Soil composition and plant nutrients at the interface between crops and saline wetlands in arid environments in NE Spain

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Abstract

In arid and semiarid environments, saline wetlands are both high-value habitats threatened by landscape transformations, and a constraint to agricultural production. There is a lack of knowledge about nutrients distribution in intermittently flooded environments subjected to soil and water salinity. The aim of this work was to characterize soil and plant nutrient status along soil transects at the interface between agricultural land and saline wetlands. These aspects were studied in Guallar and Gallocanta, two Ramsar saline wetlands in NE Spain that represent arid and semiarid conditions, respectively. Soils were characterized for nitrogen (N) and phosphorous (P) status; crop and natural vegetation nutrient status was measured with P Nutrition Index (PNI) and Nitrogen Nutrition Index (NNI). Soil salinity (EC1:5) increases towards the halophyte areas, reaching 5.4 dS m⁻¹ in Guallar and 3.7 dS m⁻¹ in Gallocanta. On average, the soils are loams or sandy loams. Carbonate-rich soils are common (39% mean calcium carbonate equivalent) and some soils in Guallar have a high gypsum content (up to 72%). The soils have a low to moderate cation exchange capacity regardless of soil salinity, with a maximum of 14 cmol⁺ kg⁻¹ in the soil with the highest organic matter content (3.8%). Overall, cereal soils show total P and N contents within the normal range for agricultural soils, although the available P is above the requirements for cereals, up to 67 mg kg⁻¹. The difference in soil nutrients between cropped and halophyte land is more noticeable when it comes to total and available P content than for N levels. The relatively high nutrient content in some halophyte soils and the total

and available P gradients along the soil transects, reflect downslope nutrient movement towards the lake. Halophyte soils can accumulate between 11% and 71% of the available P found in cropped soils. No relationship was found between the soil nutrient content and that of plants, nor between these two parameters and soil salinity. NNI and PNI indicate non-limiting nutrient status for cereals grown in Gallocanta and nutrient limitation in Guallar, probably related to the high gypsum content, and/or soil salinity. Studying the plant available nutrient content in arid and saline soils, at the interface between halophytes and crops, is crucial for improving land management strategies and reconciling production and conservation in protected saline habitats.

Keywords: halophyte, soil salinity, nitrogen, phosphorous, Monegros Desert, Gallocanta Lake.

1. INTRODUCTION

Recognition of wetlands has increased, as has scientific interest in them. However, agricultural intensification and the historical misperception of wetlands have led to decades of loss and degradation (Ramsar Convention Secretariat, 2010). Inland wetlands of arid and semiarid regions, typically with no permanent standing water, have been especially affected (Williams, 2002), and agriculture is one of their most important threats. At the continental scale, Europe follows Africa in the number of inland intermittent saline wetlands included in the Ramsar list, and almost 38% of these are in Spain. Sustainable agriculture is required to preserve these unique habitats in agricultural landscapes. In this context, knowledge of soil and plant nutrient content is crucial for understanding the distribution of habitats around wetlands and designing adapted agri-environmental measures that reconcile production and habitats preservation.

Soil nutrients content has mainly been studied in croplands to predict the amount of nutrients needed to increase crop yield, particularly in soils with poor nutrient availability. Also, from the point of view of agricultural production, soil fertility has been investigated in wetlands, due to interest in rice cultivation (Seneviratne et al., 1994; Buri et al., 1999; Edem and Ndaeyo, 2009; Wang et al., 2011), and submerged soils (Sahrawat, 2015). The variability of the physical and chemical soil properties of interest in agriculture has been investigated under different crop management strategies (Álvarez-Solís et al., 2007) and different landscape positions (Scotney and Dijkhuis, 1990). At the interface between

wetlands and adjacent agricultural fields, the variability of soil properties has been studied in order to increase knowledge on wetland ecosystem functions (Stolt et al., 2001; Yoon et al., 2015). The effect of soil fertility on plant nutrient status is frequently investigated for cultivated agrosystems (Colomb et al., 2007; Guzys and Miseviciene, 2015) but less for ecosystems with natural vegetation such as wetlands or grasslands (Jouany et al., 2004), and rarely in saline wetlands environments.

Inland wetlands in agricultural landscapes usually comprise fringes of natural vegetation. Transitional areas, from crops to natural vegetation, are suitable for studying soil and plant nutrient content as these represent a continuum of habitats where nutrient exchange between aquatic and terrestrial environments takes place (Zhao et al., 2016). In this context, these fringes of natural vegetation usually reduce the flows and inputs of agrochemicals to the wetland (Vought et al., 1994; Silvan et al., 2004).

Wetlands in arid regions are characterized by intermittent flooding and, frequently, by soil salinity due to the scarce and irregular rainfall together with high levels of evapotranspiration. Moreover, the use of fertilizers to counteract poor soil conditions contributes to water with nutrient excesses flowing towards lower lying areas. This is common in saline wetlands, which receive irrigation flows of nutrient-enriched fresh water from upland areas (Díaz et al., 1998; Valero-Garcés et al., 2000).

There are few studies on soil and plant nutrient contents in arid environments where intensification of agriculture in marginal and poor lands is facing constraints due to soil composition and the occurrence of saline wetlands. The preservation of endangered habitats, endemic or rare halophytes adapted to these harsh conditions, requires an integrated study of both cultivated and natural environments.

Hence, studies of soil and plant nutrients, which have focused on the feasibility of cash crops, have to be extended to include the adjacent saline ecosystems. The aims of this study were i) to characterize the soil and plant nutrients status at the interface between agricultural land and saline wetlands, and to emphasize the importance of identifying the continuum between the two systems, and ii) to identify the impact of cropland on natural saline ecosystem functioning and, conversely, the impact of salinity on cropland ecosystem functioning. A better knowledge of the soil and plant nutrients dynamics is required for developing and improving management strategies in order to reconcile production and conservation in protected saline habitats.

