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Contribution of soil properties to the assessment of a seawater irrigation programme as a management strategy for abandoned solar saltworks

M.N. González-Alcaraz [a,*], B. Aránega [a], H.M. Conesa [a], M.J. Delgado [b], J. Álvarez-Rogel [a]

[a] Departamento de Ciencia y Tecnología Agraria, Área de Edafología y Química Agrícola, E.T.S. de Ingeniería Agronómica, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, Cartagena, 30203 Murcia, Spain

[b] Departamento de Química Agrícola, Geología y Edafología, Facultad de Química, Universidad de Murcia, Campus de Espinardo, Espinardo, 3100 Murcia, Spain

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ABSTRACT

The installation of desalination plants close to ecosystems of interest may have environmental impacts that make corrective measures necessary. Especially, wetlands (which are water-dependent ecosystems) are prone to degradation. This is the case for the Agua Amarga salt marsh (SE Spain), that includes an abandoned solar saltworks and surrounding, topographically higher zones, in which the groundwater withdrawal to supply two desalination plants has led to a drop of the piezometric levels and the desiccation of the ecosystem. To overcome these problems, a programme to irrigate the marsh with seawater was established. This paper reports some soil characteristics of the marsh in relation to the different types of vegetation/environment identified and the seawater irrigation programme, with the objective being to propose some guidelines to improve the management of the site. Surface and subsurface samples were taken from 63 plots and the depth of the water level and the soil redox potential (Eh), moisture, electrical conductivity (EC), $CaCO_3$, organic carbon, nitrogen and bulk density were determined. Also, the soil texture, structure, consistence, accumulation of salt crystals and redoximorphic features – indicative of reduction-oxidation processes – were described. The poor structure (weak, granular, subangular and angular blocks, very fine and fine) showed that the soils were hardly developed. The periphery (mainly colonised by *Suaeda vera*, *Lygeum spartum* and *Limonium* spp.) was less saline (EC 1:5 in the upper layers ~0.4 to ~4 dS m^{-1}) and drier (water level > −1.5 m depth) than the abandoned saline ponds (EC 1:5 in the upper layers ~2 to ~9 dS m^{-1} and water level between −1 m depth and +0.2 m above the soil surface), mainly colonised by *Sarcocornia fruticosa*, *Arthrocnemum macrostachyum*, *Salicornia patula*, *Phragmites australis* and *Ruppia maritima* in the flooded ponds. The soils of the periphery were always oxic (Eh > +500 mV), but most of the abandoned saline ponds had suboxic (~ +100 mV < Eh < ~ +350 mV) and even anoxic conditions (Eh < ~ +100 mV), as shown by the existence of gley colours and redoximorphic features. The soil bulk density of the surface and subsurface layers showed that the most impermeable ponds were located in the centre of the marsh, where it is possible to maintain a surface water sheet during prolonged periods, suitable for the development of submerged plant species such as *R. maritima* and for waterbirds. Part of the seawater poured into more permeable ponds, such as those located in the southern and northern zones of the marsh, is lost by infiltration due to the lower bulk density of these soils. The latter facilitates the recovery of the piezometric levels and the growth of terrestrial plant species. Monitoring of redoximorphic features in the upper soil layers, in combination with symptoms of damage in the plants, could be used as a visual indicator of oxygen limitation due to excessive soil moisture. This would permit the regulation of the irrigation programme, hence optimising the energy and economic resources applied to maintain the ecosystem.

