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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 nutrient distribution in intermittently flooded environments subjected to soil and water salinity. The aim of this work was to characterize soil and plant nutrients 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. Selected soil properties were assessed, including the nitrogen (N) and phosphorous (P) content of the plants and soil, and the P and N nutritional indexes of the plants. 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. The plant nutritional indexes (NNI and PNI) for cereals indicate non-limiting nutrient uptake for plant growth in Gallocanta and nutrient limitation in Guallar, probably related to the high gypsum content, low C/N ratio, and/or soil salinity. Studying the nutrient content in arid and saline environments, at the interface between

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halophytes and crops, is crucial for improving land management strategies and reconciling production and conservation in protected saline habitats

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Zaragoza, Spain, February 6, 2018

Dear Editor,

Please find attached the manuscript entitled “**Soil composition and plant nutrients at the interface between crops and saline wetlands in arid environments in NE Spain**”, by E. Luna, C. Jouany and C. Castañeda for publication in CATENA Journal.

The knowledge about soils in arid and saline environments is very scarce, even if this information is required for the protection of saline habitats. There is still a lack of knowledge in understanding the link of the soil and plant nutrients along a continuous gradient including crops and their adjacent natural areas in saline environments. We have studied rainfed areas with particular soil composition, carbonate and gypsum-rich soils, and two protected saline wetlands in NE Spain with conflicts between habitats conservation, water vulnerability and agricultural intensification. The sampling sites follow transects along soil salinity gradients towards the edge of the saline lake. Characterizing soil and plant nutritional status in their natural context and integrating halophytes and crops is an approach useful in other agricultural environments. The knowledge about the distribution of nutrients is crucial to improve the fertilization strategies in order to reconcile the production with the conservation of protected habitats.

Yours sincerely,

Carmen Castañeda

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Highlights

- Soil nutrients and plant fertility are characterized in two saline wetlands
- No correlation between soil and plant nutrients and soil salinity was found
- The high nutrients in halophyte soils reflect a downslope nutrient flow to wetlands
- The sandy soils conditions their low CEC values and favour their nutrient leaching
- There are non-limiting nutrients for plant growth, in agreement with the soil nutrients

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

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9

10 **Abstract**

11 In arid and semiarid environments, saline wetlands are both high-value habitats threatened by
12 landscape transformations, and a constraint to agricultural production. There is a lack of knowledge
13 about nutrient distribution in intermittently flooded environments subjected to soil and water salinity.
14 The aim of this work was to characterize soil and plant nutrients at the interface between agricultural
15 land and saline wetlands. These aspects were studied in Guallar and Gallocanta, two Ramsar saline
16 wetlands in NE Spain that represent arid and semiarid conditions, respectively. Selected soil properties
17 were assessed, including the nitrogen (N) and phosphorous (P) content of the plants and soil, and the P
18 and N nutritional indexes of the plants. Soil salinity (EC1:5) increases towards the halophyte areas,
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21 Guallar have a high gypsum content (up to 72%). The soils have a low to moderate cation exchange
22 capacity regardless of soil salinity, with a maximum of 14 cmol+ kg⁻¹ in the soil with the highest
23 organic matter content (3.8%). Overall, cereal soils show total P and N contents within the normal
24 range for agricultural soils, although the available P is above the requirements for cereals, up to 67 mg
25 kg⁻¹. The difference in soil nutrients between cropped and halophyte land is more noticeable when it
26 comes to total and available P content than for N levels. The relatively high nutrient content in some
27 halophyte soils and the total and available P gradients along the soil transects, reflect downslope

28 nutrient movement towards the lake. Halophyte soils can accumulate between 11% and 71% of the
29 available P found in cropped soils. No relationship was found between the soil nutrient content and
30 that of plants, nor between these two parameters and soil salinity. The plant nutritional indexes (NNI
31 and PNI) for cereals indicate non-limiting nutrient uptake for plant growth in Gallocanta and nutrient
32 limitation in Guallar, probably related to the high gypsum content, low C/N ratio, and/or soil salinity.
33 Studying the nutrient content in arid and saline environments, at the interface between halophytes and
34 crops, is crucial for improving land management strategies and reconciling production and
35 conservation in protected saline habitats.

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

37

38 1. INTRODUCTION

39 Recognition of wetlands has increased, as has scientific interest in them. However, agricultural
40 intensification and the historical misperception of wetlands have led to decades of loss and
41 degradation (Ramsar Convention Secretariat, 2010). Inland wetlands of arid and semiarid regions have
42 been especially affected (Hollis, 1992; Davis and Froend, 1999) due to episodic flooding (Williams,
43 2002), even if they are protected (Herrero and Castañeda, 2009), and agriculture is one of their most
44 important threats. At the continental scale, Europe is second only to Africa in the number of inland
45 intermittent saline wetlands it has that are included in the Ramsar list, and almost 38% of these are in
46 Spain. Sustainable agriculture is required to preserve these unique habitats in agricultural landscapes.
47 In this context, knowledge of soil and plant nutrient content is crucial for understanding the
48 distribution of habitats around wetlands and designing adapted agri-environmental measures that
49 reconcile production and habitats preservation.

50 Soil nutrient content has mainly been studied in croplands to predict the amount of nutrients needed to
51 increase crop yield, particularly in soils with poor nutrient availability (Belachew and Abera, 2010).

52 Also, from the point of view of agricultural production, soil fertility has been investigated in wetlands,
53 due to interest in rice cultivation (Seneviratne et al., 1994; Buri et al., 1999; Edem and Ndaeyo, 2009;
54 Wang et al., 2011), and submerged soils (Sahrawat, 2015). The variability of the physical and
55 chemical soil properties of interest in agriculture has been investigated under different crop

56 management strategies (Álvarez-Solís et al., 2007) and different landscape positions (Scotney and
57 Dijkhuis, 1990). At the interface between wetlands and adjacent agricultural fields, the variability of
58 soil properties has been studied in order to increase knowledge on wetland ecosystem functions (Stolt
59 et al., 2001; Yoon et al., 2015). The effect of soil fertility on plant nutrient status is frequently
60 investigated under controlled conditions (Jouany et al., 2004; Guzys and Miseviciene, 2015), and
61 through laboratory or greenhouse experiments (Christie and Moorby, 1975; Gough and Marrs, 1990;
62 Fort et al., 2015), but rarely under natural conditions.

63 Inland wetlands in agricultural landscapes usually comprise fringes of natural vegetation. Transitional
64 areas, from crops to natural vegetation, are suitable for studying soil and plant nutrient content as these
65 represent a continuum of habitats where nutrient exchange between aquatic and terrestrial
66 environments takes place (Zhao et al., 2016). In this context, these fringes of natural vegetation
67 usually reduce the flows and inputs of agrochemicals to the wetland (Vought et al., 1994; Silvan et al.,
68 2004).

69 Wetlands in arid regions are characterized by intermittent flooding and, frequently, by soil salinity due
70 to the scarce and irregular rainfall together with high levels of evapotranspiration. Moreover, the use
71 of fertilizers to counteract poor soil conditions (Parida and Das, 2005; Grieve et al., 2011) contributes
72 to water with nutrient excesses flowing towards lower lying areas. This is common in saline wetlands,
73 which receive irrigation flows of nutrient-enriched fresh water from upland areas (Díaz et al., 1998;
74 Valero-Garcés et al., 2000).