85 2. MATERIAL AND METHODS

86 2.1. Ramsar Wetland sites

87 Two hypersaline Ramsar wetlands were selected in NE Spain, Gallocanta and Guallar (Figure 1). They
88 are protected under the EU Birds and Habitats Directives and play an important role in the regional
89 hydrology. These saline wetlands have been historically subject to agricultural intensification with
90 discharge of agrochemicals (application of fertilizers and return flows from adjacent irrigated areas),
91 and invasion of the halophyte fringe by land consolidation, waste and stone dumping and annual
92 plowing to obtain agricultural subsidies.

93 Gallocanta, with 14.4 km², is the largest saline lake in Western Europe. It is located 1000 m a.s.l. in
94 the Iberian Range (Figure 1) in a dry semiarid climate with a mean rainfall of 488 mm yr⁻¹ (1945-
95 2015), a mean annual temperature of 11.2 °C (1969-2015), and a mean hydric deficit of 605 mm yr⁻¹
96 (García-Vera and Martínez-Cob, 2004). The prevailing NW dry winds are very common, especially in
97 winter. Guallar, with 0.15 km², is located 336 m a.s.l. in the Monegros Desert (Figure 1). This is one
98 of the most arid regions in Europe, with a mean annual rainfall of 350 mm (1974 - 2014), a mean
99 annual temperature of 14.9 °C, and 1255 mm yr⁻¹ of mean reference evapotranspiration (Faci and
100 Martínez-Cob, 1991). All these factors contribute to the hydric deficit (mean = 867 mm yr⁻¹).

101 Water level fluctuations and intermittent desiccation constitute the most outstanding features of the
102 two saline wetlands. The maximum registered lake water depth was 2.84 m in Gallocanta, in 1974
103 (Pérez-Bujarrabal, 2014), and 0.26 m in Guallar, in 1997 (Castañeda, 2002). The action of wind and
104 water has promoted the formation of littoral landforms associated to the two lakes. In Gallocanta, the
105 southern sedimentary margin includes sandy barrier islands, lagoons and sublittoral bars (Castañeda et
106 al., 2015), and a gypsum-rich lunette has formed on the leeward margin of Guallar.

107 The natural vegetation (Figure 2) consists mostly of annual and perennial halophytes distributed in
108 concentric fringes around the bare saline lake floor, according to their soil salinity tolerance and
109 flooding (Gómez et al., 1983; Conesa et al., 2011). Some of the halophytes, such as *Puccinellia*
110 *pungens*, are protected species under the Habitats Directive and the Convention on the Conservation of
111 European Wildlife and Natural Habitats. Crops consists of winter cereals, mainly barley, soft wheat,

and durum wheat. In the Guallar area, agricultural practices include traditional cereal-fallow rotation (McAneney and Arrúe, 1993).

2.2. Weather data and related indices

Rainfall and temperature data were obtained from nearby weather stations Tornos and Valfarta, located in Gallocanta and Guallar areas, respectively. The accumulated rainfall and heat use efficiency (HUE) of the vegetation were computed to characterize the growing season, starting on October 1st for crops and on February 1st for halophytes (Fitter et al., 1995), up to the sampling date. The thermal time (TT) was calculated as the sum of the cumulative differences in temperature between the daily mean temperature and the base and optimum temperatures, and expressed in °C day. The base temperature was considered to be 10 °C for wheat (Girijesh et al., 2011) and 0 °C for halophytes, with an optimum temperature of 18°C for halophytes (Theau and Zerourou, 2008; Niqueux and Arnaud, 1967). HUE was calculated as the aboveground biomass produced per unit of TT, and expressed in kg ha⁻¹ °Cday⁻¹.

2.3 Sampling design

Soil and vegetation were sampled in each wetland, along transects extending from the edge of the wetland (excluding the water or the bare bottom) to the agricultural land (Figure 2). Sampling was undertaken during three field campaigns: April (9-16) 2013; May (25-29) 2014; and April (9-10) 2015. In Guallar (GLR), three sampling sites were located on the SE margin, along a 200 m transect with a mean slope of 1.4% (Figure 2A). GLR3 and GLR7 sampling sites corresponded to the halophyte fringe and contained *Suaeda vera*, *Sphenopus divaricatus*, and *Hymenolobus procumbens*. Site GLR6 was cropped with wheat (*Triticum aestivum*) in 2014, and left fallow in 2013 and 2015. Six sampling sites were established along a 1100 m transect, with a mean slope of 0.3%, on the southern margin of Gallocanta lake (GA) (Figure 2B). The halophyte fringe (sites GA19, GA20 and GA21) extended about 800 m from the lake edge and included plant communities with *Salicornia* sp., *Puccinellia* sp., and *Limonium* sp. (Figure 2B). Three cereal sites (GA31, GA32 and GA22) were sampled, two of them, GA31 and GA32, within the same agricultural plot but had different levels of cereal development. Wheat (*Triticum aestivum*) was

cultivated in 2013 and 2015, and barley (*Hordeum vulgare*) in 2014. Fertilizing cereals is not very common in Guallar, although NPK (8-15-15) fertilizer may be added in the spring. In Gallocanta, 160-200 kg ha⁻¹ of complete NPK (12-20-12) fertilizer is usually applied at sowing. About 160-200 kg ha⁻¹ of calcium ammonium nitrate (27g N kg⁻¹) is applied in the spring.

2.4. Sampling and characterization of plants and soils

At each site, the aerial part of the vegetation was collected within a 0.25 m² quadrat with a gauge frame. Vegetation samples were weighed before and after drying at 60 °C for 48 hours in order to measure the plant biomass production (t ha⁻¹), and then milled to a 1 mm particle size using an industrial grinder. Soils were sampled with a hand auger positioned at the frame center, for the 0-5 cm layer in natural vegetation and, 0-25 cm in the cropland; the 3 replicates were pooled in order to get a composite sample. Soil samples were air-dried and sieved to a grain size of 2 mm for subsequent chemical and particle size distribution analyses. Surface water was collected from the wetlands at the beginning of the study, in 2013. There was no vegetation at three sites in 2013 (GA20, GA21, and GLR6) and one site in 2014 (GA21) and 2015 (GLR6).