1. Introduction

For centuries, the salt extraction industry was an important economic activity in the Mediterranean basin. The general term “solar saltworks” has been used to describe the site and/or the installation where the salt making process takes place. It consists of a series of interconnected ponds through which seawater flows and, as the water is evaporated by solar energy, it becomes increasingly salty in successive ponds (Davis, 2000). The high chemical quality and yield of the salt produced made the solar saltworks profitable. However, since the mid-20th century, the salt industry has faced a deep crisis in the form of territorial pressures, changes in hydric systems, development of cold storage techniques and competition from lower priced, industrial salt. The resulting low profitability led to increasing desertion of small solar saltworks (Crisman et al., 2009). The abandonment of salt extraction and further activities may lead to the degradation and irreversible loss of these types of

* Corresponding author at: Department of Ecological Science, Faculty of Earth and Life Sciences, VU University, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands. Tel.: +31 20 5987079; fax: +31 20 5987123.
E-mail addresses: m.n.gonzalezalcaraz@vu.nl, nazaret.gonzalez@upct.es (M.N. González-Alcaraz).

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wetlands (Petanidou and Dakala, 2003; Sadoul, 2002). It is widely accepted that wetlands are ecosystems with valuable services, such as provision of food and shelter for many organisms (Beck et al., 2001; López et al., 2010), retention and/or inactivation of harmful substances (Mitsch and Gosselink, 2007), carbon sequestration (Reddy and DeLaune, 2008) and biodiversity preservation (European Communities, 2007). However, the European Commission (2002) cited wetlands as being among Europe's most threatened ecosystems and Verhoeven (2013) indicated that around 80% of the original area of the European wetlands has been lost in the past millennium. Therefore, marsh restoration is a ubiquitous practice to mitigate the loss of these ecosystems, as well as their associated environmental and economic benefits (Sparks et al., 2013). Higher public visibility of the restoration programmes is necessary, to boost the recognition of these efforts (Kaza and BenDor, 2013).

One of the impacts that may contribute to wetlands degradation is desiccation. This can be due to prolonged dry periods (e.g. as a consequence of climate change) and/or to anthropogenic activities, such as extraction of groundwater for agricultural or industrial activities. Groundwater withdrawal to supply desalination plants is one of the activities that might lead to a depression of the water table. Desalination is a suitable option to supply water to populations, mainly in arid and semiarid regions where hydric resources are scarce. From an engineering and economic point of view, there is an advantage in placing desalination plants close to the shoreline, due to the availability of saline water (Einav and Lokiec, 2006). However, corrective measures must be taken to overcome the impacts caused by these plants, particularly if they are adjacent to areas of high natural interest such as wetlands, which are water-dependent ecosystems. This is the case of the Agua Amarga salt marsh.

2. Site description

The Agua Amarga salt marsh is a Municipal Natural Park of ~180 ha, located near the city of Alicante (SE Spain) and included in the Valencia Community wetlands catalogue (Fig. S1, Supplementary material). The climate of the zone is Mediterranean semiarid (annual average temperature ~18 °C; annual average precipitation ~300 mm; annual evapotranspiration rate ~850 mm year^{-1}). The salt marsh comprises the ponds network from a former solar saltworks (altitude ~ <1 m a.s.l.), in commercial use between 1925 and 1969, and its surrounding, topographically higher areas (altitude ~1 to 3 m a.s.l.). Most of the soils of the salt marsh can be classified as Solonchaks (IUSS-WRB, 2007).

In 2003 two desalination plants (D-I and D-II) were installed at the northern edge of the marsh. Plant D-I withdraws groundwater from the aquifer located below the saltworks by means of 33 vertical wells, while D-II extracts seawater from 118 wells located inside a 1-km-long tunnel, parallel to the shoreline, plus 11 horizontal directional drillings lying on the seafloor. The constant water withdrawal of plant D-I caused a progressive lowering of the aquifer piezometric levels (from between ~−2.5 and −5 m to between ~−4 and −7 m; Alhama, 2011), which contributed to its salinisation as well as to the degradation of the marsh habitats due to their increased desiccation.