75 There are few studies on soil and plant nutrient contents in saline environments. These have been
76 addressed for salt pasture production (Bennett et al., 2009); to understand the relationship between
77 plant nutrients and soil properties in temperate grasslands along a saline gradient (García and
78 Mendoza, 2008); and in coastal saline marshes (Rathore et al., 2016). The aim of this study was to
79 characterize the soil and plant nutrients in saline environments, particularly at the interface between
80 agricultural land and saline wetlands. For this purpose, two saline wetlands were selected in NE Spain,
81 both protected under biodiversity conservation legislation and subject to agricultural intensification.
82 Knowledge of the soil and plant nutrients is required for developing and improving management
83 strategies in order to reconcile production and conservation in protected habitats.

84 2. MATERIAL AND METHODS

85 2.1. Ramsar Wetland sites

86 Gallocanta and Guallar, NE Spain (Figure 1), are two hypersaline Ramsar wetlands protected under
87 the EU Birds and Habitats Directives, and subject to agricultural intensification. Gallocanta, with 14.4
88 km², is the largest saline lake in Western Europe. It is located 1000 m a.s.l. in the Iberian Range
89 (Figure 1) in a dry semiarid climate (Liso and Ascaso, 1969), with a mean rainfall of 488 mm yr⁻¹
90 (1945-2015), a mean annual temperature of 11.2 °C (1969-2015), and a mean hydric deficit of 605 mm
91 yr⁻¹ (García-Vera and Martínez-Cob, 2004). The prevailing NW dry winds are very common,
92 especially in winter (Martínez-Cob et al., 2010). Guallar, with 0.15 km², is located 336 m a.s.l. in the
93 Monegros Desert, Figure 1. This is one of the most arid regions in Europe (Herrero and Snyder, 1997),
94 with a mean annual rainfall of 350 mm (1974 - 2014), a mean annual temperature of 14.9 °C, and 1255
95 mm yr⁻¹ of mean reference evapotranspiration (Faci and Martínez-Cob, 1991). All these factors
96 contribute to the hydric deficit (mean = 867 mm yr⁻¹).

97 Water level fluctuations and intermittent desiccation constitute the most outstanding features of the
98 two saline wetlands, and they fit the functional description of playa-lakes given by Shaw and Thomas
99 (1997). The maximum registered lake water depth was 2.84 m in Gallocanta, in 1974 (Pérez-
100 Bujarrabal, 2014), and 0.26 m in Guallar, in 1997 (Castañeda, 2002). The action of wind and water has
101 promoted the formation of littoral landforms associated to the two lakes. In Gallocanta, the southern
102 sedimentary margin includes sandy barrier islands, lagoons and sublittoral bars (Castañeda et al.,
103 2013), and a gypsum-rich lunette has formed on the leeward margin of Guallar (Mees et al., 2012).
104 The natural vegetation (Figure 2) consists mostly of annual and perennial halophytes distributed in
105 concentric fringes around the bare saline lake floor, according to their soil salinity tolerance and
106 flooding (Gómez et al., 1983; Conesa et al., 2011). Some of the halophytes, such as *Puccinellia*
107 *pungens*, are protected species under the Habitats Directive and the Convention on the Conservation of
108 European Wildlife and Natural Habitats (Moreno, 2013). Crops consists of winter cereals, mainly
109 barley, soft wheat, and durum wheat. In the Guallar area, agricultural practices include traditional
110 cereal-fallow rotation (McAneney and Arrúe, 1993).

111

112 2.2. Sampling design

113 Soil and vegetation were sampled in each wetland, along transects extending from the edge of the
114 wetland (excluding the water or the bare bottom) to the agricultural land (Figure 2). Sampling was
115 undertaken during three field campaigns: April (9-16) 2013; May (25-29) 2014; and April (9-10)
116 2015. In Guallar (GLR), three sampling sites were located on the SE margin, along a 200 m transect
117 with a mean slope of 1.4% (Figure 2A). GLR3 and GLR7 sampling sites corresponded to the
118 halophyte fringe and contained *Suaeda vera*, *Sphenopus divaricatus*, and *Hymenolobus procumbens*.
119 Site GLR6 was cropped with wheat (*Triticum aestivum*) in 2014, and left fallow in 2013 and 2015. Six
120 sampling sites were established along a 1100 m transect, with a mean slope of 0.3%, on the southern
121 margin of Gallocanta lake (GA) (Figure 2B). The halophyte fringe (sites GA19, GA20 and GA21)
122 extended about 800 m from the lake edge and included plant communities with *Salicornia* sp.,
123 *Puccinellia* sp., and *Limonium* sp. (Figure 2B).
124 Three cereal sites (GA31, GA32 and GA22) were sampled, two of them, GA31 and GA32, within the
125 same agricultural plot but had different levels of cereal development. Wheat (*Triticum aestivum*) was
126 cultivated in 2013 and 2015, and barley (*Hordeum vulgare*) in 2014. Fertilizing cereals is not very
127 common in Guallar, although NPK (8-15-15) fertilizer may be added in the spring. In Gallocanta, 160
128 - 200 kg ha⁻¹ of complete NPK (12-20-12) fertilizer is usually applied at sowing. About 160-200 kg ha⁻¹
129 ¹ of calcium ammonium nitrate (CAN-27) may also be applied in the spring.

130

131 2.3. Sampling and characterization of plants and soils

132 At each site, the aerial part of the vegetation was collected within a 0.25 m² quadrat, together with
133 either a composite sample of the upper 5 cm of soil, or 25 cm in the agricultural plots. Three quadrat
134 replicates of the vegetation were taken in order to pool samples in sites with very little vegetation or
135 heterogeneous vegetation from the point of view of height and coverage. During the 2013 campaign,
136 there was no vegetation at three sites: GA20, GA21, and GLR6. Vegetation samples were weighed
137 before and after drying at 60 °C for 48 hours, and then milled to a 1 mm particle size using an
138 industrial grinder. Soil samples were air-dried and sieved to a grain size of 2 mm for subsequent

139 chemical and particle size distribution analyses. Surface water was collected from the wetlands at the
140 beginning of the study, in 2013.

141 The phosphorous content of the plants was determined following calcination at 550°C for 5 hours and
142 digestion in H₂SO₄-H₂O₂, using the malachite green colorimetric method of Van Veldhoven and
143 Mannaerts (1987) and spectrophotometry, and the nitrogen content of plants was determined using a
144 CN gas analyzer (Elementar Vario Cube, Hanau, Germany). The phosphorous nutrition index (PNI)
145 was calculated according to the equation proposed by Duru and Ducrocq (1997), and the nitrogen
146 nutrition index (NNI) was determined following Justes et al. (1994) for wheat, and Lemaire et al.
147 (1989) for the other samples. The relationship between soil and plant properties was established using
148 Pearson's correlation coefficient. The accumulated rainfall and HUE of the vegetation were computed
149 to characterize the growing season, starting on October 1st for crops and on February 1st for halophytes
150 (Fitter et al., 1995), up to the sampling date. The thermal time (TT) was calculated as the sum of the
151 cumulative differences in temperature between the daily mean temperature and the base and optimum
152 temperatures, and expressed in °Cday. The base temperature was considered to be 10 °C for wheat
153 (Girijesh et al., 2011) and 0 °C for halophytes, with an optimum temperature of 18°C for halophytes
154 (Theau and Zerourou, 2008; Niqueux and Arnaud, 1967). HUE was calculated as the aboveground
155 biomass produced per unit of TT, and expressed in kg ha⁻¹°Cday⁻¹.