Plants nutrient concentrations were determined on dried and ground (0.5 mm) samples. Total P concentrations were obtained after wet digestion in H₂SO₄-H₂O₂, with ceruleomolybdic blue colorimetry (Murphy and Riley, 1962). Total N concentration was determined with a CN gas analyzer (LECO Corporation, St Joseph, Michigan, USA). Nitrogen nutrition Indices (NNI) were calculated as the ratio, expressed in per cent, of the measured N concentration of above-ground biomass to the critical N concentration (N critical,%), i.e. the minimal sward N concentration needed to produce maximum dry matter (DM), obtained from the critical curve given by Lemaire (1997):

$$NNI = \%N \text{ measured} / \%N \text{ critical} * 100; \text{ with } \%N \text{ critical} = 4.8\% (DM)^{-0.32} \quad (1)$$

Phosphorous nutrition index (PNI) was calculated according to Duru and Ducrocq (1997) as the ratio, expressed in per cent, of the measured P concentration of above-ground biomass to the critical P concentration (P% critical) obtained with the following relation:

$$PNI = (P\% \text{ measured} / P\% \text{ critical}) * 100; \text{ with } P\% \text{ critical} = 0.15 + 0.065 * N\% \text{ measured} \quad (2)$$

According to Lemaire (1997) for N and Duru and Ducrocq (1997) for P, an index of 80 corresponds to the critical value: a value < 80 indicates limiting nutrition for plant growth; an index value between 80 and 100 indicates that plants were in situation of non-limiting nutrient supply and a value > 100 indicates nutrient luxury consumption.

Soil salinity was measured with a conductivity cell (Orion 013605MD, cell constant: 0.55 cm^{-1}) and expressed as the electrical conductivity of the 1:5 soil:water extract (EC1:5) in dS m^{-1} at 25°C . To classify the soil salinity for agriculture (Nogués et al., 2006), the electrical conductivity value of the saturation extract (ECe) was estimated using a correlation equation, with EC1:5 data from Castañeda et al. (2015) for Gallocanta, and from unpublished data for Guallar.

Soil pH was measured in the 1:2.5 soil:water extract with a pH electrode (Orion 9157BNMD).

Calcium carbonate equivalent (CCE) was determined by gasometry, and gypsum content by thermogravimetry (Artieda et al., 2006). Soil organic matter (OM) was quantified through chromic-acid digestion and spectrophotometry with a UV/V UNICAM 8625 spectrophotometer following Heanes (1984). Particle size distribution was assessed using laser diffraction, corrected for the clay content, after Taubner et al. (2009).

Total phosphorous content in soil was determined, on 2013 soil samples, by inductively coupled plasma (ICP) following calcination at 450°C and wet digestion by HF and HClO_4 (NF X 31-147).

Total nitrogen content was determined through dry combustion (ISO 10694 and ISO 13878).

Exchange cations were established through Optical Emission Spectrometry (ICP-OES) in soil samples from 2015 using ammonium acetate and sodium acetate extractants. The electrical conductivity and pH of the water samples were also measured. Available phosphorous was determined with the method in Olsen et al. (1954) and soil solution N (N-NO_3 ; N-NH_4) with the method of Walinga et al. (1989).

Olsen P and soil solution mineral N represent the soil plant available fraction for P and N, respectively. As for plant, critical soil plant available P corresponds to the minimal minimum soil Olsen P needed to produce maximum dry matter (DM); this criteria varies according to crop (Colomb et al., 2007).

3. RESULTS

3.1. Weather conditions

On average, the first survey year was the wettest, with 282.1 mm of accumulated rainfall from October to March in Guallar, and 347.2 mm in Gallocanta. Monthly rainfall during this period was very variable between years (Figure 3), the highest standard deviation being in October, with 49.7 mm in Guallar and 43.3 mm in Gallocanta. The wettest and the driest months were always November and December, respectively, for the two wetland areas (66.9 mm vs 10.2 mm in Guallar, and 76.0 mm vs 19.3 mm in Gallocanta).

3.2. Salinity and composition of the upper soil layer

As expected, soil salinity increased along the soil transects towards the saline wetlands (Figure 4). In Gallocanta, the mean electrical conductivity (EC1:5) per sampling site, ranged from, 0.3 dS m⁻¹ in the most distal agricultural soil (GA22), to 3.7 dS m⁻¹ in the most proximal soil to the wetland (GA19). In Guallar, soil salinity varied from 2.1 dS m⁻¹ in the agricultural soil (GLR6) to 5.4 dS m⁻¹ at the lake edge (GLR3) (Table 1). Taking into account the electrical conductivity of the saturation extracts (ECe) calculated to classify the salinity phases for agriculture (Nogués et al., 2006), the Gallocanta soils were very strongly saline (mean ECe = 22.9 dS m⁻¹) near the lake (GA19, GA20) and slightly saline or non-saline in the cropped areas (GA22 to GA31), depending on the sampling year. In Guallar, the halophyte fringe also had very strongly saline soils, with a mean ECe of 29.2 dS m⁻¹. The standard deviation values (Table 1) indicated that the interannual variability of soil salinity was higher in the halophytes than in agricultural soils, especially at the intermediate halophytes area: GA20 in Gallocanta; and GLR7 in Guallar (Figure 4).

The soils were slightly basic, with pHs ranging from 7.3 to 8.1 (Table 1). In general, the mean soil OM varied from 1.2% at GLR3 to an exceptionally high value of 3.8% in the halophyte soil, GLR7 (Table 1). The CCE content was high in both wetlands, and varied from 29% at GA21 to 51% at GLR6 (Figure 5 and Table 1). The soils in Guallar had a high gypsum content that increased towards the lake edge, up to 72% (Table 1 and Figure 5A). Overall, the soils were loams or sandy loams with a high

percentage of sand-sized material, especially at the edges of the wetlands: 87.3% and 88.7% in Gallocanta and Guallar, respectively (Table 1 and Figure 5B).

