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Review

The use of electromagnetic induction techniques in soils studies

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ABSTRACT

Electromagnetic induction (EMI) has been used to characterize the spatial variability of soil properties since the late 1970s. Initially used to assess soil salinity, the use of EMI in soil studies has expanded to include: mapping soil types; characterizing soil water content and flow patterns; assessing variations in soil texture, compaction, organic matter content, and pH; and determining the depth to subsurface horizons, stratigraphic layers or bedrock, among other uses. In all cases the soil property being investigated must influence soil apparent electrical conductivity (EC_a) either directly or indirectly for EMI techniques to be effective. An increasing number and diversity of EMI sensors have been developed in response to users' needs and the availability of allied technologies, which have greatly improved the functionality of these tools. EMI investigations provide several benefits for soil studies. The large amount of georeferenced data that can be rapidly and inexpensively collected with EMI provides more complete characterization of the spatial variations in soil properties than traditional sampling techniques. In addition, compared to traditional soil survey methods, EMI can more effectively characterize diffuse soil boundaries and identify areas of dissimilar soils within mapped soil units, giving soil scientists greater confidence when collecting spatial soil information. EMI techniques do have limitations; results are site-specific and can vary depending on the complex interactions among multiple and variable soil properties. Despite this, EMI techniques are increasingly being used to investigate the spatial variability of soil properties at field and landscape scales.

Contents

1. Introduction

It is widely recognized that there is considerable variability within soils (Brevik et al., 2003; Doolittle et al., 1996; Miller, 2012). Electromagnetic induction (EMI) is widely used by soil scientists to better understand the spatial variability of soils and soil properties at field and landscape scales (Corwin, 2008; Toushmalani, 2010). Because of its speed, ease of use, relatively low cost, and volume of data collected, EMI has immense advantages over traditional methods used to collect soil information. Recent improvements in instrumentation and integration with other technologies (global-positioning systems (GPS), data processing software, and surface mapping programs) have fostered the expanded use of EMI in soils applications. The impetus for this expanded use has been the need for more accurate soil maps than those provided by traditional mapping techniques (Batte, 2000; Brevik et al., 2003, 2012) and the demonstrated efficiency of EMI to improve the accuracy and reliability of soil maps and provide more detailed information on soils and soil properties.

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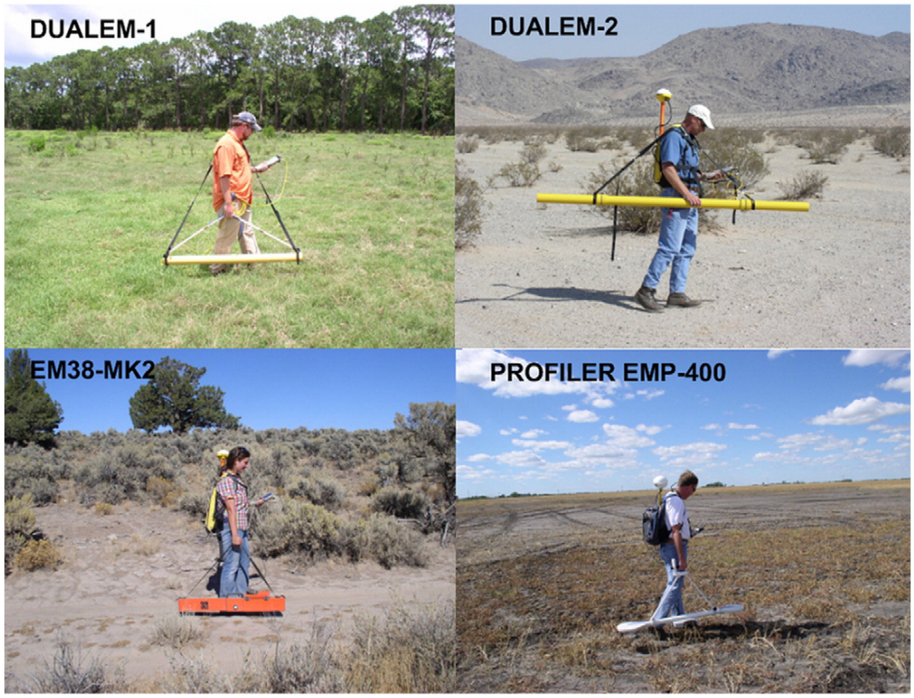

Fig. 1. Four EMI sensors commonly used in soil investigations are the DUALEM-1 meter, the DUALEM-2 meter, the EM38-MK2 meter, and the Profiler EMP-400.