156 Soil salinity was measured with a conductivity cell (Orion 013605MD) and expressed as the electrical
157 conductivity of the 1:5 soil:water extract (EC1:5) in dS m⁻¹ at 25 °C. To classify the soil salinity for
158 agriculture (Nogués et al., 2006), the electrical conductivity value of the saturation extract (ECe) was
159 estimated using a correlation equation, with EC1:5 data from Castañeda et al. (2015) for Gallocanta,
160 and from unpublished data for Guallar, according to the equation proposed by Herrero and Pérez-
161 Coveta (2005).

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

163 Calcium carbonate equivalent (CCE) was determined by gasometry, and gypsum content by
164 thermogravimetry (Artieda et al., 2006). Soil organic matter (OM) was quantified through chromic-
165 acid digestion and spectrophotometry with a UV/V UNICAM 8625 spectrophotometer following

166 Heanes (1984). Particle size distribution was assessed using laser diffraction, corrected for the clay
167 content, after Taubner et al. (2009).

168 Soil nutrient content was assessed according to total and available phosphorous, total nitrogen, and
169 soil cation exchange capacity (CEC). Total phosphorous content in soil was determined by inductively
170 coupled plasma (ICP) following calcination at 450 °C and wet digestion by HF and HClO₄ (NF X 31-
171 147). Total nitrogen content was determined through dry combustion (ISO 10694 and ISO 13878).
172 The levels of both nutrients were measured in soil samples from 2013. Available phosphorous was
173 determined with the method in Olsen et al. (1954). Exchange cations were established through Optical
174 Emission Spectrometry (ICP-OES) in soil samples from 2015. The electrical conductivity and pH of
175 the water samples were also measured.

176

177 **3. RESULTS**

178

179 3.1. Salinity and composition of the upper soil layer

180 As expected, soil salinity increases along the soil transects towards the saline wetlands (Figure 3). The
181 mean electrical conductivity (EC1:5) per sampling site, ranges from, in Gallocanta, 0.3 dS m⁻¹ in the
182 most distal agricultural soil (GA22), to 3.7 dS m⁻¹ in the most proximal soil to the wetland (GA19). In
183 Guallar, soil salinity varies from 2.1 dS m⁻¹ in the agricultural soil (GLR6) to 5.4 dS m⁻¹ at the lake
184 edge (GLR3) (Table 1). Taking into account the electrical conductivity of the saturation extracts (ECe)
185 calculated to classify the salinity phases for agriculture (Nogués et al., 2006), the Gallocanta soils are
186 very strongly saline (mean ECe = 22.9 dS m⁻¹) near the lake (GA19, GA20) and slightly saline or non-
187 saline in the cropped areas (GA22 to GA31), depending on the sampling year. In Guallar, the
188 halophyte fringe also has very strongly saline soils, with a mean ECe of 29.2 dS m⁻¹. The standard
189 deviation values (Table 1) indicate that the interannual variability of soil salinity is higher in the
190 halophytes than in agricultural soils, especially at the intermediate halophytes area: GA20 in
191 Gallocanta; and GLR7 in Guallar (Figure 3).

192 The soils are slightly basic, with pHs ranging from 7.3 to 8.1 (Table 1). In general, the mean soil OM
193 varies from 1.2% at GLR3 to an exceptionally high value of 3.8% in the halophyte soil, GLR7 (Table

194 1). The CCE content is high in both wetlands, and varies from 29% at GA21 to 51% at GLR6 (Figure
195 4 and Table 1). The soils in Guallar have a high gypsum content that increases towards the lake edge,
196 up to 72% (Table 1 and Figure 4A). Overall, the soils are loams or sandy loams with a high percentage
197 of sand-sized material, especially at the edges of the wetlands: 87.3% and 88.7% in Gallocanta and
198 Guallar, respectively (Table 1 and Figure 4B).

199 The surface water is hypersaline, especially so in Guallar ($EC = 170.5 \text{ dS m}^{-1}$), being up to four times
200 the salinity of seawater, and 4.3 times higher than in Gallocanta ($EC = 40 \text{ dS m}^{-1}$). The pH of the
201 surface water is 7.2 in Gallocanta, and 6.3 in Guallar (Table 2).

202

203 3.2. Nutrient availability

204 3.2.1. Soil nutrients and cation exchange capacity

205 In general, the agricultural soils have a higher nutrient content than the halophyte soils (Table 2). The
206 difference in soil nutrients between cropped and halophytic areas is more noticeable for total and
207 available P content than for N. Available P in the agricultural soils of Gallocanta (mean = 65.8 mg kg^{-1})
208 is up to 16 times higher than in the halophytes soils, and up to 2.5 times higher in the agricultural
209 soils of Guallar (23.8 mg kg^{-1}). A difference in the N content between cropped and halophytes soils is
210 only observed in Guallar (Table 2), where it is 2.4 times higher in the agricultural soils. In Gallocanta
211 the mean N content of the soil transect is 1.3 g kg^{-1} (Table 2).

212 The soil content of both N and P decreases along the transect in Guallar towards the edge of the
213 wetland: total N goes down from 2.92 g kg^{-1} to 0.97 g kg^{-1} ; total P decreases from 1.85 g kg^{-1} to 0.58 g
214 kg^{-1} ; and available P drops from 23.8 mg kg^{-1} to 2.2 mg kg^{-1} (Table 2). However, the distribution of the
215 soil nutrient content in Gallocanta is highly variable along the transect (Table 2): total N varies from
216 0.94 to 1.74 g kg^{-1} ; total P from 0.11 g kg^{-1} to 1.57 g kg^{-1} ; and available P from 66.7 mg kg^{-1} to 2.3 mg
217 kg^{-1} . In the halophyte areas next to the lakes in both wetlands, available P reaches relatively high
218 values: 7.4 mg kg^{-1} at GA19; and 16.9 mg kg^{-1} at GLR7.

219 The CEC is low to moderate and very variable along the two transects, varying from $2.4 \text{ cmol+ kg}^{-1}$ to
220 $14.2 \text{ cmol+ kg}^{-1}$. The lowest CEC value in all the soils corresponds to the gypsum-rich substrate at the
221 edge of Guallar Lake, GLR3, where together gypsum and carbonate accounts for about 90% of the soil

222 composition (Figure 4A). The greatest CEC value (14 cmol+ kg^{-1}) is found in soils with the highest
223 OM content in both of the wetlands: in the slightly saline agricultural soil GA22; and in the very
224 strongly saline soil GLR7 covered with *Suaeda vera* (Figure 2). CEC shows a significant negative
225 correlation with increasing sand-sized particle content ($r=-0.73$, $p<0.05$).

