}) and without differences between profiles. The soils of the depression can be classified as saline-sodic soils (US Salinity Laboratory Staff, 1954) according to the ECe and SAR values (Table 3) and as sodium dominated saline soils (Figure 3), according to ions ratio (ISSS, 1998).

Table 2. Physical properties of the soil profiles

Geoform	Ref. profile	Horizon	Depth (cm)	Gravels (%)	Texture class (USDA)	SAS (%)	FC (%)	PWP (%)	WHC (mm)
Main platform	B1	Ap1	15	17.5	Loam	34.7	24.0	12.3	16.6
		Ap2	30	28.0	Loam	31.5	24.7	12.6	19.4
Lower Main Platform	B2	Ap1	10	23.7	Loam	27.2	23.1	12.6	11.3
		Ap2	30	29.0	Loam	22.1	23.2	13.4	21.6
Step	B3	Ap	30	52.0	Loam	31.2	22.3	13.0	14.7
		C	35	81.0	Loam	17.6	28.8	13.7	1.7
Upper Concave Depression	B4	Ap1	10	3.8	Silty clay loam	8.2	24.5	12.2	13.1
		Ap2	40	1.1	Silty clay loam	8.1	23.3	13.6	34.6
		C	60	1.4	Silt loam	6.2	23.8	8.3	40.3
Main Depression	B5	Apz1	15	0.0	Silty-clay loam	1.8	29.4	12.0	28.7
		Apz2	35	0.0	Silt loam	3.9	25.4	7.2	43.7
		Cz	75	0.0	Silt loam	4.4	26.4	7.4	98.8
Lower Main Depression	B6	Ahz	26	0.0	Silt loam	9.3	26.1	9.7	46.9
		Btnz	50	0.0	Silty clay loam	2.2	25.1	10.9	40.9
		Cyz	80	17.0	Loam	2.6	20.6	10.3	33.3

SAS = Soil Aggregate Stability; FC = Field Capacity; PWP = Permanent Wilting Point; WHC = Water Holding Capacity.

Table 3. Chemical properties of the soil profiles

Geoform	Ref. profile	Horizon	Depth (cm)	pH H_2O (1:2.5)	OM (%)	CEC ($cmol_c$ kg^{-1})	$CaCO_3$ (%)	Gypsum (%)	ECe (dS m^{-1})	SAR (mmol $L^{-1})^{-0.5}$	NH_4^+ (mmol L^{-1})	NO_3^- (mmol L^{-1})
Main platform	B1	Ap1	15	8.2	2.80	16.5	24.8	0.0	0.80	0.59	0.02	3.03
		Ap2	30	8.3	2.71	16.1	26.2	0.0	0.68	0.57	0.02	2.00
		Bkm	60	8.8			82.5					
		Ckm	90	8.8			83.8					
Lower Main Platform	B2	Ap1	10	8.1	1.69	15.9	34.3	0.0	0.82	0.65	0.03	2.71
		Ap2	30	8.1	1.56	13.1	34.8	0.0	0.93	0.75	0.01	1.47
		Ckm	60	8.7			66.2					
Step	B3	Ap	30	8.5	1.55	13.6	40.4	0.0	0.69	0.91	0.02	1.90
		Ck	35	8.6	1.21	11.1	60.7	0.0	0.78	1.35	0.02	1.34
Upper Concave Depression	B4	Ap1	10	8.8	1.17	13.8	29.6	0.0	6.15	18.90	0.02	1.08
		Ap2	40	8.7	1.01	12.7	27.6	0.0	6.86	16.00	0.02	2.36
		C	60	8.9	0.57	12.0	41.4	0.0	5.68	17.80	0.01	1.71
Main Depression	B5	Apz1	15	8.0	0.77	12.6	21.3	0.0	40.00	18.50	0.18	11.60
		Apz2	35	8.2	0.72	10.6	30.7	0.0	23.20	15.50	0.03	8.20
		Cz	75	8.1	0.72	9.0	27.5	0.0	27.60	22.70	0.01	8.70
Lower Main Depression	B6	Ahz	26	8.1	1.09	12.3	26.0	0.0	35.60	29.80	0.09	1.59
		Btnz	50	8.8	0.41	15.2	31.9	0.0	16.10	38.30	0.10	1.90
		Cyz	80	8.3	0.11	9.7	10.6	29.5	22.60	27.80	0.01	1.78