The CEC was low to moderate and very variable along the two transects, varying from 2.4 cmol+ kg⁻¹ to 14.2 cmol+ kg⁻¹. The lowest CEC value in all the soils corresponded to the gypsum-rich substrate at the edge of Guallar Lake, GLR3, where together gypsum and carbonate accounted for about 90% of the soil composition (Figure 5A). The greatest CEC value (14 cmol+ kg⁻¹) was found in soils with the highest OM content in both of the wetlands: in the slightly saline agricultural soil GA22 and in the very strongly saline soil GLR7 covered with *Suaeda vera* (Figure 2). CEC showed a significant negative correlation with increasing sand-sized particle content ($r=-0.73$, $p<0.05$).

The lake surface water was hypersaline, especially so in Guallar (EC = 170.5 dS m⁻¹), being up to four times the salinity of seawater, and 4.3 times higher than in Gallocanta (EC = 40 dS m⁻¹). The pH of the surface water was 7.2 in Gallocanta, and 6.3 in Guallar (Table 2).

3.3. Nutrient availability

3.3.1. Soil nutrients

The difference in soil nutrients between cropped and halophytic areas was more noticeable for plant available pools than for total N and P pools (Table 2). Concerning the total nutrient stocks in Guallar, the total N content was highly variable along the transect, from 1.5 g kg⁻¹ in the cropland to 0.8 g kg⁻¹ at the wetland fringe with a maximum (2.8 g kg⁻¹) at GLR7. In parallel, total P gradually declined from 1.85 g kg⁻¹ to 0.58 g kg⁻¹. In Gallocanta, total soil N and P did not show any continuous variations between cropland and the lake fringe. Total N remained stable along the transect with a mean N content of 1.6 ± 0.4 g kg⁻¹ in the cropland and 1.8 ± 0.1 g kg⁻¹ in the halophyte soils. Total P in the cropland was three times higher (1.3 ± 0.3 g kg⁻¹) than in the halophyte soils (0.4 ± 0.3 g kg⁻¹). Total soil solution N (N-NO₃ + N-NH₄) varied between 1.8 ± 1.5 mg L⁻¹ and 5.2 ± 2.9 mg L⁻¹ in Guallar, and 4.4 ± 0.6 mg L⁻¹ and 10.1 ± 2.3 mg L⁻¹ in Gallocanta.

In Guallar, Olsen P gradually declined from $23.8 \pm 11.1 \text{ g kg}^{-1}$ in the crops to $2.2 \pm 0.0 \text{ g kg}^{-1}$ in the halophyte fringe, whereas in Gallocanta, Olsen P ranged from $66.7 \pm 12.7 \text{ mg kg}^{-1}$ to $2.3 \pm 0.3 \text{ mg kg}^{-1}$. In both wetlands, in the halophyte areas next to the lakes, available P reached relatively high values: $7.4 \pm 5.2 \text{ mg kg}^{-1}$ at GA19; and $16.9 \pm 3.9 \text{ mg kg}^{-1}$ at GLR7. Average Olsen P of agricultural soils at Gallocanta ($65.8 \pm 1.2 \text{ mg kg}^{-1}$) was up to 16 times higher than in the halophyte soils ($5.8 \pm 2.7 \text{ mg kg}^{-1}$) and up to 2.5 times higher in Guallar (23.8 mg kg^{-1}).

3.3.2. Nutritional status of plants

On average, cereals had a higher P and N content than the halophytes in Gallocanta, where the mean P content (3.9‰) was almost 4 times the halophyte mean P (1‰), and the mean N content (3.5%) was about 2.3 times higher than the halophytes mean (1.5%). In contrast, in Guallar the cereals had a low P and N content, slightly lower than the halophytes (Table 2), with a crop P content of 1.3‰, and a N content of 0.8%, which was about a half that found in the halophytes (1.9%). In general, the variability of crop nutrient content was much higher than that seen in the halophytes (Table 2).

Considering the plant nutrients content for crops and halophytes separately, in Gallocanta, P increased slightly along the transect, downslope to the lake, from $3.5 \pm 1.2 \text{ ‰}$ to $4.3 \pm 1.2 \text{ ‰}$ for cereals and from 0.7 ‰ to $1.6 \pm 0.3 \text{ ‰}$ for halophytes. Likewise, the N content of halophytes increased slightly towards the lake (from 1.3% to $1.9 \pm 0.6\%$), although the crops maintained similar N values along the transect (mean = 3.5%). In Guallar the N increased towards the wetland, from 0.8% to $1.9 \pm 0.4\%$. No relationship was found between plant N and P content and soil salinity.

The nutritional indexes, PNI and NNI, of crops were around 100% in Gallocanta in the three agricultural sites (Table 2), whereas the wheat nutritional indexes in Guallar were below the critical value of 80%. PNI and NNI calculated for halophytes were low in both wetlands and they were slightly higher in Guallar than in Gallocanta. The NNI varied between 35.7% at GA20 (*Puccinellia* sp. and *Limonium* sp.) and 72% at GLR7 (*Suaeda vera*), and the PNI varied between 29%, also at GA20, and 59% at the edge of the Gallocanta wetland, at GA19 (Table 2). The overall plant N/P ratio ranged from 7.7 ± 0.4 to 19.0 in Gallocanta, and from 7.6 ± 1.8 to 13.3 ± 3.6 in Guallar. On average, the halophytes presented higher N/P ratio (14.9) than the crops (8.4).

