Journal of Applied Geophysics 89 (2013) 11–20

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Electromagnetic induction for mapping textural contrasts of mine tailing deposits

Grey S. Nearing [a], Markus Tuller [b,*], Scott B. Jones [c], Robert Heinse [d], Mercer S. Meding [b]

[a] Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ 85721, United States
[b] Department of Soil, Water and Environmental Science, The University of Arizona, Tucson, AZ 85721, United States
[c] Department of Plants, Soils and Climate, Utah State University, Logan, UT 84322, United States
[d] Department of Plant, Soil and Entomological Sciences, University of Idaho, Moscow, ID 83844, United States

ARTICLE INFO

Article history:
Received 25 May 2012
Accepted 5 November 2012
Available online 27 November 2012

Keywords:
Mine tailings
Electromagnetic induction
Apparent electrical conductivity
Geostatistics
Nonlinear regression

ABSTRACT

Mine tailings present an important legacy of past and present ore-extraction activities in the Desert Southwest. Inactive mine tailings have no immediate economic role in current mining operations, yet from an environmental point of view it is important that such deposits are stabilized to prevent mass movement, wind or water erosion, leaching of chemicals such as acid mine drainage, and to reduce visual blight. In the presented study, we assess the potential for inferring textural properties of mine tailing deposits with electromagnetic induction (EMI) mapping as a means of informing efforts to establish vegetation at mine waste sites. EMI measurements of apparent electrical conductivity (EC_a) and tailing samples were collected at a mine waste site in Southern Arizona, USA and used to test empirical and theoretical relationships between EC_a and physical and mineralogical properties using linear and Gaussian process regression. Sensitivity analyses of a semi-theoretical and a regression model of EC_a as a function of tailing properties indicated that volumetric clay fraction in the top 60 cm was a primary influence on bulk electrical conductivity along with water content, conductivity of the soil water and the presence of conductive minerals hematite and pyrite. At this site, latitude and longitude were better predictors of clay content than EC_a, and while it was possible to obtain information about the spatial distribution of tailing texture using EMI, simple Kriging of texture data was a more powerful textural mapping technique. We conclude that EMI is a useful tool for mapping tailing texture at waste deposit sites, but due to physical and chemical heterogeneity of tailing deposits, it is necessary to collect more in situ samples than are needed for agricultural applications.

1. Introduction

The ability to sustain native vegetation on inactive mine tailings mitigates several environmental issues such as mass movement due to wind and water, leaching of chemicals, and aesthetic concerns. Highly variable physical and chemical properties of mine tailings in combination with low precipitation in the southwestern United States, where mine tailing deposits are common, create challenges for the establishment of vegetation. For adequate supply of water to vegetation it is necessary that (*i*) the root zone has a sufficient water holding capacity, (*ii*) that the pore-size distribution allows for the release of water at capillary pressures between field capacity (0.1 or 0.33 bar) and permanent wilting point (15 bar for agricultural vegetation, higher for desert vegetation), (*iii*) that infiltration capacity is sufficient, and (*iv*) that the hydraulic conductivity is low enough so that percolation through the root zone is not too rapid yet not so low that water logging or excess runoff occurs. These characteristics are largely related to texture. Remediation efforts often require amendment with parent soil material, biosolids, or chemically synthesized compounds to create a new root zone over existing tailing material; this can constitute a large portion of the remediation expense. Ideally it is desirable to use existing material as much as possible and limit the amount of amendments. Mapping the physical and hydraulic properties of tailings at a waste site is a necessary first step toward the development of layering and mixing strategies designed to maximize the utility of in-situ material. Knowledge about the spatial texture distribution is desired; this information could then be used to estimate design and management parameters such as hydraulic conductivity, infiltration capacity and water retention properties.

Electromagnetic induction (EMI) techniques interpreted through geostatistics are often used to derive spatial maps of soil physical properties at the field scale. EMI estimates apparent electrical conductivity (EC_a), which is a measure of charge mobility due to the propagation of an electromagnetic field. Most notably, variations in EC_a have empirically been related to salinity, texture, water content, and cation exchange capacity (Corwin and Lesch, 2005). These relationships may be described according to the conceptual model for EC_a proposed by Rhoades et al. (1976) and semi-empirical parameterizations for this model proposed by Rhoades et al. (1989) and others.

Interpretation of EMI data at the field scale is usually done via statistical models, due to the fact that inverse solutions using the physical theory of EC_a response tend to be non-unique. Most studies

* Corresponding author at: The University of Arizona, SWES Department, Shantz 38, Room 526, Tucson, AZ 85721-0038, United States. Tel.: +1 520 621 7225.
E-mail address: mtuller@cals.arizona.edu (M. Tuller).

0926-9851/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jappgeo.2012.11.005

that use EMI measurement techniques relate EC_a to soil properties of interest using linear regression, often based on recommendations by Lesch et al. (1995a), who argue that linear models are preferable to more sophisticated spatial statistical techniques due to simplicity in application and the fact that they require fewer soil sampling sites for similar accuracy. However, other techniques have been used. For instance, nonlinear regression by neural networks trained and forced with EC_a data from local neighborhoods around soil sampling locations was found by Cockx et al. (2009) to be superior to linear regression at a particular study site. When using EMI measurements to map soil properties across a field, it is sometimes beneficial to include location coordinates in the set of potential regressor variables (along with EC_a) in order to capture underlying information about the spatial structure of field soil properties (Abdu et al., 2008; Lesch et al., 1995a).