OM = Organic Matter; CEC = Cation Exchange Capacity; ECe = Electrical Conductivity of the saturated paste extract; SAR = Sodium adsorption ratio.

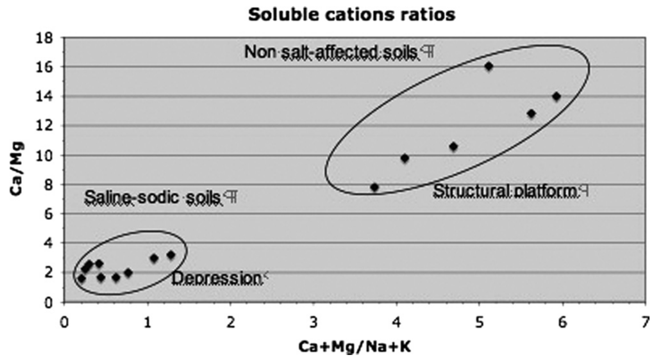


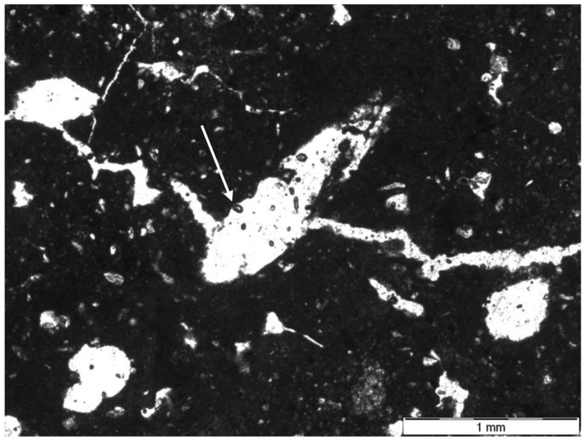
Figure 3. Soil classification based on soluble ions ratio.

Soil Forming Processes and Classification

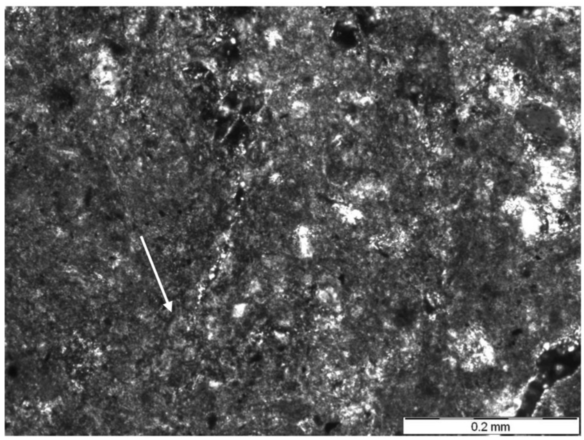
The main processes of formation in the soils of the platform are the accumulation of pedogenic carbonates in the subsurface horizons and a light rubefaction in surface horizons. The calcification process results in the development of diagnostic petrocalcic horizons on the platform; there is evidence that similar thick horizons have developed in neighboring zones from the Middle Pleistocene (Badía et al., 2009). On the other hand, the soils developed on the Holocene sediments of the depression show light colors, platy structure, a surface crust, and C content around 0.4%; consequently, these horizons are at the limit to be qualified as hyperochric. These soils have an accumulation of salts more soluble than gypsum and high exchangeable sodium, therefore developing salic and, more occasionally, natric horizons. Natric horizon formation can be related to the oscillation of the saline-sodic water table, as has been previously described in neighboring zones of the Flumen area (Margarit, 1991) and Baix Segre (Rosell et al., 1997). The rise of the saline groundwater saturates the soil profile with different ions (both soil solution and the adsorption ion complex), yet with a sustained hydraulic conductivity; the decrease of the water table level and moderate but repetitive rainfall leach the soluble ions from surface horizons but not the exchangeable sodium ions. The leaching effect must have been important as is shown by the presence of lenticular shaped voids after the dissolution of gypsum (Figure 4a). Saline solutions containing ions such as Na^+, Mg^{2+}, Cl^-, and NO_3^-, abundant in these soils, enhance the solubility of gypsum by both ionic strength effect and ionic association effect (Tanji, 1996). If the Ca^{2+} availability from weathered minerals (as gypsum and calcite) decreases, the clay (especially illite, with irregular surfaces) can be dispersed and illuviated. This fact is shown by the microlaminated clay coatings along voids and also by a predominance of vesicular voids showing structural instability in the leached natric horizon (Figure 4b).