226

227 3.2.2. Nutritional status of plants

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

234 Considering the plant nutrients for crops and halophytes separately, in Gallocanta, P increases slightly
235 along the transect, downslope to the lake, from 3.5‰ to 4.3‰ in cereals and from 0.7‰ to 1.6‰ in
236 halophytes. Likewise, the N content of halophytes increases slightly towards the lake (from 1.3% to
237 1.9%), although the crops maintain similar N values along the transect (mean = 3.5%). In Guallar the
238 mean P content is quite similar for all the sites along the transect (mean 1.4 ‰), and the N increases
239 towards the wetland, from 0.8% to 1.9%. No relationship was found between plant N and P content
240 and soil salinity.

241 The nutritional indexes, PNI and NNI, of crops are around 100% in Gallocanta in the three agricultural
242 sites (Table 2), whereas the wheat nutritional indexes in Guallar are below the critical value of 80%.

243 The nutritional indexes calculated for halophytes are low in both wetlands; the PNI and NNI are
244 slightly higher in Guallar than in Gallocanta. The NNI varies between 35.7% at GA20 (*Puccinellia* sp.
245 and *Limonium* sp.) and 72% at GLR7 (*Suaeda vera*), and the PNI varies between 29%, also at GA20,
246 and 59% at the edge of the Gallocanta wetland, at GA19 (Table 2). The overall plant N/P ratio ranges
247 from 7.7 to 19.0 in Gallocanta, and from 6.2 to 12.7 in Guallar. On average, the halophytes present a
248 higher N/P ratio (14.7) than the crops (8.6).

249

250 3.2.3. Biomass and conditions for plant development

251 The lowest mean above-ground biomass in Gallocanta was 2.2 t ha^{-1} , corresponding to the halophytes
252 *Puccinellia pungens* and *Limonium* sp. at GA21, whereas the highest biomass was produced by crops,
253 reaching 4.3 t ha^{-1} at GA22. Along the Gallocanta transect towards the edge of the wetland, the cereal
254 biomass decreased and that of the halophytes increased (Table 2). The mean biomass was higher in
255 Guallar than Gallocanta, both for crops and halophytes. The lowest biomass value was 3.6 t ha^{-1} ,
256 relating to *Suaeda vera* at GLR7, and the highest biomass, 8.2 t ha^{-1} , corresponded to wheat at GLR6,
257 (Table 2). The spring (April-May) above-ground biomass was very variable between years and sites,
258 with a standard deviation of up to 95%, as was the case of sampling site GA22. Local differences of
259 about 1.2 t ha^{-1} were also observed within the same agricultural plot in Gallocanta (GA31 and GA32)
260 (Figure 2B). No relationship was found between plant biomass and soil salinity. In Guallar the
261 biomass showed a significant negative correlation with the gypsum content ($r=-0.88$, $p<0.05$, $n=6$).
262 On average, the first survey year was the wettest, with 282.1 mm of accumulated rainfall from October
263 to March in Guallar, and 347.2 mm in Gallocanta. Monthly rainfall during this period was very
264 variable between years (Figure 5), the highest standard deviation being in October, with 49.7 mm in
265 Guallar and 43.3 mm in Gallocanta. The wettest and the driest months were always November and
266 December, respectively, for the two wetland areas (66.9 mm vs 10.2 mm in Guallar, and 76.0 mm vs
267 19.3 mm in Gallocanta).
268 Considering halophytes and crops together, in Guallar the mean TT was $200 \text{ }^{\circ}\text{Cday}$ higher and the
269 accumulated rainfall was 20% lower than in the Gallocanta area. The 2015 growing season was very
270 dry for the halophytes in Guallar (Table 3). Mean HUE for halophytes (Table 3) was slightly higher in
271 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
272 higher mean HUE than halophytes, especially in Guallar, with $14.3 \text{ kg ha}^{-1} \text{ }^{\circ}\text{Cday}^{-1}$ versus 10.9 kg ha^{-1}
273 $\text{ }^{\circ}\text{Cday}^{-1}$ in Gallocanta. Maximum HUE values were seen in 2014 in the two wetland areas. Overall, no
274 relationship was found between HUE and the accumulated rainfall during the growing season.
275 The cereal biomass showed significant correlation with both TT ($r = 0.67$, $p<0.005$) and rainfall ($r = -$
276 0.77 , $p<0.05$), the latter being negative.

277

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278 4. DISCUSSION

279 4.1. Variations in soil properties along the transect

280 The heterogeneity of soil properties found along the studied soil transects is related to differences in
281 soil morphology and sediments in these highly dynamic environments (Castañeda et al., 2013; 2015),
282 especially in Gallocanta, due to the significant size of the lake (14.4 km²). Moreover, the upper soil
283 layer studied is the most influenced by rains and the intermittent flooding of the saline lake (Luna et
284 al., 2016). Interestingly, the conspicuous pattern of agricultural fields in narrow strips (typically 30 m
285 wide), oriented perpendicularly to the lake edge (Figure 3 in Castañeda et al., 2015), results from the
286 inheritance of land plots with similar agricultural value.

287 The smaller size of Guallar playa-lake (0.15 km²), together with its lower flooding frequency and the
288 relatively higher slope of the sampling transect (1.4%, Figure 2A), constrain the effects of the flooding
289 on the wetland margins leading to a simpler succession of very distinct environments from the cereal
290 to the lake. Additionally, the shorter length of the soil transect in Guallar seems to facilitate the
291 recognition of soil property gradients, such as increased soil salinity, pH, and gypsum content, and
292 decreased carbonates towards the lake (Figure 4; Table 2). In other wetland environments, the
293 variability of the soil properties, including nutrient content, along wetland margins has been associated
294 with differences in topography, flooding frequency, and sediments, among other factors (Stolt et al.,
295 2001).

296 The CEC of the agricultural soils is below the value reported by Garrido (1994) as indicative of a poor
297 soil for crop production (20 cmol⁺ kg⁻¹). The low to moderate cation exchange capacity of the studied
298 soils (2.4 - 14.2 cmol⁺ kg⁻¹) is similar to that observed in other saline wetland soils with a very low
299 clay content (Edem and Ndaeyo, 2009), about 11-16 cmol⁺ kg⁻¹. The high percentage of sand-sized
300 grains in the studied soils conditions their low CEC values and, as a consequence, there is reduced
301 nutrient fixation (Scotney and Dijkhuis, 1990; Gaines and Gaines, 1994; Abe et al., 2009). Moreover,
302 due to the sandy texture, the exchangeable cations in the low-CEC soils are very susceptible to
303 leaching or being washed by rain towards the lake. Differences in soil nutrient content related to soil
304 texture were also observed by Muhammad et al. (2008) in agricultural areas within a soil salinity
305 gradient. The low CEC value of the soil at the edge of Guallar Lake could be conditioned by the sandy

306 texture resulting from the high gypsum content (72.2%). Moreover, gypsum-rich soils limit plant and
307 root growth in certain ways related to soil water-holding capacity, and nutrient and water availability,
308 as observed in previous studies in the area (Rodríguez-Ochoa and Artieda, 1999; Castañeda and
309 Moret-Fernández, 2013).