3.3.3. Biomass and conditions for plant development

The lowest mean above-ground biomass in Gallocanta was 2.2 t ha^{-1} , corresponding to the halophytes *Puccinellia pungens* and *Limonium* sp. at GA21, whereas the highest biomass was produced by crops, reaching 4.3 t ha^{-1} at GA22. Along the Gallocanta transect towards the edge of the wetland, the cereal biomass decreased and that of the halophytes increased (Table 2). The mean biomass was higher in Guallar than Gallocanta, both for crops and halophytes. The lowest biomass value was 3.6 t ha^{-1} , relating to *Suaeda vera* at GLR7, and the highest biomass, 8.2 t ha^{-1} , corresponded to wheat at GLR6, (Table 2). The spring (April-May) above-ground biomass was very variable between years and sites, with a standard deviation of up to 95%, as was the case of sampling site GA22. Local differences of about 1.2 t ha^{-1} were also observed within the same agricultural plot in Gallocanta (GA31 and GA32) (Figure 2B). No relationship was found between plant biomass and soil salinity. In Guallar the biomass showed a significant negative correlation with the gypsum content ($r=-0.88$, $p<0.05$, $n=6$). Considering halophytes and crops together, in Guallar the mean TT was $200 \text{ }^{\circ}\text{Cday}$ higher and the accumulated rainfall was 20% lower than in the Gallocanta area. The 2015 growing season was very dry for the halophytes in Guallar (Table 3). Mean HUE for halophytes (Table 3) was slightly higher in Guallar ($7.0 \text{ kg ha}^{-1} \text{ }^{\circ}\text{Cday}^{-1}$) than in Gallocanta ($5.5 \text{ kg ha}^{-1} \text{ }^{\circ}\text{Cday}^{-1}$). In contrast, cereals displayed higher mean HUE than halophytes, especially in Guallar, with $14.3 \text{ kg ha}^{-1} \text{ }^{\circ}\text{Cday}^{-1}$ versus $10.9 \text{ kg ha}^{-1} \text{ }^{\circ}\text{Cday}^{-1}$ in Gallocanta. Maximum HUE values were seen in 2014 in the two wetland areas. Overall, no relationship was found between HUE and the accumulated rainfall during the growing season. Though the data are limited, as a first approximation the cereal biomass showed significant correlation with TT ($r = 0.67$, $p<0.005$) though negative with rainfall ($r = -0.77$, $p<0.05$).

4. DISCUSSION

4.1. Variations in soil properties along the transect

The heterogeneity of soil properties found along the studied soil transects is related to differences in soil morphology and sediments in these highly dynamic environments (Castañeda et al., 2015), especially in Gallocanta, due to the significant size of the lake (14.4 km^2). Moreover, the upper soil

layer studied is the most influenced by rains and the intermittent flooding of the saline lake. The smaller size of Guallar playa-lake (0.15 km²), together with its lower flooding frequency and the relatively higher slope of the sampling transect (1.4%, Figure 2A), constrain the effects of the flooding on the wetland margins leading to a simpler succession of very distinct environments from the cereal to the lake. Additionally, the shorter length of the soil transect in Guallar seems to facilitate the recognition of soil property gradients, such as increased soil salinity, pH, and gypsum content, and decreased carbonates towards the lake (Figure 5; Table 2). In other wetland environments, the variability of the soil properties, including nutrient content, along wetland margins has been associated with differences in topography, flooding frequency, and sediments, among other factors (Stolt et al., 2001).

The CEC of the agricultural soils is below the value reported by Garrido (1994) as indicative of a poor soil for crop production (20 cmol⁺ kg⁻¹). The low to moderate cation exchange capacity of the studied soils (2.4 - 14.2 cmol⁺ kg⁻¹) is similar to that observed in other saline wetland soils with a very low clay content (Edem and Ndaeyo, 2009), about 11-16 cmol⁺ kg⁻¹. The high percentage of sand-sized grains in the studied soils conditions their low CEC values and, as a consequence, there is reduced nutrient fixation. Moreover, due to the sandy texture, the exchangeable cations in the low-CEC soils are very susceptible to leaching or being washed by rain towards the lake. Differences in soil nutrient content related to soil texture were also observed by Muhammad et al. (2008) in agricultural areas within a soil salinity gradient. The low CEC value of the soil at the edge of Guallar Lake could be conditioned by the sandy texture resulting from the high gypsum content (72.2%). Moreover, gypsum-rich soils limit plant and root growth in certain ways related to soil water-holding capacity, and nutrient and water availability, as observed in previous studies in the area (Rodríguez-Ochoa and Artieda, 1999; Castañeda and Moret-Fernández, 2013).

4.2. Nutrient availability in soils and plant nutritional status

The Total N content of the cereal soils studied (1.1 - 1.9 g kg⁻¹) is within the normal range established in Brady and Weil (2002) for surface mineral soils (0.2 - 5.0 g kg⁻¹). The available P content in cereal soils (from 23.8 mg kg⁻¹ to 66.7 mg kg⁻¹) is very high according to the mean value reported by

333 Davidescu and Davidescu (1982) for agricultural soils (20 mg kg^{-1}). Available P is also higher than the
334 critical value above which the wheat yield does not respond significantly to P fertilizer: 16.3 mg kg^{-1} ,
335 according to Tang et al. (2009); or 7.8 mg kg^{-1} after Colomb et al. (2007). The soil C/N ratio varies
336 between 7.1 and 8.1, and is lower than the median ($\text{C/N} = 12$) reported by Brady and Weil (2002) for
337 agricultural soils.

338 The total N content of the halophytes soils ($0.8 - 2.8 \text{ g kg}^{-1}$) is not different to that obtained in the
339 corresponding cereal-cropped soils, but slightly lower than the values reported in other saline wetlands
340 (1.6 to 4.1 g kg^{-1} ; Edem and Ndaeyo, 2009).

341 Overall, soil solution N concentration remains within the range of values reported for cropland
342 (Leimer et al., 2014). The higher concentration observed for N- NO_3 pool in cropland at Gallocanta is
343 the consequence of the fertilizers supplied to wheat by farmer (Kabala et al., 2017).

344 The decrease in soil nutrients along the Guallar transect towards the lake and the high available P
345 content in the halophyte fringe, in both wetlands, could be related to the mobilization of nutrients
346 downslope due to runoff and/or subsurface water flows. Actually, the total and available P determined
347 in the halophyte fringe can be as much as 75% (GLR7, 16.9 mg kg^{-1}) of that found in the cereal soil
348 upslope in the transect, probably due to the effect of rains intensity. The vegetation fringe of Guallar
349 can be playing the role of a buffer zone, reducing the amount of agrochemicals entering the wetland.

