Characterization of soil magnetic susceptibility: a review of fundamental concepts, instrumentation, and applications

Authors: Shirzaditabar, Farzad, and Heck, Richard J.

Source: Canadian Journal of Soil Science, 102(2) : 231-251

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/CJSS-2021-0040

Canadian Science Publishing

REVIEW

Characterization of soil magnetic susceptibility: a review of fundamental concepts, instrumentation, and applications

Farzad Shirzaditabar and Richard J. Heck

Abstract: The characterization of magnetic susceptibility (MS) has become an accepted technique in soil science. This review examines the concept of volume and mass-specific MS, magnetism, frequency dependence, and thermal behavior of MS, as they pertain to soil material. A comparison is presented of the two types of instrumentation for measuring soil MS, based on magnetic field and electromagnetic induction (EMI). These are discussed with respect to applications including magnetic granulometry, detection of pollutants, identification of organic matter, the delineation of drainage class, paleo-environmental studies, archaeology, as well as soil erosion and degradation. Instruments that use magnetic fields can precisely measure the MS of small amounts of soil, thinly deposited layers or soil exposures, but cannot effectively measure materials at distances ≥10 cm from the sensor. EMI instruments, instead, are capable of quickly measuring apparent MS of a finite volume of the soil, and are utilized in mapping of soil MS in agricultural and archaeological investigations; however, the measured apparent MS values need to be further processed to give the real volume MS values of soil layers/segments. Although both kinds of instruments are widely used in soil science, their measured data are not interchangeable. Future work should be conducted to increase the understanding of the comparability of these instruments to find better utility among soil scientists.

Key words: soil magnetic susceptibility, magnetic instruments, electromagnetic instruments, electromagnetic induction, frequency dependence.

Résumé : Caractériser la sensibilité magnétique (SM) est devenu une technique reconnue en science du sol. Les auteurs examinent les concepts de la SM volumique et massique, du magnétisme ainsi que de la fonction de la fréquence et du comportement thermique de la SM en regard des matériaux pédologiques. Ils comparent deux sortes d'instruments permettant de mesurer la SM du sol d'après le champ magnétique ou par induction électromagnétique, puis en discutent en fonction de leurs applications, dont la granulométrie magnétique, la détection des polluants, l'identification de la matière organique, la délimitation des classes de drainage, les études paléo-environnementales, l'archéologie ainsi que l'érosion et la détérioration du sol. Les appareils qui utilisent le champ magnétique mesurent avec précision la SM de petites quantités de sol, des dépôts minces ou du sol exposé, mais ne peuvent quantifier efficacement les matériaux situés à dix centimètres ou plus du capteur. En revanche, ceux qui recourent à l'induction électromagnétique mesurent rapidement la SM apparente d'un volume fini de sol et on s'en sert pour cartographier la SM des sols dans les études agricoles et archéologiques. Quoi qu'il en soit, les valeurs de la SM apparente obtenues doivent être traitées si l'on veut établir la véritable SM volumique des couches ou des parties du sol. Bien qu'on utilise abondamment les deux types d'appareils en science du sol, leurs données ne sont pas interchangeables. Il faudrait entreprendre d'autres recherches pour mieux comprendre la comparabilité de ces instruments et en accroître l'utilité pour les spécialistes de la science su sol. [Traduit par la Rédaction]

Mots-clés : sensibilité magnétique du sol, appareils magnétiques, instruments électromagnétiques, induction électromagnétique, fonction de la fréquence.

Introduction

Magnetic susceptibility (MS) is a physical property of matter, defined as the extent to which a material can be magnetized. The first use of the concept in soil science goes back to the work of Le Borgne (1955), who found that the MS increases from parent material to the subsoil, then to the topsoil. This MS enhancement with decreasing depth was attributed to the changes in

Received 8 April 2021. Accepted 7 October 2021.

F. Shirzaditabar and R.J. Heck. School of Environmental Sciences, University of Guelph, Guelph, ON, Canada, N1G2W1.

Corresponding author: Farzad Shirzaditabar (email: fshirzad@uoguelph.ca).

Can. J. Soil Sci. **102:** 231–251 (2022) dx.doi.org/10.1139/cjss-2021-0040

clay-size fraction, which experienced conversion of weakly magnetic forms of iron oxides and hydroxides to maghemite, or magnetite, during successive oxidation-reduction processes within the soil. Le Borgne (1960) also observed and reported MS enhancement by fire. Since then, researchers have pursued the mechanisms by which MS is changed in the topsoil. Lukshin et al. (1968) and Vadyunina and Babanin (1972) have demonstrated how susceptibility enhancement is linked to key soil forming processes and may be utilized to get a broad understanding of the processes impacting iron minerals throughout pedogenesis, as well as particular impacts such as gleying. The influence of lithology (Mullins and Tite 1973) and climate (Tite and Linington 1975), on MS changes, has been also reported. Mullins (1977) summarized the factors affecting MS of the soil and concluded that soil MS depends on the size, shape, and concentration of magnetite and maghemite; as well as on the method of measurement. He also observed that pedogenic maghemite can be developed in soils with low MS parent material. A study of the relations between magnetic minerals and soil forming processes was done by Maher (1986). Based on isothermal measurements of mineral magnetic parameters, Maher (1986) concluded that the presence of magnetite and maghemite within the soil is widespread. It has also been shown that magnetotactic bacteria, which exist in organic matter, can generate ultrafine-grained magnetite in the presence or absence of oxygen (Løvely et al. 1987; Maher and Taylor 1988). Schwertmann (1988), Schwertmann and Taylor (1989), and Singer et al. (1996) separately studied the factors affecting MS enhancement in soils and deduced that temperature and annual precipitation, as well as parent material, are other main factors that impact soil MS.

