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Multivariate analysis of soil salination-desalination in a semi-arid irrigated district of Spain

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ABSTRACT

Long-term studies of the changes in soil salinity are scarce and most overlook individual ions. Here, we assess changes in soil ionic contents using 42 soils repeatedly sampled during three campaigns over 24 years in a semi-arid irrigated district. Multivariate analysis (MVA) was used to evaluate the spatial distribution of ions and the temporal changes at comparable soil depths in relation to environmental and management factors. In general, the position of the soil in the landscape governed the spatial distribution of the salinity, while the temporal variations were related to irrigation, with incidences depending on the location in the district. Many soils on the slopes and foothills became salinated during the first years due to land leveling, but salination eventually tapered off after sprinkler utilization. At high and middle elevations, most soils were slightly saline in the first campaign but underwent desalination during the study period. At lower elevations, an initial desalination was followed by a pronounced salination, which was attributed to a water table rise with generalized irrigation in the basin. Whereas univariate salinity assessment might lead to conclusions that are over-simplistic at the landscape scale, MVA detects singular behaviors of groups of soils or single cases and has enormous potential coupled with GIS assessment of soil salinity data.

1. Introduction

Soil salinity and sodicity are the two major concerns in irrigated agriculture in dry regions of the world, and they are increasing worldwide due to poor management of water and soil resources (Shahid, 2013). Periodic information on the status of soil salinity and sodicity in irrigation districts can suggest management practices and corrective measures to improve the profitability and sustainability of irrigated agriculture (Young, 1991; Rhoades et al., 1997; Herrero et al., 2011).

Temporal monitoring of soil salinity is mainly based on the comparison of point-size data for several years (regular observations and sampling in the same point) or on the comparison of soil salination maps developed in different years (Rhoades et al., 1997; Rukhovich et al., 2013). The standard method for appraising agricultural salinity is to measure the electrical conductivity of a saturated soil paste extract (ECe—dS m^{-1}) following the United States Salinity Laboratory Staff (1954) approach. This extract can be used to determine the pH and the ionic composition of the soil solution. Focus is set on the concentration of undesirable ions, e.g., high contents of chloride (Cl^{-}) which causes toxicity in plants. Attention is also paid to the relationships between ions, e.g., the ratio of sodium (Na^{+}) to calcium (Ca^{2+}) and magnesium (Mg^{2+}), as expressed by the sodium adsorption ratio (SAR), which has long been the standard measure of potential sodication hazard for irrigated soils (United States Salinity Laboratory Staff, 1954). In recent decades, soil salinity and sodicity has been indirectly monitored through its expression on vegetative cover using remote sensing (Metternicht and Zinck, 2009; Domínguez-Beisiegel et al., 2016) or proximal sensors (Amezketa, 2007; Corwin, 2008; Herrero et al., 2011; Swanhart et al., 2014; Aldabaa et al., 2015). Studies addressing the temporal variation in the ionic composition of soil solutions are much less abundant. Most of these studies are based either on laboratory analyses of soil samples taken at different times (Pisinaras et al., 2010; Corwin, 2012; Ammari et al., 2013) or on chronosequences of soil use (Barbiéro et al., 2004; Dou et al., 2011).

Monitoring soil salinity is difficult due to its spatial and temporal variability and is complicated by management practices, such as irrigation, drainage, and plowing; by weather, and by the salinity and depth of water tables (Herrero and Snyder, 1997; Rhoades et al., 1997; Akramkhanov et al., 2011). The multivariate nature of ionic composition

Abbreviations: ECe, electrical conductivity of the saturation extract; GIS, geographic information system; MVA, multivariate analysis; PCA, principal components analysis; RDA, redundancy analysis; SAR, sodium adsorption ratio.

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makes monitoring more difficult, often resulting in different variation patterns for each particular ion or ionic ratio. In this regard, multivariate analysis (MVA) can be very useful because this technique can simplify multivariate datasets (e.g., ionic composition) without a substantial loss of information. It also allows for handling of complex and often highly collinear matrices of data, as is often the case in soil studies, and accounting for the effects of environmental and management variables (Johansson and Stenberg, 2000; Young and Hammer, 2000). There are three main classes of MVA which are used in environmental analyses: (i) cluster analysis, in which the observations are assigned into groups (clusters) on the basis of their similarity; (ii) indirect gradient analysis, such as principal components analysis (PCA), which ranks observations along variation axes that represent gradients derived from intrinsic and/or environmental factors; and (iii) direct gradient analysis, such as the redundancy analysis (RDA) in which a second set of explanatory variables is incorporated to ordination, and the effects of this set on the original variables are evaluated by regression techniques (Legendre and Legendre, 2012). Cluster and indirect gradient analysis are commonly used when studying the ionic composition of soil solutions (e.g., Mora et al., 2005; Aguilera et al., 2011), while direct gradient analysis has been used to study the effects of the ionic composition of soil solutions on vegetation (Álvarez Rogel et al., 2001; Rodríguez Rodríguez et al., 2005; Tug et al., 2012). However, direct gradient analysis has not been used frequently to study the environmental or management factors responsible for the spatial variability in the ionic composition of soil solutions. To our knowledge, no works are available that use all of these tools to examine the temporal variation in soil salinity.