350 Probably due to the lower gradient of the Gallocanta transect, the halophytes soils only accumulate
351 26% of the total P, and 11% of the available P found upslope in the cereal-cropped soils. The available
352 data on surface water chemistry in Gallocanta Lake shows a P concentration from 0.1 mg L^{-1} to 0.5 mg
353 L^{-1} (CHE, 2013). Moreover, since P adsorption and release is highly affected by intermittent flooding
354 events (Tian et al., 2017), the P released into the surface water of Gallocanta Lake may accumulate in
355 the soil at the lake edge, especially under anaerobic conditions (Castañeda et al., 2017), as probably
356 occurs at GA19 (7.4 mg kg^{-1} , Table 2).

357 In general, the N and P content of cereals are within the common ranges established by Davidescu and
358 Davidescu (1982), $\text{N} = 2 - 4\%$ and $\text{P} = 3 - 6\%$, in accordance with the nutrient availability of the
359 soils. The wheat in Guallar display a low N and P content even more so when taking into account the
360 high total N and available P in the soil (Table 2). Also the nutritional indexes, $\text{PNI} = 62.6\%$ and $\text{NNI} =$

37.4%, are considerably lower than the critical value of 80%. This result confirms that in Guallar cereal growth is limited for both N and P nutrition (Duru and Ducrocq, 1997). In contrast, the nutritional indexes of cereals in Gallocanta are close to 100% (Table 2) indicating that soil provides non-limiting nutrients for plant growth, in agreement with the high soil nutrient availability, which is a consequence of common fertilizer supplies (Colomb et al., 2007). Some samples even have index values over 100%, as is the case of the PNI value at GA31 and NNI at GA32 (Table 2), indicating a luxury consumption of nutrients above crop requirements. Differences observed between wetlands can be explained by fewer fertilizer applications in Guallar.

With regard to halophyte nutrients, the N and P contents (mean N = 1.6% and P = 1.2‰) are similar to those reported in other salt-tolerant species by García and Mendoza (2008), N = 1.5% and P = 1.4‰, and also similar to those obtained in April by Rathore et al. (2016) for *Salicornia brachiata*, N = 1.5% and P = 1.1‰. Since no specific nutritional indexes and N/P ratio thresholds for halophyte growth have been found in the literature, we consider the NNI and PNI indexes to characterize the crop and halophytes nutritional status. First NNI have been developed and parameterized for crops monocultures (see the review by Lemaire et al., 2008); then the approach has been extended and evaluated for multi species swards (Lemaire, 1997). Similarly, Salette and Huché (1991) proposed a general model for P (and K) dilution indices which was extended to multi species grassland by Duru and Ducrocq (1997). Several studies have demonstrated that nutrition indices can be used in natural eco systems such as multi species grasslands (Liebisch et al 2013). Garnier et al. (2007) demonstrated that at ecosystem level, NNI and PNI provide an appropriate evaluation of functional response of species and communities to fertility gradients induced by practices. The PNI and NNI indexes applied to halophytes result in very low values, less than 80%, indicating nutrient limitation (Duru and Ducrocq, 1997), especially in Gallocanta (< 30%, Table 2). Also the mean N/P ratio (16.2) is above the critical value of nutrient limitation (14) established by Koerselman and Meuleman (1996) for plant growth in freshwater wetlands. However, although a low nutritional status or plant growth could be inferred from these indexes, it must be considered that on the sampling dates the halophilous plant species presented a significantly earlier phenological stage than the cereals. Moreover, in Gallocanta

there was limited plant growth compared to the more advanced development stage of halophytes in the warmer climate of Guallar.

4.3. Biomass variability

The local climatic conditions of the Gallocanta and Guallar study sites are associated with their relative locations in the Ebro basin and their distinct elevations, 1000 m a.s.l and 336 m a.s.l, respectively (Figure 2). The higher aridity of the Guallar area is evidenced by the lower level of accumulated rainfall and higher TT. In nearby areas of the Ebro Basin, wheat yields have been related to seasonal rainfall (McAneney and Arrúe, 1993). However, we found no clear relationship between cereal biomass in spring and accumulated rainfall (Table 3) probably due to the limited amount of data used, uncertain nature of the rainfall distribution and other factors such as soil conditions, pests and diseases (McAneney and Arrúe, 1993). In fact, the variability of the accumulated rainfall (Figure 3), TT, and heat use efficiency over the three campaigns (Table 3), must have directly affected the high variability of the biomass obtained, both in crops and halophytes (Table 2). Due to the late sampling date in 2014 (May, 25-29), that year's biomass results are probably less easy to compare than those obtained in April 2013 and 2015.

Although barley and wheat are two of the most salt-tolerant cereals (Ayers and Westcot, 1976) they can still be affected by soil salinity (Setter et al., 2016), especially during germination (Munns and Tester, 2008), when the E_{ce} should not exceed 4-5 dS m⁻¹ (Ayers and Westcot, 1976). In Gallocanta, the salinity of agricultural soils is far below the critical E_{ce} value at which the yield production starts to decrease (6 dS m⁻¹ and 8 dS m⁻¹ for wheat and barley, respectively, Ayers and Westcot (1976)). Nevertheless, even if the upper soil layer is non-saline, the seasonal rising of the saline water table and /or the occasional waterlogging reported by local farmers can reduce crop development. Saline groundwater is common in topographically low areas neighboring the halophyte fringe (Castañeda et al., 2015) and local soil salinity can explain the difference in wheat biomass obtained within the same agricultural plot, e.g., at GA31 (3.0 t ha⁻¹) and GA32 (4.2 t ha⁻¹). The mean halophyte biomass (3.9 t ha⁻¹) is similar to that produced by *Salicornia brachiata* in salt marshes in India, which had a mean of 4 t ha⁻¹ (Rathore et al., 2016). The high biomass (7.0 t ha⁻¹) found in the most strongly saline soil in

Guallar, GLR7, was probably favored by the high cation exchange capacity and the available nutrients that had come from the adjacent agricultural plot.