310

311 4.2. Nutrient availability in soils and plant nutritional status

312 The Total N content of the cereal soils studied (0.9 - 2.9 g kg⁻¹) is within the normal range established
313 in Brady and Weil (2002) for surface mineral soils (0.2 - 5.0 g kg⁻¹). Even the soil N content in the
314 Guallar wheat-growing area is twice as high as the mean content (1.5 g kg⁻¹) indicated by these
315 authors. The available P content in cereal soils (from 23.8 mg kg⁻¹ to 66.7 mg kg⁻¹) is very high
316 according to the mean value reported by Davidescu and Davidescu (1982) for agricultural soils (20 mg
317 kg⁻¹). Available P is also higher than the critical value above which the wheat yield does not respond
318 significantly to P fertilizer: 16.3 mg kg⁻¹, according to Tang et al. (2009); or 7.8 mg kg⁻¹ after Colomb
319 et al. (2007). The soil C/N ratio varies between 3.7 and 9.2, and is lower than the median (C/N = 12)
320 reported by Brady and Weil (2002) for agricultural soils, indicating that plants are somehow limited in
321 releasing nutrients from the soil (Troeh and Thompson, 2005).

322 The total N content of the halophytes soils (1.0 - 1.6 g kg⁻¹) is similar to that obtained in the
323 corresponding cereal-cropped soils, but slightly lower than the values reported in other saline wetlands
324 (1.6 to 4.1 g kg⁻¹; Edem and Ndaeyo, 2009).

325 The decrease in soil nutrients along the Guallar transect towards the lake and the high available P
326 content in the halophyte fringe, in both wetlands, could be related to the mobilization of nutrients
327 downslope due to runoff and/or subsurface water flows. Actually, in spite of the scarcity of rainfall,
328 the available P found in the halophyte fringe can be as much as 71% (GLR7, 16.9 mg kg⁻¹) of that
329 found in the cereal soil upslope in the transect. There is also a similar percentage of total P (75%).
330 Probably due to the lower gradient of the Gallocanta transect, the halophytes soils only accumulate
331 26% of the total P, and 11% of the available P found upslope in the cereal-cropped soils. The available
332 data on surface water chemistry in Gallocanta Lake shows a P content from 0.1 mg L⁻¹ to 0.5 mg L⁻¹
333 (CHE, 2013). Moreover, since P adsorption and release is highly affected by intermittent flooding

334 events (Tian et al., 2017), the P released into the surface water of Gallocanta Lake may accumulate in
335 the soil at the lake edge, especially under anaerobic conditions (Castañeda et al., 2017), as probably
336 occurs at GA19 (7.4 mg kg^{-1} , Table 2).

337 In general, the N and P content of cereals are within the common ranges established by Davidescu and
338 Davidescu (1982), $N = 2 - 4\%$ and $P = 3 - 6\%$, in accordance with the nutrient availability of the
339 soils. The low N and P content of the wheat in Guallar is an exception, even more so when taking into
340 account the high total N and available P in the soil (Table 2). Probably, the low C/N ratio of this soil,
341 (3.7) limits plant nutrient release (Troeh and Thompson, 2005), even if fertilizers are used. Also the
342 nutritional indexes, $PNI = 62.6\%$ and $NNI = 37.4\%$, are considerably lower than the critical value of
343 80% below which cereal growth is limited (Duru and Ducrocq, 1997). In contrast, the nutritional
344 indexes of cereals in Gallocanta are close to 100% (Table 2) indicating that there are non-limiting
345 nutrients for plant growth, in agreement with the soil nutrient availability, usually ensured through
346 fertilization. Some samples even have index values over 100% , as is the case of the PNI value at
347 GA31 and NNI at GA32 (Table 2), indicating a luxury consumption of nutrients above crop
348 requirements.

349 With regard to halophyte nutrients, the N and P contents (mean $N = 1.6\%$ and $P = 1.2\%$) are similar to
350 those reported in other salt-tolerant species by García and Mendoza (2008), $N = 1.5\%$ and $P = 1.4\%$,
351 and also similar to those obtained in April by Rathore et al. (2016) for *Salicornia brachiata*, $N = 1.5\%$
352 and $P = 1.1\%$. However, PNI and NNI are lower than 80% , indicating nutrient limitation (Duru and
353 Ducrocq, 1997). No specific nutritional indexes and N/P ratio thresholds for halophyte growth have
354 been found in the literature. The PNI and NNI indexes applied to halophytes result in very low values,
355 especially in Gallocanta ($< 30\%$, Table 2). Also the mean N/P ratio (16.2) is above the critical value of
356 nutrient limitation (14) established by Koerselman and Meuleman (1996) for plant growth in
357 freshwater wetlands. However, although a low nutritional status or plant growth could be inferred
358 from these indexes, it must be considered that on the sampling dates the halophilous plant species
359 presented a significantly earlier phenological stage than the cereals. Moreover, in Gallocanta there was
360 limited plant growth compared to the more advanced development stage of halophytes in the warmer
361 climate of Guallar.

362

363 4.3. Biomass variability

364 The local climatic conditions of the Gallocanta and Guallar study sites are associated with their
365 relative locations in the Ebro basin and their distinct elevations, 1000 m a.s.l and 336 m a.s.l,
366 respectively (Figure 2). The higher aridity of the Guallar area is evidenced by the lower level of
367 accumulated rainfall and higher TT. In nearby areas of the Ebro Basin, wheat yields have been related
368 to seasonal rainfall (McAneney and Arrúe, 1993). However, we found no clear relationship between
369 cereal biomass in spring and accumulated rainfall (Table 3). In fact, the variability of the accumulated
370 rainfall (Figure 5), TT, and heat use efficiency over the three campaigns (Table 3), must have directly
371 affected the high variability of the biomass obtained, both in crops and halophytes (Table 2). Due to
372 the late sampling date in 2014 (May, 25-29), that year's biomass results are probably less easy to
373 compare than those obtained in April 2013 and 2015.

374 Although barley and wheat are two of the most salt-tolerant cereals (Ayers and Westcot, 1976) they
375 can still be affected by soil salinity (Setter et al., 2016), especially during germination (Munns and
376 Tester, 2008), when the ECe should not exceed 4-5 dS m⁻¹ (Ayers and Westcot, 1976). In Gallocanta,
377 the salinity of agricultural soils is far below the critical ECe value at which the yield production starts
378 to decrease (6 dS m⁻¹ and 8 dS m⁻¹ for wheat and barley, respectively, Ayers and Westcot (1976)).
379 Nevertheless, even if the upper soil layer is non-saline, the seasonal rising of the saline water table and
380 /or the occasional waterlogging reported by local farmers can reduce crop development. Saline
381 groundwater is common in topographically low areas neighboring the halophyte fringe (Castañeda et
382 al., 2015) and local soil salinity can explain the difference in wheat biomass obtained within the same
383 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
384 ha⁻¹) is similar to that produced by *Salicornia brachiata* in salt marshes in India, which had a mean of
385 4 t ha⁻¹ (Rathore et al., 2016). The high biomass (7.0 t ha⁻¹) found in the most strongly saline soil in
386 Guallar, GLR7, was probably favored by the high cation exchange capacity and the available nutrients
387 that had come from the adjacent agricultural plot.