In the present article, MVA (i.e., PCA, RDA, and cluster analysis) was used to analyze salinity (i.e., ECe) and sodicity/alkalinity (SAR, pH) indices as well as the salt composition (e.g., Na^+, $Ca^{2+} + Mg^{2+}$) of soil solutions, in a semi-arid irrigation district using data collected at three time steps (i.e., 1975, 1985/1986, and 1999). Our aim was to determine the usefulness of MVA to discern the temporal impact of environmental (e.g., landscape position) and management (e.g., land use) factors on the soil salt composition over this period.

2. Methods

2.1. Study area

The study was conducted in the irrigated district of Flumen, located in the Ebro basin of north-east Spain, between 41° 40′ and 42° 5′ N, and 0° 0.5′ and 0° 35′ W. The Flumen district is representative of the changes produced by irrigation in the semiarid middle Ebro Basin. In this area, salinity mostly stems from the weathering of the saliferous Miocene strata, which were often brought to the surface by the movement of soil needed to establish new irrigation districts in the middle 20th century. Currently, a significant amount of irrigated lands in the Ebro Basin are salt-affected, despite that, in the last decades, drip and sprinkler irrigation using water of low ionic content has driven the abatement of water tables and the desalination of many soils. The abatement of the salt-affection of soils in Flumen between 1975 and 1999, with a more pronounced trend in more saline soils, was reported by Herrero and Pérez-Coveta (2005); however, examining the changes in the ionic composition remained outside the scope of that study.

The studied area is bound by the rivers Flumen and Alcanadre and by the Flumen Canal (Fig. 1). The area is 263 km^2 (including non-agricultural lands). The elevation ranges from 260 m to 400 m above sea level with an overall decrease from N to S. The climate is Mediterranean semiarid; the mean-annual precipitation is 423 mm and the mean-annual temperature is 14.5 °C (Herrero and Pérez-Coveta, 2005). The potential evapotranspiration (ET_0) has an annual value of approximately 1150 mm according to the FAO Blaney-Criddle method, with the ET_0 exceeding precipitation from February to October (Martínez-Cob et al., 1998). In these conditions, irrigation practices began at least 600 years ago at the riverbanks and were extended to include most of the land in the 1950′s. The main crops are alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), forage (*Lolium multiflorum* Lam.), corn (*Zea mays* L.), rice (*Oryza sativa* L.), sunflower (*Helianthus annuus* L.), and wheat (*Triticum aestivum* L.). The traditional controlled flood basin and border irrigation is gradually being changed to sprinkling, except the rice paddies, which are inundated from May to September. Most water comes from reservoirs in the Pyrenees, and its ionic contents are low with an electrical conductivity <0.4 dS m^{-1} and an SAR < 1 $(mmol\ L^{-1})^{-0.5}$ (Nogués et al., 2000; Herrero and Pérez-Coveta, 2005). Following the FAO guidelines (Ayers and Westcot, 1994), such low electrical conductivity poses no salinity hazard but may cause slight to moderate infiltration problems, even though the SAR is low.

The geological materials are subhorizontal Miocene strata of alternating sandstone and lutite, the latter being often saliferous. The main landforms are platforms (A), slopes (B), terraces (C), and valley bottoms (D) (Table 1), and the characteristics of the soils on the different landforms are very different. The calcium carbonate content of the soils is always >25%. Saline soils are common in several landform units (B1, B2, C2, C3, C4, and D), but saline-sodic soils occur only in spots at C3, C4, and D (Nogués et al., 2000; Nogués and Herrero, 2003).

2.2. Sampling design and field work

The soil samples in this study were taken from soils cultivated under irrigation in three sampling campaigns. The first campaign was between June 26 and August 20, 1975; the second was from July 19, 1985 to June 16, 1986; and the third was between April 19 and May 15, 1999. The soil sampling campaign in 1975 was designed by INYPSA (Informes y Proyectos, S.A., Madrid, Spain), a consulting company contracted by the Spanish Government. The aim of the 1975 campaign was to serve as the base of a soil map intended for the development of the irrigated district, and the results were recorded and discussed in an unpublished report. The second and third campaigns were designed and performed by one of the authors (J.H.) to appraise the evolution of salt-affected soils. For this purpose, the strategy was to relocate and resample the sites that were sampled in 1975, using the 1975 campaign as a baseline set of data. The sites were re-sampled using an auger. Several of the sites from 1975 were excluded in the successive samplings because the documentation from 1975 made the sites difficult to locate or because the results of the analyses were illegible due to the degradation of the 1975 report.

More details about the study sites selection and field work can be found in Herrero and Pérez-Coveta (2005). In the present study, we considered only those sites where the sampling depth was considered sufficient in the three campaigns, which made 42 sites (of the 66 sites studied by Herrero and Pérez-Coveta (2005)).

2.3. Laboratory data

All soil analyses were performed on the fine earth fraction obtained after air-drying the samples and passing them through a 2 mm sieve. The soil analyses performed for the three sampling campaigns were pH in water and potassium chloride (KCl), electrical conductivity of the saturated soil paste extract (ECe), and determining the ion concentrations of Cl^-, Na^+, and ($Ca^{2+} + Mg^{2+}$) in each extract. In the second and third sampling campaigns, sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), Ca^{2+}, and Mg^{2+} were also titrated. Chemical determinations were performed per the official methods of the Spanish Ministry of Agriculture (MAPA, 1974, 1994), with some adaptations (Table 2) related to advances in laboratory equipment. As discussed in the paper by Herrero and Pérez-Coveta (2005), the high quality and coherence of the analytical results from the three sampling campaigns allowed for comparisons between these results, with some indicated exceptions.