5. CONCLUSIONS

Overall, halophytes and agricultural ecosystems interfere at the saline wetlands fringe. Soils in the cropped areas show a higher mean nutrient content than the natural areas, as expected due to the use of fertilizers. However, halophytes soils can display a total soil solution N content similar to cereal soils and, in some sites, a high concentration of available P. The nutrients move downslope along the soil transects, especially P, and accumulate in the halophyte areas closer to the lake. This transfer of nutrients towards the wetlands is favored by the predominantly sandy texture, especially in the case of the gypsum-rich soils. The halophyte fringes of the studied wetlands play an important role as nutrient retention areas and they can prevent the full transfer of P to the lake reducing the subsequent ecosystem pollution.

Plant nutrients show no relationship with soil nutrients, as revealed by the low nutritional indexes in Guallar and the relatively low halophyte biomass in Gallocanta. Low nutritional indexes for crops and halophytes, indicative of nutrient uptake limitation by plants, occur in soils with salinity, high gypsum content, especially under the arid conditions found in Guallar. In both sites, low PNI and high N/P ratios indicate that P is more limiting than N for halophyte growth. Only the cereal in Gallocanta has non-limiting nutrients for growth.

Soil salinity can extend beyond the halophyte fringe at the border of saline wetlands, though no significant relationship with wheat biomass production and yield was found. At both sites, results evidenced salinity gradients from wetland to cropland and interactions between topography and cropping activity which led to lateral transfer of P from cropland to halophytes vegetation's.

These preliminary results are encouraging; still the general value of these patterns needs to be confirmed on a more robust sampling design with intra wetland replication transects. A larger set of data would improve this study in three points: 1) Identify the impact of environmental variables (soil, topography, salinity) on these processes; 2) Allow a quantitative evaluation of P fluxes at the landscape level and consequently a better evaluation of environmental risk associated with; and 3)

Serve to develop decision support systems for sustainable management of halophyte vegetation, set at the fringe of saline wetland, and cropland.

Knowledge of soil and plant nutritional status can be used in decision-making processes regarding land use and agricultural management, and is crucial for preventing wetland pollution in agricultural areas and to emphasize the preservation of vegetation fringes that act as buffer zones.

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Figure captions

Figure 1. Locations of Guallar and Gallocanta Ramsar wetlands in the Ebro basin (inset) and on a false color composition (RGB123) of the SPOT 5 image from 2009.

Figure 2. Schema of the topographic cross-sections and distribution of sampling sites along the soil transects in Guallar (A) and Gallocanta (B). Plant design is adapted from Conesa et al. (2011).

Figure 3. Monthly rainfall from October to March during the three-year period from 2013 to 2015 in Guallar (A) and Gallocanta (B). The line represents the three-year mean monthly rainfall.

Figure 4. Soil salinity (EC1:5) values determined during the three sampling campaigns along the soil transects in: A) Guallar (GLR); and B) Gallocanta (GA).

Figure 5. Soil composition (percentage of gypsum, calcium carbonate equivalent (CCE), organic matter (OM) and siliceous-silicatic material) and particle size distribution (percentage of clay, silt, and sand) in A) Guallar (GLR); and B) Gallocanta (GA) soil transects.

642 Table 1. Mean ($\pm$ standard deviation) of three years of soil physical and chemical properties at the Guallar (GLR) and Gallocanta (GA) sites, together with the
643 surface water samples. EC1:5: electrical conductivity of the soil:water 1:5 extract; ECe: electrical conductivity of the saturation extract; pH1:2.5: pH of the
644 soil:water 1:2.5 extract; and CCE: calcium carbonate equivalent.

Sampling site	EC1:5 dS m ⁻¹	ECe*	pH1:2.5	Gypsum	CCE	Organic matter	Sand %	Silt	Clay	USDA Textural class
<i>Guallar</i>										
GLR3	5.1 $\pm$ 1.6	27.6	7.9 $\pm$ 0.7	72.2 $\pm$ 7.1	17.4 $\pm$ 5.3	1.2 $\pm$ 0.9	88.7 $\pm$ 1.2	9.6 $\pm$ 1.2	1.7 $\pm$ 0.0	Sand
GLR7	5.4 $\pm$ 2.4	30.7	7.6 $\pm$ 0.1	17.2 $\pm$ 6.5	33.9 $\pm$ 4.4	3.8 $\pm$ 0.1	37.7 $\pm$ 0.3	45.3 $\pm$ 0.1	17.01 $\pm$ 0.2	Loam
GLR6	2.1 $\pm$ 0.3	**	7.5 $\pm$ 0.2	8.5 $\pm$ 4.6	51.3 $\pm$ 5.4	1.9 $\pm$ 0.1	44.3 $\pm$ 16.3	40.1 $\pm$ 10.6	15.5 $\pm$ 5.7	Loam
<i>Gallocanta</i>										
GA19	3.7 $\pm$ 2.0	24.3	7.3 $\pm$ 0.2	3.7 $\pm$ 1.1	33.8 $\pm$ 2.6	1.8 $\pm$ 0.1	87.3 $\pm$ 1.4	12.1 $\pm$ 1.4	4.15 $\pm$ 0.1	Loamy sand
GA20	3.3 $\pm$ 2.2	21.5	7.7 $\pm$ 0.2	3.2 $\pm$ 0.8	47.2 $\pm$ 4.6	2.3 $\pm$ 0.1	52.2 $\pm$ 1.4	27.3 $\pm$ 1.3	20.5 $\pm$ 0.1	Sandy clay Loam
GA21	0.5 $\pm$ 0.4	3.0	8.0 $\pm$ 0.2	1.3 $\pm$ 0.3	29.1 $\pm$ 11.4	2.3 $\pm$ 0.0	78.6	16.6	4.7	Loamy sand
GA31	0.4 $\pm$ 0.1	2.3	7.6 $\pm$ 0.4	2.1 $\pm$ 0.6	48.2 $\pm$ 5.4	2.1 $\pm$ 0.7	61.7 $\pm$ 2.7	27.2 $\pm$ 1.5	11.1 $\pm$ 4.2	Sandy loam
GA32	0.3 $\pm$ 0.1	1.9	8.1 $\pm$ 0.3	1.4 $\pm$ 0.5	39.9 $\pm$ 2.7	1.3 $\pm$ 0.5	73.0 $\pm$ 10.9	21.8 $\pm$ 6.2	5.2 $\pm$ 4.7	Sandy loam
GA22	0.3 $\pm$ 0.1	2.1	8.1 $\pm$ 0.2	2.2 $\pm$ 0.3	47.4 $\pm$ 0.8	2.3 $\pm$ 0.1	62.7 $\pm$ 4.1	26.2 $\pm$ 0.1	11.1 $\pm$ 4.2	Sandy loam
<i>Surface water</i>										
	EC		pH							
GLR	170.5		6.3							
GA	39.9		7.2							