388

389 5. CONCLUSIONS

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390 Based on N and P contents, the soil nutritional status of the two saline wetlands studied is good, and
391 suitable for plant growth despite the soil salinity. Overall, soils in the cropped areas show a higher
392 mean nutrient content than the natural areas, as expected due to the use of fertilizers. However,
393 halophytes soils can display a similar N content to cereal soils and, in some sites, a high concentration
394 of available P. The nutrients move downslope, along the soil transects, and accumulate in the
395 halophyte areas closer to the lake. This transfer of nutrients towards the wetlands is favored by the
396 predominantly sandy texture, especially in the case of the gypsum-rich soils. Plant nutrients show no
397 relationship with soil nutrients, as revealed by the low nutritional indexes in Guallar and the relatively
398 low halophyte biomass in Gallocanta. Low nutritional indexes for crops and halophytes, indicative of
399 nutrient uptake limitation by plants, occur in soils with salinity, a high gypsum content, and a low C/N
400 ratio, especially under the arid conditions found in Guallar. Low PNI and high N/P ratios indicate that
401 P is more limiting than N for halophyte growth. Only the cereal in Gallocanta has non-limiting
402 nutrients for growth. Soil salinity can extend beyond the halophyte fringe though no relationship with
403 biomass was found. The halophyte fringes of the studied wetlands are important as they can act as
404 nutrient retention areas. Knowledge of soil and plant nutritional status is crucial for reconciling the
405 preservation of habitats with production, and can be used in decision-making processes regarding land
406 use and agricultural management.

407

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413

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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 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 soil:water 1:2.5 extract; and CCE: calcium carbonate equivalent.

Sampling site	EC1:5	ECe*	pH1:2.5	Gypsum	CCE	Organic matter	Sand	Silt	Clay	USDA Textural class
	dS m ⁻¹									
<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	45.26 \pm 0.02	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 0.02	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 10.87	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							

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

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

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Table 2. Soil nutrient content and cation exchange capacity (CEC), and plant nutrient content in Guallar (GLR) and Gallocanta (GA). Three-year mean \pm standard deviation. PNI: phosphorous nutritional index; NNI: nitrogen nutritional index. Shadowed rows correspond to the sampling sites located within the halophyte fringe.

Sampling site	Soil				Plant						
	Total P	Available P	Total N	C/N	CEC	P	N	N/P	Biomass	PNI	NNI
	g kg ⁻¹	mg kg ⁻¹	g kg ⁻¹		cmol+ kg ⁻¹	‰	%		t ha ⁻¹	%	%
<i>Guallar</i>											
GLR3	0.58	2.2 \pm 0.0	1.0	7.0	2.4	1.5 \pm 0.5	1.8 \pm 0.4	12.2	3.6 \pm 0.7	55.39 \pm 16.08	56.8 \pm 12.25
GLR7	1.38	16.9 \pm 3.9	1.5	15.0	14.1	1.4 \pm 0.4	1.9 \pm 0.1	12.7	6.9 \pm 1.2	54.1 \pm 13.5	72.01 \pm 8.08
GLR6	1.85	23.8 \pm 11.1	2.9	3.7	11.2	1.3	0.8	6.2	8.2	62.6	37.4
<i>Gallocanta</i>											
GA19	0.55	7.4 \pm 5.2	1.2	8.8	9.1	1.6 \pm 0.3	1.9 \pm 0.6	11.5	3.7 \pm 2.2	59.5 \pm 0.2	54.5 \pm 3.9
GA20	0.58	2.3 \pm 0.3	1.3	10.0	11.0	0.7 \pm 0.04	1.2 \pm 0.2	18.1	3.0 \pm 0.3	29.1 \pm 0.2	35.7 \pm 6.9
GA21	0.11	2.6 \pm 0.6	1.6	8.1	9.2	0.7	1.3	19	2.2	29.7	36.2
GA31	1.57	66.7 \pm 12.7	1.3	9.2	12.6	4.3 \pm 1.2	3.3 \pm 0.9	7.7	3.0 \pm 2.2	116.8 \pm 13.4	93.6 \pm 41.4
GA32	1.26	66.2 \pm 4.2	0.9	8.2	7.4	3.9 \pm 1.5	3.7 \pm 1.5	9.4	4.2 \pm 3.1	98.4 \pm 14.9	109.7 \pm 27.5
GA22	1.03	64.5 \pm 20.7	1.7	7.7	14.2	3.5 \pm 1.2	3.4 \pm 1.8	9.5	4.3 \pm 4.1	95.4 \pm 4.3	91.0 \pm 35.9

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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	58.73	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

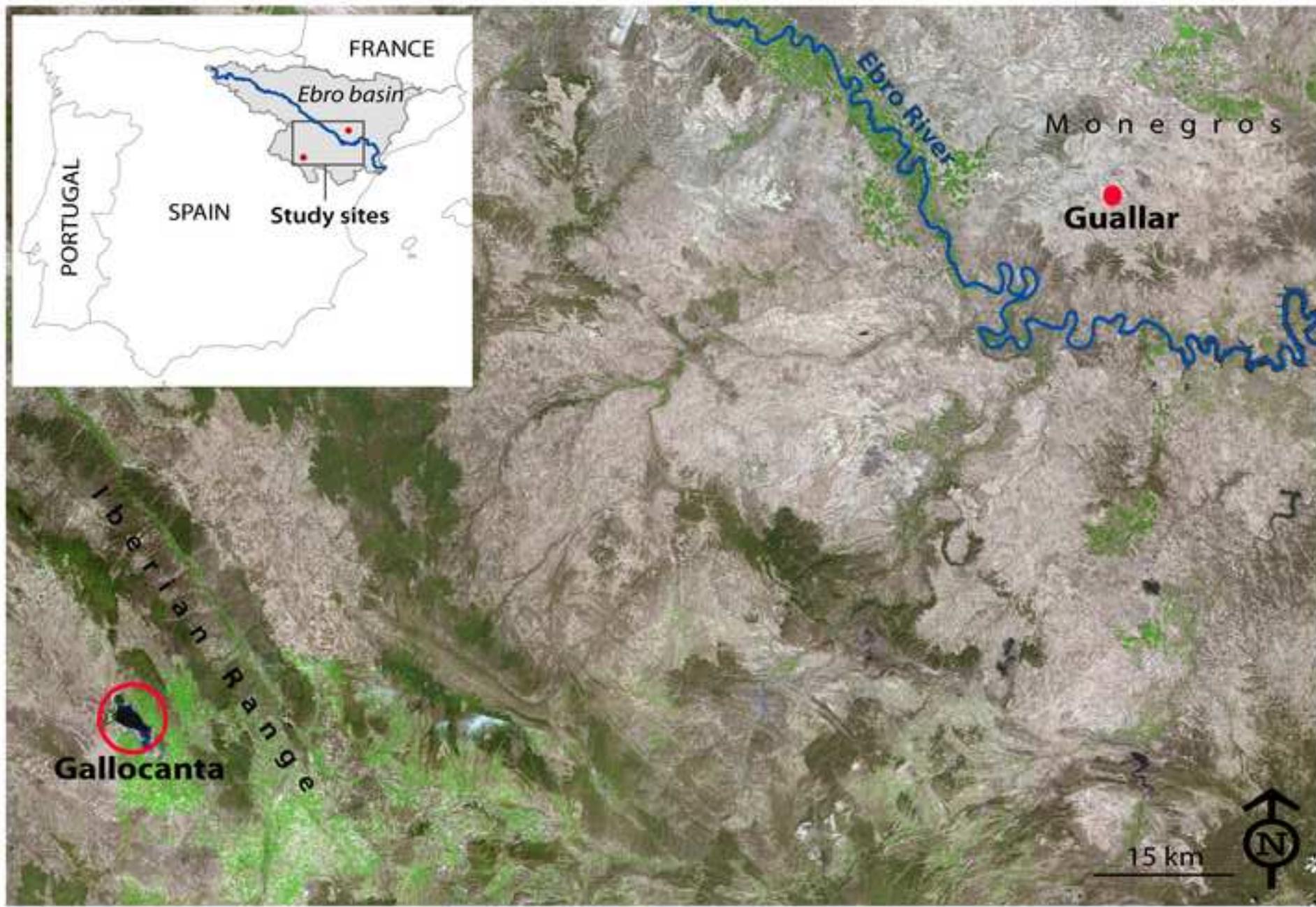
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Figure1

