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Digital assessment of soil-salinity dynamics after a major flood in the Niger River valley

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ABSTRACT

Salinisation threatens the sustainability of irrigated paddy fields in western Africa. To reclaim saline soils and improve the management of irrigated paddy fields, it is necessary to evaluate and monitor soil salinity in space and time. Proximal soil sensing by apparent electrical resistivity (ER) measurements can help to survey soil salinity. This study aimed to assess changes in the spatial pattern of salinity in vertisols using high resolution 3D mapping at 2 dates on an 8-ha experimental site located at Kollo, Niger, along the Niger River. For each measurement campaign, the survey combined ER and electrical conductivity (*EC*) measurements of a 1:5 soil:water extract. This procedure was performed in May 2008 and again in March 2011 after a 100-year flood of the study area by the Niger River. *EC* measurements were performed on soil samples collected at 3 depths at 140 points. ER measurements were performed at 420 points at 2 and 4 depths for the first and second campaigns, respectively. We built an inference model of *EC* using a regression-tree method for 3 prediction depths. The predictive data were the two ER measurements, their ratio and a qualitative description of land use. The maps generated by ordinary kriging of predicted *EC* revealed strong lateral salinity gradients ranging from 0.3 to 5.0 dS/m (RMSE = 0.79–0.83 dS/m). Vertical variability in salinity was also significant and its pattern could be explained by land use, mainly irrigation intensity. In 2011, salt stocks in the upper 60 cm of the soil ranged from low stocks (<2 kg/m^2) to extremely high stocks along the levee border (5.5–8.0 kg/m^2). Comparisons of the 2008 and 2011 salinity maps at 3 depths indicated stable spatial patterns and highlighted the high resilience of the system. Consequently, desalinisation efforts can only minimise soil salinity in the upper cultivated horizon.

1. Introduction

In Niger, the introduction and development of irrigated agricultural systems have increased the extent of arable soils in the Niger River valley. Irrigation has improved yields and decreased food scarcity but may enhance salinisation: concentration and precipitation of water-soluble salts such as chlorides, sulfates and carbonates of sodium, magnesium or calcium may not only occur at the soil surface but also in the subsoil and ground water. Primary salinity is linked to geological, climatic, topographic and hydrological factors without human influence, while secondary salinity, or salinisation, results from inefficient or inappropriate human activities, mainly irrigation, drainage or soil management practices (Shrestha, 2006; Szabolcs, 1992). This salinisation process threatens the sustainability of crop production in irrigated zones by decreasing yields and/or killing plants. The mechanisms by which soil salinity affects plant growth are summarised by Rengasamy (2010). In Niger, the main crop in irrigated fields is rice (*Oryza sativa*). Its threshold of salt tolerance, i.e. the maximum soil salinity without reducing yield, was established at 3.0 dS/m of electrical conductivity of saturated paste (ECe) (Maas and Hoffman, 1977). Ponded irrigation may decrease salinity in the rice root zone by inducing a downward salt flux and hindering capillary rise of salts from the water-table (Wopereis et al., 1998). In the Senegal River delta, Ceuppens et al. (1997) showed the impact of field water management and rice cropping intensity on soil salinisation. They observed that fields with two rice crops per year and drainage facilities were the least saline, followed by single-cropped fields with drainage, single-cropped fields without drainage and abandoned fields. Irrigation by continuous or intermittent ponding of water can therefore favour soil desalinisation when the soil is relatively permeable (Hoffman, 1986; Qadir et al., 2000). But in clayey soils characterised by low saturated hydraulic conductivity, salt leaching by water ponding is limited and requires large amounts of water. Adam et al. (2012) performed a desalinisation experiment in a vertisol of an unplanted 100-m^2 rice plot in the irrigated paddy fields of Kollo (Niger). Desalinisation induced by successive cycles of ponding and water removal by flushing was significant in surface layers but

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limited at depth: salt removal was estimated at 35, 23 and 11% of the initial stock at depths of 0–10, 10–20 and 20–40 cm, respectively. However, the desalinisation efficiency of ponding may be improved by tilling under water-saturated conditions, called puddling (Haëfele et al., 1999).

Managing soil salinisation requires knowing its spatial extent and evaluating its dynamics over time, especially to evaluate the efficiency of remediation techniques that aim to desalinate soils. Mapping salinity from soil samples taken at several depths is a costly and difficult operation, particularly if performed repeatedly for temporal monitoring. In addition, many geostatistical studies of soil salinity data (Douaoui et al., 2006; Hajrasuliha et al., 1980; Hosseini et al., 1994; Odeh et al., 1998; Walter et al., 2001) have shown that spatial estimates obtained from intermittent measures of electrical conductivity were of limited accuracy. Reasons for this are linked to variability in soil salinity over short distances, as well as the presence of non-stationary processes that may affect the accuracy of geostatistical methods.

Introducing auxiliary information that is correlated with soil salinity and can be acquired at a higher spatial resolution may improve the mapping of soil salinity. Many studies have shown that processing of remotely-sensed images, especially in the visible-light range, provides information that is highly correlated with salinity of soil surfaces (Khan et al., 2001; Metternicht and Zinck, 1997, 2003; Mougenot, 1993; Rahman et al., 1994). In addition, several authors have shown the advantage of combining remote sensing with measurements obtained on the ground (Bishop and McBratney, 2001; Carré and Girard, 2002; Douaoui et al., 2006; Shrestha, 2006). Nonetheless, despite its advantages for mapping salinity over vast expanses and repeating observations over time, this combination does not provide enough information to map the salinity profile, in particular detecting subsurface salinity that is not associated with surface salinity.