Based on their morphogenetic processes and horizon properties, soil classification according to WRB (IUSS, 2007) and STS (SSS, 2010) is shown in Table 4.

Three of the Reference Soil Groups described in the toposequence (Calcisols, Solonchaks, and Solonetzes) can be found in very small areas in Europe, in combination covering less than 1% of the total surface area (Tóth et al., 2008); this emphasizes the soil diversity of El Basal protected area. The equivalences in Soil Taxonomy System (SSS, 2010), at great group level, are Petrocalcids, Torriorthents/Xerorthents, and Natrixeralfs, respectively.



(a)



(b)

Figure 4. Photomicrographs of the Btnz horizon of the Solonetz (B6 profile). The image length is indicated for each image. (a) Main void with a lenticular shape, pseudomorph after gypsum; the other voids are isolated vesicles (image with parallel polarized light). (b) Coating of microlaminated clay affected by argilliturbation, and fragments of clay coatings in the micritic groundmass (crossed polarized light).

Soil groups of WRB (IUSS, 2007) and the proposed equivalences at subgroup level of Soil Taxonomy System (STS) show evident differences in relation to the use of soil moisture regime and salinity/sodicity properties. STS takes into account soil moisture regime at Order level but no direct information is available in the region about that, therefore soil classification at the highest STS category is just based on modeling (Jarauta, 1989). On the other hand, the properties related to salinity/sodicity are not made evident at STS subgroup level.

Landscape, Soils, and Irrigation Management Considerations

The most limiting factors of soil toposequence are the low water holding capacity in the platform and step, and high soil salinity and sodicity in the depression. For these

Table 4. Soil forming processes, horizons and diagnostic properties and classification of the soils by WRB (IUSS 2007) and Soil Taxonomy System (SSS 2010)

Ref.	Geomorphic unit	Soil forming processes	Horizons and diagnostic properties	World reference base (IUSS 2007)	Soil taxonomy system (SSS 2010)
B1	Main Platform	Calcification	Ocric (SSS) Petrocalcic	Epipetric Calcisol	Xeric Petrocalcid
B2	Lower Main Platform	Calcification	Ocric (SSS) Petrocalcic	Epipetric Calcisol	Xeric Petrocalcid
B3	Step	–	Ocric (SSS) Lithic contact	Epileptic Regosol (calcaric, skeletic)	Lithic Torriorthent
B4	Upper Concave Depression	Salinization Sodification	Ocric (SSS) Salic	Endoleptic Regosol (calcaric, hiposalic, sodic)	Xeric Torriorthent (phase slightly saline, sodic)
B5	Main Depression	Hypersalinization Sodification	Ocric (SSS) Salic	Hipersalic Solonchak (sodic, cloridic)	Typic Xerorthent (phase strongly saline, sodic)
B6	Lower Main Depression	Hypersalinization Sodification Clay illuviation Gypsification	Ocric (SSS) Salic Natric Gypsic	Salic Gypsic Solonetz	Typic Natrixeralf (phase strongly saline, gypsic)

reasons, the soils have little (class III) or no (Class VI) capacity for being irrigated (USBR, 1953).