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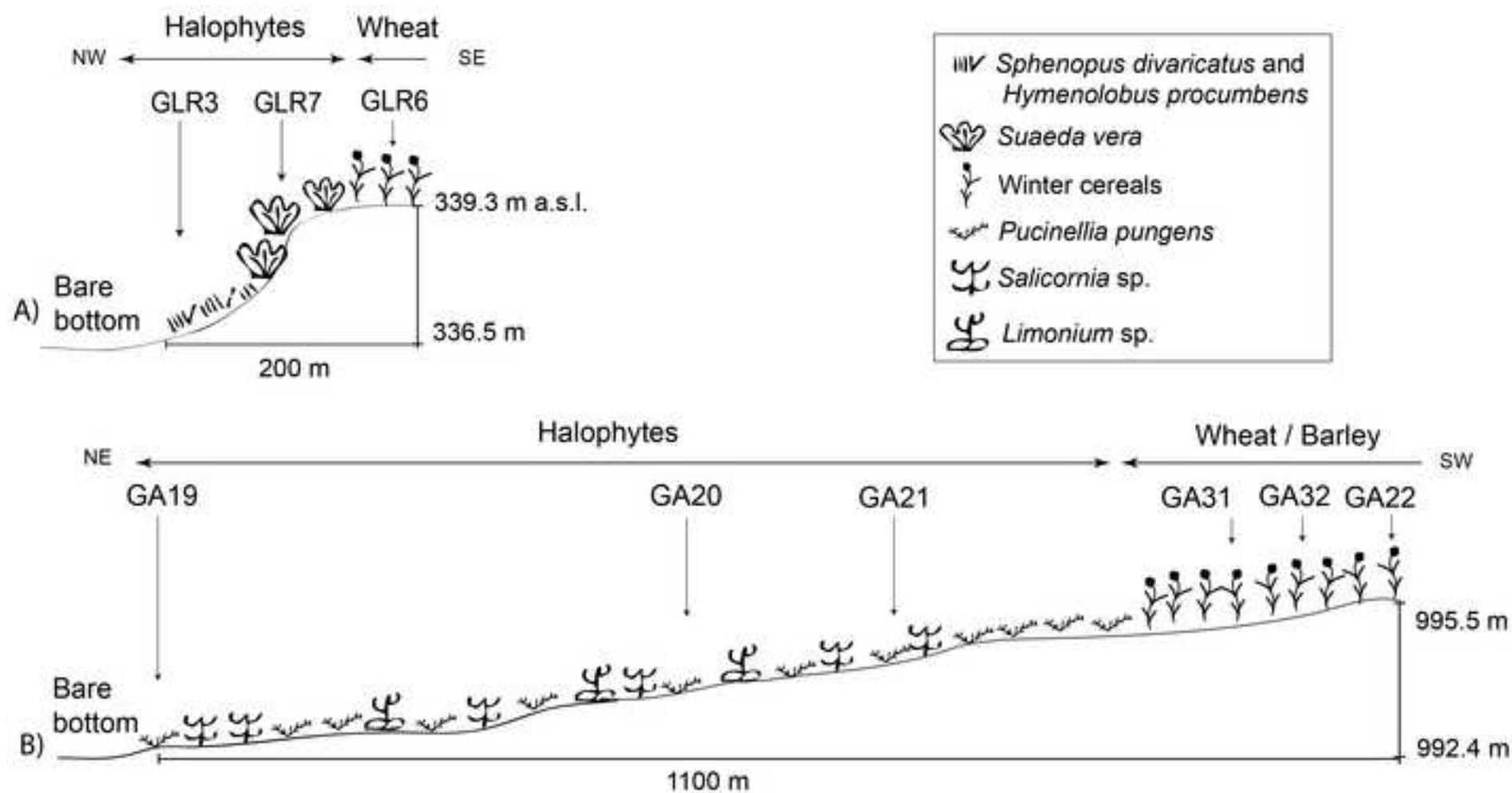
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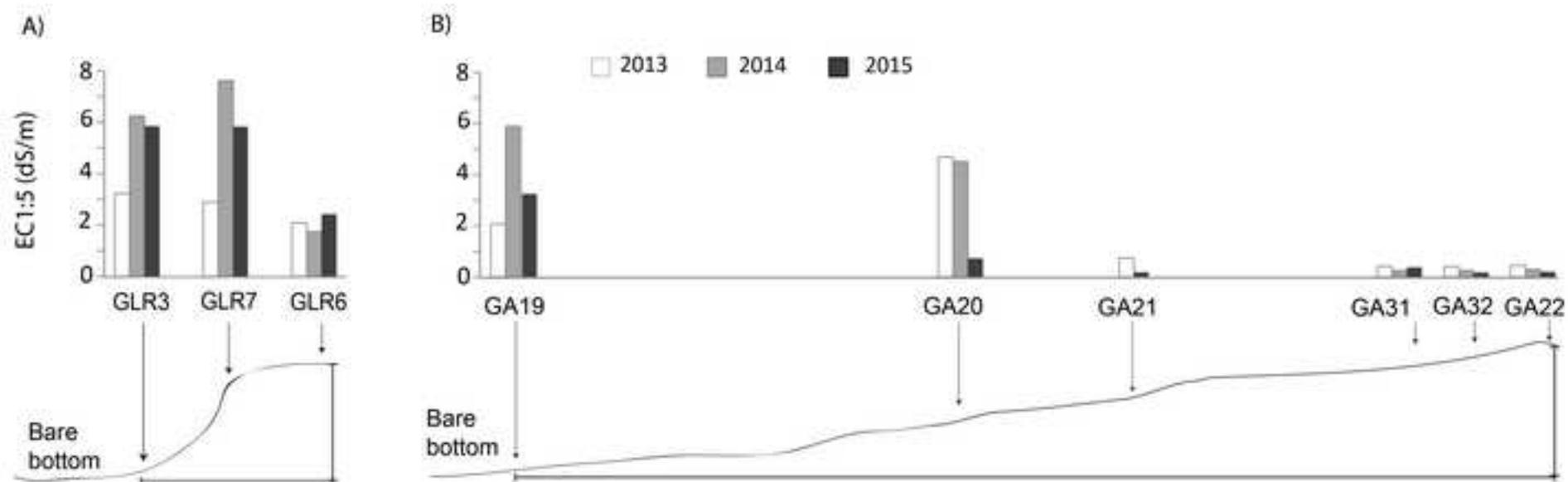


