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Transect-scale imaging of root zone electrical conductivity by inversion of multiple-height EMI measurements under different salinity conditions

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The ability to determine the effects of salts on soils and plants, are of great importance to agriculture. To control its harmful effects, soil salinity needs to be monitored in space and time. This requires knowledge of its magnitude, temporal dynamics, and spatial variability. Soil salinity can be evaluated by measuring the bulk electrical conductivity (σb) in the field. Measurements of σb can be made with either in situ or remote devices (Rhoades and Oster, 1986; Rhoades and Corwin, 1990; Rhoades and Miyamoto, 1990). Time Domain Reflectometry (TDR) sensors allow simultaneous measurements of water content, θ, and σb. They may be calibrated in the laboratory for estimating the electrical conductivity of the soil solution (σw). However, they have a relatively small observation volume and thus they only provide local-scale measurements. The spatial range of the sensors is limited to tens of centimeters and extension of the information to a large area can be problematic. Also, information on the vertical distribution of the σb soil profile may only be obtained by installing sensors at different depths. In this sense, the TDR may be considered as an invasive technique.
Compared to the TDR, non-invasive electromagnetic induction (EMI) techniques can be used for extensively mapping the bulk electrical conductivity in the field. The problem is that all these techniques give depth-weighted apparent electrical conductivity (ECa) measurements, depending on the specific depth distribution of the σb, as well as on the depth response function of the sensor used. In order to deduce the actual distribution of local σb in the soil profile, one may invert the signal coming from EMI sensors.
Most studies use the linear model proposed by McNeill (1980), describing the relative depth-response of the ground conductivity meter. By using the forward linear model of McNeill, Borchers et al. (1997) implemented a Least Squares inverse procedure with second order Tikhonov regularization, to estimate σb vertical distribution from EMI field data. More recent studies (Hendrickx et al., 2002; Deidda et al., 2003; Deidda et al., 2014, among others), extended the approach to a more complicated non linear model of the response of a ground conductivity meter to changes with depth of σb. Noteworthy, these inverse procedures are only based on electromagnetic physics. Thus, they are only based on ECa readings, possibly taken with both the horizontal and vertical configurations and with the sensor at different heights above the ground, and do not require any further field calibration. Nevertheless, as discussed by Hendrickx et al. (2002), important issues on inverse approaches are about: i) the applicability to heterogeneous field soils of physical equations originally developed for the electromagnetic response of homogeneous media and ii) nonuniqueness and instability problems inherent to inverse procedures, even after Tikhonov regularization. Besides, as discussed by Cook and Walker (1992), these mathematical inversions procedures using layered-earth models were originally designed for interpreting porous systems with distinct layering. Where subsurface layers are not sharply defined, this type of inversion may be subject to considerable error.
With these premises, the main aim of this study is estimating the vertical σb distribution by ECa measured using ground surface EMI methods under different salinity conditions and using TDR data as ground-truth data for validation of the inversion procedure. The latter is based on a regularized 1D inversion procedure designed to swiftly manage nonlinear multiple EMI-depth responses (Deidda et al., 2014). It is based on the coupling of the damped Gauss-Newton method with either the truncated singular value decomposition (TSVD) or the truncated generalized singular value decomposition (TGSVD), and it implements an explicit (exact) representation of the Jacobian to solve the nonlinear inverse problem.
The experimental field (30 m x 15.6 m; for a total area of 468 m2) was divided into three transects 30 m long and 4.2 width, cultivated with green bean and irrigated with three different salinity levels (1 dS/m, 3 dS/m, and 6 dS/m). Each transect consisted of seven rows equipped with a sprinkler irrigation system, which supplied a

water flux of 2 l/h. As for the salt application, $CaCl_2$ were dissolved in tap water, and subsequently siphoned into the irrigation system. For each transect, 24 regularly spaced monitoring sites (1 m apart) were selected for soil measurements, using different equipments: i) a TDR100, ii), a Geonics EM-38; iii). Overall, fifteen measurement campaigns were carried out.