The majority of early measurements of soil MS were based on the analysis of a magnetic hysteresis curve, in which the magnetization values of matter (M), obtained in the laboratory by employing magnetic fields (H) in different intensities, were plotted against magnetic field intensity. The volume MS of matter, commonly represented by the Greek letter kappa "κ," was the ratio of magnetization to applied magnetic field intensity such that $\kappa = M/H$. It was also realized from magnetic hysteresis curves that MS is almost constant in low magnetic field intensities, but increases nonlinearly to a maximum in high intensity fields (Jackson et al. 1998). With innovations in computers and electronic hardware, as well as digital technologies, various MS instruments have been designed and produced by different manufacturers, and are being used by soil scientists. Two basic types of instrumentation are currently available to measure soil MS: those that employ magnetic fields and those that utilize electromagnetic induction (EMI) methods. More explanations regarding these MS instruments will be presented in Section 3.

Measurements of MS have a variety of applications in soil sciences. These include soil drainage assessments (e.g., de Jong 2002; de Jong et al. 2005; Owliaie et al. 2006; Grimley et al. 2008; Asgari et al. 2018; Gholamzadeh et al. 2019), magnetic granulometry using frequency dependence (FD) of MS (e.g., Hrouda et al. 2013; Ustra et al. 2018, 2019), soil pollution (Schibler et al. 2002; Petrovský et al. 2004; Zawadzki et al. 2010, 2012; Boadi et al. 2014; Cao et al. 2015; Liu et al. 2016; Rachwał et al. 2017; Wang et al. 2021), soil erosion (Venture et al. 2001; Jakšík et al. 2016; Menshov et al. 2018; Liu et al. 2019; Ding et al. 2020), land degradation (Sadiki et al. 2009; Łukasik et al. 2015; Magiera et al. 2019), and paleoclimate reconstruction (Maher and Thompson 1995; Maxbauer et al. 2016; Jordanova and Jordanova 2021). While almost all of these studies have focused on a specific application of a particular instrument, other publications have addressed the comparison between MS values measured using various handheld and (or) laboratory-based MS instruments for specific applications (e.g., Benech and Marmet 1999; Lecoanet et al. 1999; Simpson et al. 2009; Simpson et al. 2010; Lee and Morris 2013; Deng and Smith 2016; Grison et al. 2017). A comprehensive review of different types of instruments for measuring soil MS and their specific applications in soil science has not yet been carried out. Recently, Jordanova (2017) published a book regarding applications of MS in pedology, agriculture, and environmental sciences. Although this book dealt with applications of soil MS in detail, the MS instruments used for measuring soil MS and comparison between their applicabilities were not explained therein.

Despite the fact that both types of instruments can measure soil MS, not all devices are suitable for all of the aforementioned uses due to some constraints like measurement accuracy and speed, as well as physical differences in designing MS instruments. For instance, while EMI instruments can quickly measure apparent MS of topsoil, the measured values need to be further analyzed and inverted to give real MS values of soil layers; however, the speed of measurement makes the EMI instruments suitable for mapping soil MS, which is the main advantage of using these kinds of instruments for measuring soil MS. On the other hand, although the instruments that use magnetic fields for measuring soil MS give precise values for soil samples, such measurements are costly and time-consuming. Moreover, they are not designed for mapping purposes. Accordingly, the main objectives of this paper are: (*i*) to provide an overview of relevant fundamental concepts of MS, with emphasize on MS of soil constituents; (*ii*) to conduct a review of current analytical solutions (or instrumentation) for measuring soil MS; and (*iii*) to discuss the suitability of available instruments for characterizing soil MS.

Magnetic Susceptibility of Soil Constituents

Volume vs. mass-specific MS

The fundamental rules and concepts of MS have long been clarified. Each electron in an atom has magnetic moments due to its orbital and spin motions. When a material is exposed to an incident uniform magnetic field (H), it will be magnetized due to alignment of these magnetic moments with the magnetic field. The ratio of magnetization (M) to the magnetic field intensity (H) is defined as "volume MS" of that material (κ), which is a dimensionless quantity defined as:

$$(1) \qquad \kappa = M/H$$

Because this value directly depends on the amount of the material, dividing this value by the bulk density (ρ) of the material provides a "mass-specific MS" (χ), which is an intrinsic property of the matter having dimension of volume/mass, defined as (Mullins 1977):

$$(2) \qquad \chi = \kappa/\rho$$

Direct MS measurements of intact soil, such as soil core samples, are reported as volume MS. This is because the weight of the soil, which in this case interacts with instrument magnetic field, is unknown. On the other hand, for powder or crushed soil samples, a specified amount of soil sample is used, from which the mass-specific MS of the sample can easily be calculated.