On the platforms and steps, irrigation would need to deliver small water volumes at frequent intervals, to decrease the dangers of water table rise and salt accumulation in the root zone. However, with the saline-sodic soils in the depression unit, chemical amendments and additional leaching fractions with drainage systems should be applied in order to improve soil conditions.

The presence of salts, with a high osmotic pressure in the soil solution and the toxicity of the occurring ions such as Na^+, reduces crop growth and leads to the appearance of specific salt-tolerant vegetation. The ion ratios can affect the availability of some nutrients, such as nitrogen. The Cl^-/NO_3^- ratio is less than 1 in the soils of the platform and step units but is over 180 in soils of the bottom part of the depression unit (Table 5). Because Cl^- and NO_3^- are competitive in the uptake process, there is a Cl^- -induced nitrogen deficiency (Grattan & Grieve, 1999).

Additionally, the K^+ uptake by plants can be markedly suppressed by Na^+ and even Ca^{2+} by Mg^{2+} (Badía & Meiri, 1994). The studied soils in the depression unit have a much higher Mg^{2+}/Ca^{2+} ratio and especially a higher Na^+/K^+ ratio in the soil solution, compared with soils in the platform and step units. Because the Mg^{2+}/Ca^{2+} ratio is below 1, it is not expected that there would be Mg^{2+}-induced Ca^{2+} deficiency in plants. However, with a Na^+/K^+ ratio higher than 10, the K^+ uptake by plants can be markedly suppressed (Tanji, 1996; Qadir et al., 2007).

In addition to direct plant effects, high amounts of sodium create structural problems in the physical processes of the soil (slaking, swelling, and dispersion of clay minerals) and its superficial conditions (surface crusting and sodification). The soil aggregate stability decreases as SAR increases due to the dispersion of clays, mainly illite (mica), which is the most likely to be dispersed. These deleterious effects of sodicity on the structural stability of soils have been widely documented in the literature (Shainberg & Letey, 1984). These affect water and air movement, plant available water holding capacity, root penetration, seedling emergence, runoff erosion, and tillage and sowing operations (Qadir et al., 2007). The main factor determining the extent of the adverse effects of Na^+ on the soil properties is the ambient electrolyte concentration in the soil solution, with low concentrations exacerbating the deleterious effects of exchangeable Na^+ (Amézketa & Aragués, 1995). The soils of the depression have high sodicity ($ESP > 15$; $SAR > 13$) but the scarce content of soluble HCO_3^- (and nil of $CO_3^=$), combined with a $C_{Na}/(C_{Cl} + C_{SO_4}))$ ratio lower than 1, currently sustain a relative control on soil swelling and dispersion.

The new agricultural district will be irrigated with low-salinity water (0.5 dS m^{-1}) from a system of large dumps and canals coming from the Pyrenees Mountains. If this water is applied to saline-sodic soils, clay deflocculation will increase and the soil porosity will diminish; thus, its reclamation will be not economically feasible. The soil structure could be partially recovered by an adequate management of organic matter (Badía, 2000), and especially by increasing the electrolyte concentration up to a threshold concentration or flocculation value, where clay flocculates with chemical amendments such as gypsum (Amézketa & Aragués, 1995). The gypsum requirement can be determined considering the initial exchangeable sodium content of the soil (from 20 to 35% in the depression unit), the level to which it has to be reduced (i.e., 10%) and the quality of irrigation water. The quantity of gypsum also depends upon the depth of the soil to which it has to be applied (i.e., 10 cm depth), its bulk

Table 5. Salinity (ECe), ion ratios, sodicity (SAR), mineral nitrogen, and Water Holding Capacity (WHC) of every profile, as a weighted average of their own horizons