The use of surface geophysical methods, often called “proximal soil sensing” (Fouad et al., 2007; Viscarra Rossel et al., 2010), was tested in the 1980s to understand better the vertical variability of soil salinity and increase its spatial resolution. The set of geophysical methods used relies on detecting the variations in electrical conductivity caused by soil salinity and is based mainly on the injection of an electric current or application of an electromagnetic field (Allred et al., 2008; Rhoades et al., 1999). These methods allow rapid and exhaustive acquisition of soil-salinity data from a large volume of soil in a non-intrusive way. It is preferable to perform non-destructive investigation as any excavation modifies the structure of the soil profile at sampling points and its hydrological functioning over a potentially larger volume. Continuous-current electrical methods or frequency-domain electromagnetic methods permit assessment of overall variability of soil salinity via apparent electrical resistance (or its inverse, apparent electrical conductivity) without disturbing the milieu. In western Africa, several studies (Barbiéro et al., 2001; Haëfele et al., 1999; Montoroi, 1996) have used these approaches to estimate the spatial variability of soil salinity.

It seems important to describe not only the spatial variability in salinity at a given date but also its combined variability in space and time to identify the main processes of salinisation (Cetin and Kirda, 2003; Cetin et al., 2012; Lesch et al., 1998; Li et al., 2011; Zheng et al., 2009) or the efficiency of desalinisation procedures. Adam et al. (2012) showed that electrical resistivity coupled with in-situ measurements allowed the salinity monitoring of a vertisol during a desalinisation experiment. This approach has been tested only at the local scale of an experimental plot, and uncertainties remain about the presence of salt flows deep in the soil and lateral transfers that can be observed only at larger spatial scales. The occurrence of a major 100-year flood of the Niger River in 2010 (Sighomnou et al., 2010) provided an opportunity to observe natural desalinisation of the irrigated zone of Kollo, Niger, and thus to study the spatio-temporal variability of salinity in this soil system at the scale of the entire zone.

The objectives of this study were to (i) map soil salinity in the study zone at high spatial resolution as a function of depth by combining non-destructive geophysical measurements with salinity measurements of the profile; (ii) estimate and map salt stocks in the upper 60 cm of the soil and (iii) analyse the change in the spatial pattern of salinity within the study zone after the 100-year flood of the Niger River that covered it.

2. Material and methods

2.1. Study site

The rice-producing zone of Kollo, with an area of 380 ha, is located 50 km southeast of Niamey, Niger (13° 16′ 35.32″ N, 2° 21′ 31.81″ E). The climate is Sudano-Sahelian, with mean monthly temperatures ranging from 40 °C in April to 25 °C in December. Mean annual precipitation is 700 mm, mainly occurring from June to September. The rice variety cultivated at Kollo is primarily *O. sativa*. It is double-cropped in rice paddies of 0.25 ha, the first during the wet season, from May to October, the second during the dry season, from November to April. High water deficit occurs throughout the year. The potential evapotranspiration for rice is estimated at 990 mm in the wet season and 1707 mm in the dry season (Mossi Maiga, 2005). Basin irrigation is practiced in both seasons by pumping water from the Niger River and distributing it via irrigation canals by gravity to the paddies.

The studied fields occupy a surface of nearly 8.5 ha (Fig. 1). Site vegetation is composed essentially of *Eucalyptus camaldulensis*, *Tamarix senegalensis*, and *Prosopis juliflora* bordering rice paddies or planted on levees.

Paddy soils studied at Kollo correspond to Solontchak vertic or vertisol salic soils (FAO, 2006) and have a clay content >80%, pH ranging from 3 to 5, and high salinity, with electrical conductivity of saturated paste ranging from 13 dS/m at the surface to 29 dS/m at a depth of 1.2 m. Soil profiles are marked by saline efflorescence on the surface and many spots of iron oxidation–reduction and salt precipitation in depth. X-ray diffraction showed the occurrence of kaolinite, smectite, illite and goethite. Salinity is influenced by precipitation and the dissolution of magnesium and calcium sulfates such as hexahydrite, epsomite and gypsum (Adam, 2011). The estimated thickness of the clayey cover on the study site varies from 76 cm on the north end to 175 cm in the middle and southeast end (Fig. 1). Overall, the thickness of the clay layer increases from the northeastern border of the study zone toward the levee. However, a decrease in the thickness of the clay layer has been observed in parts of the rice paddies located in the western part of the zone. Thicknesses measured in trenches or from core samples ranged from 110 to 150 cm (Adam, 2011). In saturated conditions, the hydraulic conductivity of clayey horizons was estimated at 2×10^{-8} m/s (Adam et al., 2012).

2.2. Soil sampling and electrical resistivity prospection

2.2.1. Pre-flood campaign—2008

The first campaign occurred from 7 to 20 May 2008, at the end of the dry season. Non-irrigated fields in the study site were at maximum dryness, and many deep cracks (median distance ≈ 40 cm) were observed in them. One-hundred forty soil-sampling points were selected within the 28 fields of the study zone, according to a systematic triangular-grid sampling plan, with 25 m between each point (Fig. 2). The points were set using a measuring tape and slightly displaced, if necessary, to keep them at least 1 m from paddy field bunds (boundary banks). Points were georeferenced by GPS (Trimble® Recon PC) with a precision of 2–4 m. At each point, samples were taken at 3 depths (0–10, 30–40, and 60–70 cm) with a manual auger (diameter = 7 cm). A total of 291 samples were taken, fewer than the 420 (=140 × 3) planned, because the soil was too hard to be sampled at certain depths. Samples from 0–10, 30–40, and