To correct these impacts, a seawater pumping programme commenced in 2009. In this programme, part of the seawater extracted by the tunnel system is poured over the ponds of the former saltworks by means of a system of buried pipes (Photograph S1, Supplementary material). The network of saline ponds was divided into four zones with different irrigation programmes (Fig. S1, Supplementary material). Most areas in Zones 1, 2 and 3 correspond to the former evaporation and crystallisation ponds and most of Zone 4 to the former salt store deposits (Box, 1987). The amount of seawater pumped into each zone depends on the conditions of the underlying aquifer and the presence of different habitats in the salt marsh (Alhama et al., 2012b). Between 2011 and 2012, the amounts of seawater pumped were the following. Zone 1 (a total of 357,113 m^3 of seawater pumped) was irrigated three days a week in December 2011 and twice a week from January to June 2012. Zone 2 (a total of 363,771 m^3 of seawater pumped) was irrigated twice a week from November 2011 to June 2012, except for some ponds that were additionally irrigated three days more each week in January 2012 and one day more each week in April 2012, to maintain a permanent water sheet (hereafter, ponds with prolonged irrigation). Zone 3 (a total of 56,716 m^3 of seawater pumped) was irrigated in May 2012, five days a week. Zone 4 was not irrigated, except for three ponds next to those with continuous irrigation. Alhama et al. (2012b) stated that the seawater recharge programme had aided the hydric recovery of the aquifer, with an increase in the piezometric levels of between 1 and 4 m. Also, and in spite of the irrigation with seawater, these authors found a general decrease in the electrical conductivity (EC) of the groundwater due to the dilution of the salts.

3. Objective and hypothesis

The aim of this study was to contribute to the assessment of the effects of the seawater irrigation programme in the salt marsh. The paper describes the main physical, chemical and physico-chemical characteristics of the marsh soils, in relation to the different types of vegetation/environment identified and to the seawater irrigation programme, as well as some guidelines for improving the management of the area. This work is complementary to a previous paper in which the spatial-temporal gradients of salinity, moisture and redox potential were related to plant distribution by means of multivariate analysis (González-Alcaraz et al., 2014a). Our hypothesis was that knowledge of the soil conditions might help to identify some effects of the irrigation programme and to establish some recommendations for improving it.

We expected that the soils with physical properties indicative of low permeability would be those with higher capacity to support longer flooding periods and, if so, then morphological characteristics such as redoximorphic features should show the effects of flooding. Because we did not measure infiltration rates, characteristics such as colour patterns in the soil profile could act as an approach to the behaviour of the infiltration water.

4. Materials and methods

4.1. Soil sampling and data collection

The sites for the collection of soil samples were chosen based on the vegetation distribution inside the salt marsh. After several field trips, and with the help of aerial images, a total of 63 sampling plots were located (Fig. S1, Supplementary material). They were distributed throughout the marsh, to represent the physiographic variability, different types of vegetation/environment and the irrigation regimes (Table S1, Fig. S1 and Photographs S2 to S5, Supplementary material). In each plot, the percentage of species cover was estimated visually and 12 types of vegetation/environment were established according to the dominant species (species representing more than 50% ground cover among the species growing within the plot) (Table S1, Supplementary material).

The periphery of the salt marsh was dominated by halophilous shrubs of *Suaeda vera* (Sv), dense stands of the steppe grass *Lygeum spartum* (Ls) and formations of shrubs with several *Limonium* species (L). The ponds of the abandoned solar saltworks were mainly occupied by the succulent halophytes *Sarcocornia fruticosa* (Sf) and *Arthrocnemum macrostachyum* (Am). *Sarcocornia fruticosa* formed dense stands while *A. macrostachyum* was growing in disperse patches with areas of bare soil among them — these were sampled separately (BsAm). In the southern part of the marsh, a great number of new seedlings of *A. macrostachyum* (AmSd) appeared, growing among the patches of the mature plants. Also, there were mixed stands with co-dominance of *S. fruticosa* and *A. macrostachyum* (Sf + Am). The succulent halophyte *Salicornia patula* (Sp), with an annual life-form (a terophyte), was observed in the southern part, growing among the plants of *S. fruticosa*