Electromagnetic induction sensors measure changes in the apparent electrical conductivity (EC_a) of the subsurface without direct contact with the sampled volume (Allred et al., 2008; Daniels et al., 2003). Apparent electrical conductivity is a depth-weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Variations in EC_a are produced by changes in the electrical conductivity of earthen materials. Apparent electrical conductivity will increase with increases in soluble salt, water, clay contents, and temperature (Brevik and Fenton, 2002; Kachanoski et al., 1988; McNeill, 1980a; Rhoades et al., 1976).

2. EMI sensors

An increasing number of commercially available EMI sensors are available (Fig. 1). Electromagnetic induction sensors commonly used in agriculture and soil investigations include the DUALEM-1 and DUALEM-2 meters (Dualem, Inc., Milton, Ontario); the EM31, EM38, EM38-DD, and EM38-MK2 meters (Geonics Limited, Mississauga, Ontario), and the Profiler EMP-400 (Geophysical Survey Systems, Inc., Salem, New Hampshire).[1] These EMI sensors transmit a primary electromagnetic field, which induces electrical currents in the soil. These currents generate a secondary electromagnetic field, which is read by the sensor's receiver. Under conditions known as "operating under low induction numbers", the secondary field is proportional to the ground current and is used to calculate the "apparent" or "bulk" electrical conductivity (EC_a) for the volume of soil profiled. The dual-geometry configuration of the DUALEM-1 and DUALEM-2 meters, the dual orientation of the EM38-DD meter, and the dual receiver–transmitter spacings of the EM38-MK2 meter allow the simultaneous measurement of EC_a and/or apparent magnetic susceptibility (MSa) over two distinct depths. The depth of investigation (DOI) for EC_a measurements made with sensors developed by Dualem, Inc. and Geonics Limited is commonly taken as the depth of 70% cumulative response. The Profiler EMP-400 is a multi-frequency sensor and its DOI is assumed to be "skin-depth" limited and dependent upon the frequency and the conductivity of the profiled materials. All of the aforementioned sensors support GPS communication, data loggers, and proprietary software. Some EMI sensors, such as the DUALEM-1, DUALEM-2S, and Profiler EMP-400, come with internal GPS receivers and display/keypads.

Each of the aforementioned sensors has distinct operational advantages and disadvantages (Sudduth et al., 2003). Comparative studies have generally revealed close similarities between EC_a data collected with different sensors (Doolittle et al., 2001, 2002a; Saey et al., 2009a; Sudduth et al., 1999, 2003; Urdanoz and Aragüés, 2012). However, differences in sensor calibration, depth sensitivity and volume of soil material measured will affect measurements and result in slightly different EC_a values. In comparative studies using different sensors, the highest correlations in measured EC_a were obtained with sensors having similar depth sensitivities (Sudduth et al., 1999, 2003). Differences in EC_a data collected with different sensors have been attributed to differences in sensing depths and data collection modes (e.g., coil spacing, orientation, or geometry). In general, differences in EC_a data collected with different sensors have been more noticeable over soils with highly contrasting layers (Sudduth et al., 2003).

3. History

The first use of EMI in agriculture was for the assessment of soil salinity (Corwin and Rhoades, 1982; de Jong et al., 1979; Rhoades and Corwin, 1981; van der Lelij, 1983; Williams and Baker, 1982). In 1976, Geonics Limited patented and manufactured the EM31 meter. The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9.8 kHz (Fig. 2). This meter provides DOI of 3 m and 6 m when operated in the horizontal (HDO) and vertical (VDO) dipole orientations, respectively. Consideration for near-surface applications in agronomy and soil science lead to the development of the EM38 meter in 1980. The EM38 meter is the most widely used EMI sensor in agriculture (Sudduth et al., 2001). The EM38 meter has a coil separation of 1 m and operates at a frequency 14.6 kHz. This meter provides DOI of 0.75 and 1.5 m when operated in the HDO and VDO, respectively.

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.