	Geoform unit					
	Main platform	Lower main platform	Step	Upper concave depression	Main depression	Lower main depression
Parameter/Profile	B1	B2	B3	B4	B5	B6
ECe (dS m^{-1})	0.74	0.89	0.70	6.35	28.9	24.90
Cl^-/NO_3^- ratio	0.36	0.77	0.21	15.80	30.7	180.80
Na^+/K^+ ratio	41.10	22.00	40.30	730.10	2100.0	2654.00
SAR $(mmol\,L^{-1})^{-0.5}$	0.58	0.71	0.97	17.10	22.6	31.60
$\sum$ mineral N (kg ha^{-1})	44.30	36.00	22.90	118.00	669.8	166.80
$\sum$ WHC (mm $profile^{-1}$)	35.90	33.00	16.50	82.00	171.2	121.10

ECe = Electrical Conductivity of the saturated paste extract; SAR = Sodium adsorption ratio; WHC = Water holding capacity.

density (1.10 g cm^{-3}) and gypsum richness (i.e., 90% for 2–5 mm particle size). Taking into account these factors, the gypsum requirement for the studied saline-sodic soils ranged from 2200 to 4100 kg ha^{-1}. Subsequently, drainage will be necessary to prevent rising water tables and to allow for the leaching of salts. The drainage water, with a high content of salts, should be exported from the irrigated area without affecting the protected habitat located near the south of the irrigated area, just inside the depressed relief. Additional problems could arise if soils prone to instability were to cause subsidence in open ditches or clogging of pipe drains (Herrero et al., 1989).

After the start of irrigation, the type and the degree of changes to be expected in the saline wetland close to these soils are unknown. For now, new roads created by land consolidation have been constructed, and these roads are intercepting and reducing runoff entry to the saline wetland. The proximity of the newly irrigated areas will increase the risk of saline wetland flooding and eutrophication, changing the original conditions of the endorheic ecosystem. As examples of possible changes, previous similar land use changes have transformed the saline wetlands to sweet permanent wetlands, for example, at La Unilla de Candasnos, in Bajo Cinca (Badía, 2009a), or La Laguna de Sariñena, in Los Monegros (Pedrocchi, 1998).

Conclusions

In this arid zone, the soil profile development and its properties are strongly related to its topographic position, especially the soil salinity distribution under current rainfed conditions. The soils developed on the structural platform on limestone are non salt-affected soils with a loam textural class, moderate soil aggregate stability, and moderate organic matter content. They have high carbonate content with hard and massive pedogenic accumulations (petrocalcic horizon) at depth (Epipetric Calcisols), and high stoniness that reduces the rooting soil thickness and the plant available water holding capacity. The soil developed on the step has similar characteristics, but its thickness is reduced by a lithic contact (Epileptic Regosol) and not by a petrocalcic horizon. In contrast, soils developed in the depression have moderate water holding capacity, silty-loam textural class, very low aggregate stability and organic matter, and very high contents of both soluble salts and exchangeable sodium (Solonchak, Solonetz, etc.). Salt-affected soils in the depression unit (with osmotic and specific ionic effects and ionic imbalances on plant growth) and the low water holding capacity in the soils of the platform and the step, are limiting factors for agricultural use.

In conclusion, the studied soil toposequence shows a high pedodiversity in El Basal area but demonstrates that the main soils have a comparatively low interest from the agricultural point of view, as they require expensive amelioration through technical measures (such as gypsum amendments and drainage systems). To combine sustainable irrigation use with protection of the environment, these measures should be applied without affecting the nearby protected saline wetland, which would also not be easy. For these reasons, lands with marginal soils should be designated as a buffer zone around the currently protected area, thereby changing the agricultural grants to environmental grants for farmers. Land-use changes should be preceded by detailed soil studies to define accurately the limits between different uses, such as the irrigable and protected ones.

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