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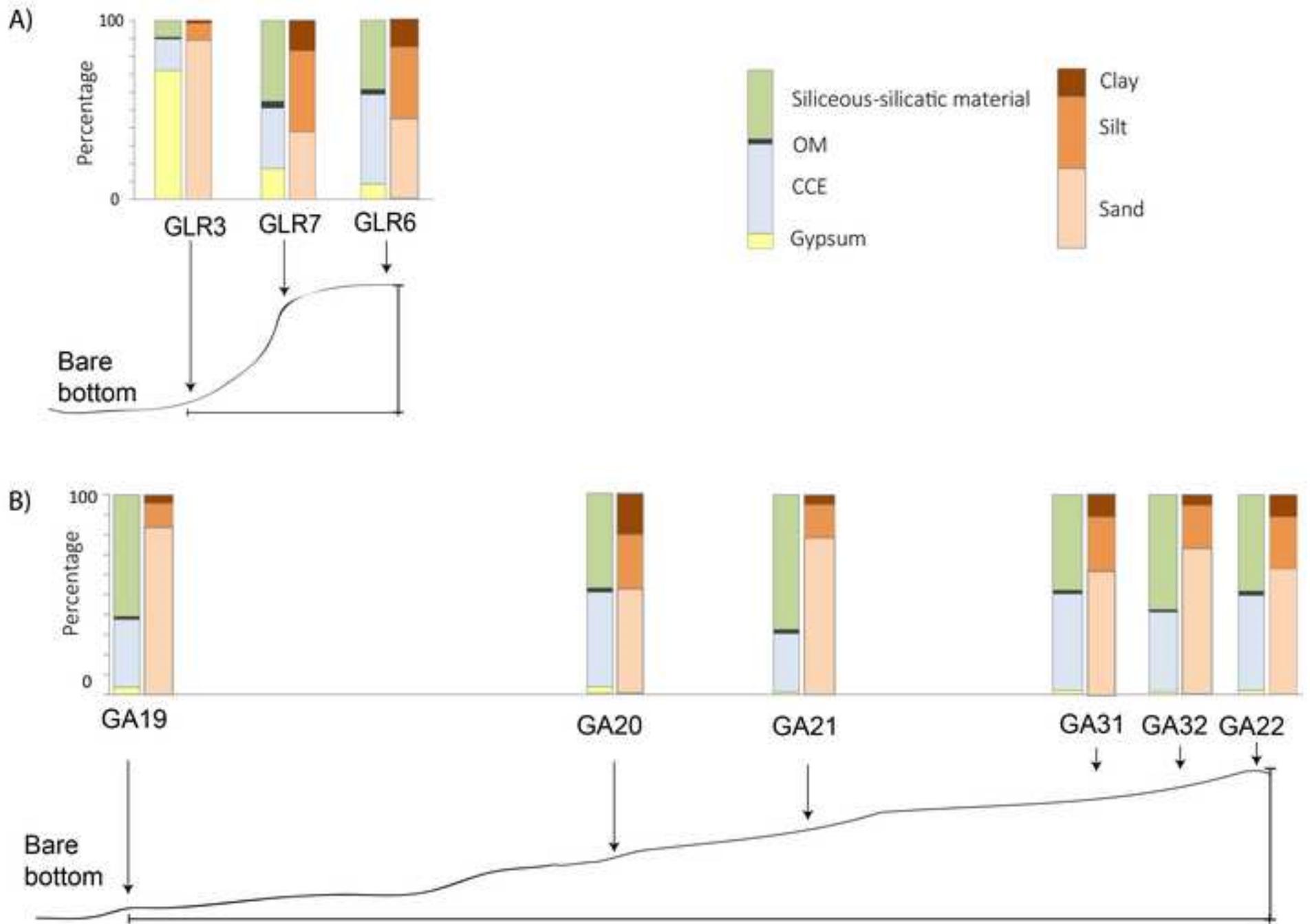
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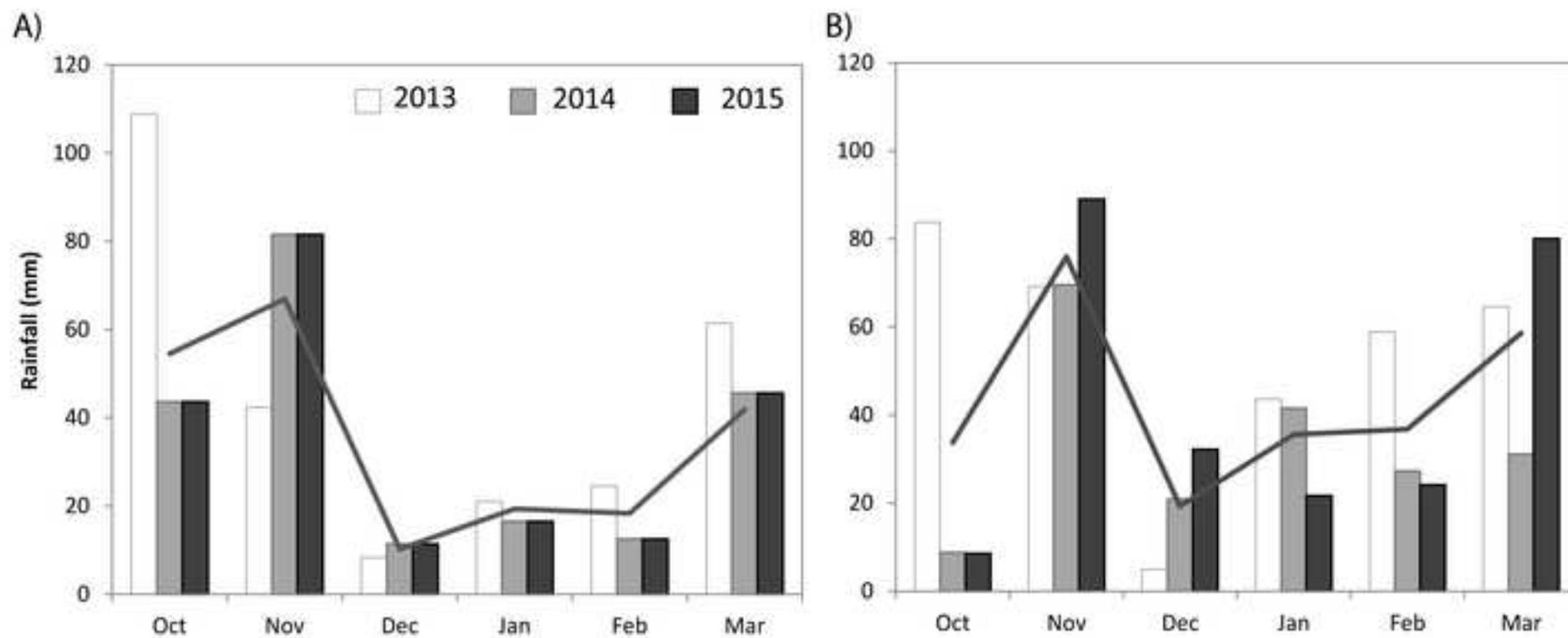
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