Clearly, it would be desirable to use EMI measurements to infer textural and hydraulic properties of mine tailings given the success that this technique has had elsewhere. However, mine tailings are physically and chemically different from soils found in natural and agricultural environments, and it has yet to be shown whether EMI measurements of EC_a can be related to the texture of tailing deposits. The goal of this study was to assess feasibility and value of using EC_a measurements to characterize near-surface textural properties at mine waste sites. Specifically we focus on mapping fractional volumetric clay content. This problem was approached from a physical and statistical perspective; the experiment consisted of the following steps (details of specific methods are given in Section 2):

(1) EMI measurements taken on the surface of a mine tailing deposit site were interpolated to a grid over the entire waste deposit field. Tailing samples were collected from selected points both on ($N=11$) and off ($N=10$) the EMI path and analyzed to provide a comprehensive collection of textural and chemical property estimates at point-scale locations.
(2) Measurements of tailing material properties were used to predict EC_a with a calibrated conceptual–physical model. The sensitivity of this model to volumetric clay content was assessed by Sobol's method (Saltelli et al., 2009).
(3) A Gaussian process regression automatic relevance determination sensitivity analysis was used to assess the sensitivity of EC_a as a theoretical (nonparametric) function of tailing properties.
(4) The feasibility of inverting the calibrated conceptual–physical model to map clay content was investigated.
(5) Linear regressions were developed to predict clay content from EC_a measurements. These were evaluated at sample locations independent of those used for calibration both on and off the EMI measurement path.
(6) Gaussian process regressions (nonlinear, nonparametric) were developed to predict clay content from EC_a measurements. These were evaluated at sample locations independent of those used for calibration both on and off the EMI measurement path.

2. Materials and methods

2.1. Study area and measurements

The study was conducted on a highly acidic site (pH: 2.39–5.73) with bulk electrical conductivity (EC_a: 0.70–8.75 dS/m) and virtually no vegetation. The site, designated as impoundment no. 6, is located at Resolution Copper Mine in Superior, AZ (33.3° N, 111.1° W). A motivating factor for choosing this particular impoundment was the assumption that if viable and cost-efficient strategies for remediation could be developed for such extreme conditions they should also be applicable to more moderate environments. Two ore bodies were mined at the Superior site. The Magma Vein, a quartz-sulfide vein deposit was mined until 1940 followed by mining of a carbonate replacement ore body until 1998. Milled silt- and clay-sized fractions of the later ore body were discharged into impoundment no. 6 from 1971 until cessation of mining in 1998 via a slurry pipeline located on the west edge of the impoundment (Fig. 1). Since then, the impoundment was inactive and only used for storm water storage and evaporation. At the time of this study there was a large evaporation pond located near the east edge of the tailings about halfway between the northern- and southern-most points; this can be seen in the aerial photograph in Fig. 1. Hematite, quartz and pyrite are the dominant minerals of the carbonate replacement body; chalcopyrite, bornite, enargite, tennantite and chalcocite are the ore-bearing minerals.

2.1.1. EMI measurements

Geo-referenced (Trimble ProXT GPS, Trimble Navigation Limited, Sunnyvale, CA, USA) measurements of apparent electrical conductivity from perpendicular (V-H) and parallel (V-V) coil-mode configurations were obtained with a DUALEM-1S ground conductivity instrument (DUALEM, Milton, ON, Canada) (Fig. 2). Geo-referencing of EC_a data was accomplished with geographic information system software (HGIS, StarPal Inc., Fort Collins, CO, USA) installed on an Allegro CX handheld field computer (Juniper Systems, Logan, UT, USA) with the EMI measurement path illustrated in Fig. 1.

The DUALEM-1S has 1-m spacing between the vertically-oriented transmitter coil and the dual-geometry receiver coils. The depth of exploration of the perpendicular (V-H) coil-mode configuration is approximately 0.5 m below the surface and for the coplanar (V-V) coil-mode configuration it is approximately 1.5 m. This means that 70% of the cumulative sensitivity of the perpendicular coil-mode response is a function of properties of the material above approximately 0.5 m depth (Urdanoz and Aragüés, 2012). Since remediation efforts are primarily interested in tailing properties in the near surface, we use EC_a estimates from the perpendicular coil-mode configuration.

EC_a measurements from the EMI path were interpolated and extrapolated to a 1 [m]×1[m] grid over the tailing impoundment using ordinary Kriging as implemented by GsLib (Deutsch and Journel, 1992). Ordinary Kriging is similar to Gaussian process regression (Rasmussen and Williams, 2006), which is used formally in Sections 2.3.2, 2.4.1 and 2.4.3, however since an existing software package was employed to perform this EC_a field extrapolation, we will discuss the operations from the perspective of the software developers. First, EC_a data were normalized using a normal-score transform (Goovaerts, 1997) and spatial autocorrelation was estimated by a Gaussian semivariogram,

$$\gamma = \sigma_s\left(1 - \exp\left(-\frac{r^2}{l^2}\right)\right), \quad (1)$$

where the Euclidean distance between grid locations is r [m] and the sill and range hyperparameters are $\sigma_s = 1.1$ and $l = 50$ [m]. This analytic function is compared to a data-estimated version in Fig. 3. The interpolated EC_a map is depicted in Fig. 4.

2.1.2. Tailing sampling and analysis

Corwin and Lesch (2003) reported that, typically, between six and twenty soil sample sites should be chosen to develop linear regressions between soil properties and EC_a. We extracted twenty-one 60-cm core samples at various points at the mine tailing deposit site with a Giddings probe (Giddings Machine Company, Windsor, CO, USA). Eleven of these samples were taken at points on the EMI measurement path and ten were taken along transects separate from the EMI measurement path (Fig. 1). On-path sampling locations were selected using the site selection algorithm in the ESAP software package (Lesch et al., 2000) using an algorithm developed by Lesch et al. (1995b) to predict field scale soil salinity from EC_a survey data using linear regression. Tailing cores taken at the sampling locations were divided into two increments so that the material properties in