645

646 *Estimated with data from Castañeda et al. (2015) for Gallocanta, and from unpublished data for Guallar.

647 ** Not estimated due to uncertainty: the EC1:5 value must be related to the gypsum content.

648

649 Table 2. Soil P and N content, cation exchange capacity (CEC), Olsen P and mineral Nitrogen (N-NO₃ and N-NH₄) of the soil solution, and plant nutrient
650 content in Guallar (GLR) and Gallocanta (GA). Three-year mean $\pm$ standard deviation, excepting for n=1 samples. PNI: phosphorous nutrition index; NNI:
651 nitrogen nutrition index. Shadowed rows correspond to the sampling sites located within the halophyte fringe.

Sampling sites (in order from wetland to crop)	Soil								Plant					
	Total P	Total N	C/N	CEC	Olsen P	N-NO3	N-NH4	n	P	N	N/P	Biomass	PNI	NNI
	g kg ⁻¹	g kg ⁻¹		cmol ⁺ kg ⁻¹	mg kg ⁻¹	mg L ⁻¹			‰	%		t ha ⁻¹	%	%
Guallar														
GLR3	0.58	0.8±0.4	7.2±1.1	2.4	2.2 ± 0.0	1.1±1.0	0.7±0.4	3	1.5 ± 0.5	1.8 ± 0.4	12.8±3.3	3.6 ± 0.7	55.4 ± 16.1	56.8 ± 12.3
GLR7	1.38	2.8±0.5	7.4±1.3	14.1	16.9 ± 3.9	1.5±0.9	3.7±2.3	3	1.4 ± 0.4	1.9 ± 0.1	13.3±3.6	6.9 ± 1.2	54.1 ± 13.5	72.01 ± 8.1
GLR6	1.85	1.5±0.1	7.0±0.2	11.2	23.8 ± 11.1	0.8±0.9	1.7±0.8	1	1.3	0.8	7.6±1.8	8.2	62.6	37.4
Gallocanta														
GA19	0.55	1.7±0.5	7.7±0.1	9.1	7.4 ± 5.2	1.6±1.6	4.0±1.6	3	1.6 ± 0.3	1.9 ± 0.6	11.5±2.4	3.7 ± 2.2	59.5 ± 0.2	54.5 ± 3.9
GA20	0.58	1.8±0.1	7.2±0.4	11.0	2.3 ± 0.3	0.7±0.1	3.8±0.5	3	0.7 ± 0.0	1.2 ± 0.2	18.1±1.8	3.0 ± 0.3	29.1 ± 0.2	35.7 ± 6.9
GA21	0.11	1.8±0.2	7.8	9.2	2.6 ± 0.6	2.4±0.9	3.9±0.9	1	0.7	1.3	19.0	2.2	29.7	36.2
GA31	1.57	1.7±0.4	7.3±0.3	12.6	66.7 ± 12.7	7.6±3.0	2.6±0.7	3	4.3 ± 1.2	3.3 ± 0.9	7.7±0.4	3.0 ± 2.2	116.8 ± 13.4	93.6 ± 41.4
GA32	1.26	1.1±0.2	8.1±2.8	7.4	66.2 ± 4.2	4.7±2.8	2.2±0.4	3	3.9 ± 1.5	3.7 ± 1.5	9.3±0.7	4.2 ± 3.1	98.4 ± 14.9	109.7 ± 27.5
GA22	1.03	1.9±0.1	7.0±0.3	14.2	64.5 ± 20.7	4.9±2.9	3.0±0.9	3	3.5 ± 1.2	3.4 ± 1.8	9.0±2.4	4.3 ± 4.1	95.4 ± 4.3	91.0 ± 35.9

Table 3. Characterization of the growing season for halophytes and crops: accumulated rainfall, thermal time (TT), biomass, and heat use efficiency (HUE) in the Gallocanta and Guallar wetlands.

Year	Sampling date	----- Halophytes -----					----- Crops -----				
		Growing season	Accumulated rainfall from February to the sampling date	TT	Biomass	HUE	Growing season	Accumulated rainfall from October to the sampling date	TT	Biomass	HUE
		days	mm	°Cday	t ha ⁻¹	kg ha ⁻¹ °Cday ⁻¹	days	mm	°Cday	t ha ⁻¹	kg ha ⁻¹ °Cday ⁻¹
<i>Guallar</i>											
2013	Apr, 16	75	101.6	655.3	5.23	8.0	198	282.1	253.0		
2014	May, 29	118	103.3	1411.7	4.76	3.4	241	215.8	601.3	8.2	13.7
2015	Apr, 10	69	58.7	595.0	5.72	9.6	192	211.8	330.1	2.7	8.1
<i>Gallocanta</i>											
2013	Apr, 16	75	145.7	483.5	1.42	2.9	198	347.2	150.9	1.5	9.7
2014	May, 25	114	101.1	1106.9	4.55	4.1	237	235.1	394.0	7.4	18.7
2015	Apr, 09	68	109.5	312.3	2.95	9.5	191	255.9	187.5	2.7	14.5

Fig3

Fig.4

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667 Fig.5