Magnetism

In some atoms, the arrangement and number of electrons are such that the magnetic moments cancel each other. If such atoms are placed in a magnetic field, the rotation of electrons, according to the Lorentz force, produces a weak magnetic moment in the opposite direction of magnetic field (Evans and Heller 2003); this effect is called "Diamagnetism." So, diamagnetic materials have weak negative MS. Quartz, feldspars, calcium carbonate, organic matter, plastic, and water are most common diamagnetic materials encountered in the soil. If the magnetic moments in the atom are partially canceled out, the atom has a permanent magnetic moment; this effect is known as "Paramagnetism." While such atoms tend to be aligned with external magnetic fields, the thermal energy always limits this alignment. So, paramagnetic minerals have weak positive MS. Silicates and aluminosilicates containing iron, as well as biotite and olivine, are examples of paramagnetic minerals in the soil. In the pure form of some elements, like iron, nickel, and cobalt, not only there is a permanent magnetic moment in each atom, but there is also a strong interaction between the adjacent moments, which eventually results in a strong magnetic moment. This phenomenon is known as "Ferromagnetism." Since the natural appearance of pure iron is rare in the earth's crust and soil, the iron must occur in other mineral forms in the nature. If atomic moments in such materials occur in the opposite direction but have the same strength, the material will have zero net magnetic moment in the absence of an applied magnetic field. This effect is called "Antiferromagnetism"; goethite and hematite are two important antiferromagnetic minerals in the soil. Although these minerals are "canted" antiferromagnetic or weakly ferromagnetic above ~250 K (or ~−23 °C), and exhibit high MS at room temperatures due to spin or defective spin compensations, they have zero net magnetization below this temperature (Dzyaloshinsky 1958). "Ferrimagnetism" is another phenomenon of iron bearing materials, on which exchange coupling acts. In this case, the adjacent magnetic moments are in the opposite direction, but one of them has a higher strength than the other, which give rise to a strong pure magnetic moment. Magnetite, maghemite, pyrrhotite, and greigite are the most well-known ferrimagnetic minerals in the soil (Mullins 1977). By comparison, the MS of diamagnetic matter is typically a hundred times smaller than that of paramagnetic matter, and a hundred thousand times smaller than ferromagnetic matter (Evans and Heller 2003). A detailed explanation of magnetic materials can be found in Butler (1998) and Thompson and Oldfield (1986).

The MS of natural soil, which is extremely variable, is almost completely controlled by the content of ferrimagnetic minerals, their grain sizes, and their distribution in the soil. Although various attempts have been made to express the relationship between susceptibility and the content of ferrimagnetic minerals, there is still no universal agreement (Parasnis 1986). Table 1 contains mass specific MS values for common minerals, as well as volume MS values for common rocks that exist on the earth's surface. Soils developed from igneous rocks have relatively higher volume MS values than those developed from metamorphic and sedimentary rocks. In fact, the MS value of soil directly reflects MS of parent material. Table 1 also shows some small negative mass-specific MS values, which belong to diamagnetic minerals.

FD of MS

The MS of materials is frequency dependent due to the relaxation time (τ) of the magnetic dipoles, where increasing the frequency of the measuring magnetic field results in a decrease in the MS value (Debye 1929). As a range of fine to coarse grained minerals and rocks, soil includes superparamagnetic (SP), single domain (SD), and multi-domain (MD) magnetic particles, as well as organic matter. All these particles contribute to the soil MS; however, when using a low intensity magnetic field, in which there is a linear relationship between magnetic field (H) and magnetization (M), it has been observed that the soil MS decreases when the frequency of the applied magnetic field increases (Mullins and Tite 1973). This means that high frequency MS (χ_{hf}) is usually less in magnitude

Table 1. Magnetic susceptibility values of some common soil constituents (data from Carmichael 1989; Dearing 1999; Reynolds 2011).

Constituent	Mass-specific MS (10^{-6} $m^3 \cdot kg^{-1}$)	Constituent	Volume MS (ppm)
Ferrimagnetic		Sedimentary rocks	
Magnetite	390–580	Limestone	10–25 000
Maghemite	410–440	Sandstone	0–21 000
Titanomagnetite	196–290	Shale	60–18 600
Titanomaghemite	281–315	Coal	25
Pyrrhotite	50–53	Average of various	0–360
Antiferromagnetic		Metamorphic rocks	
Hematite	1.19–1.69	Schist	315–3000
Goethite	0.35–1.26	Slate	0–38 000
Paramagnetic		Gneiss	125–25 000
Ilmenite	1.7–2	Serpentine	3100–75 000
Biotite	0.05–0.95	Average of various	0–73 000
Pyrite	0.3	Igneous rocks	
Chalcopyrite	0.03	Granite	10–65
Lepidocrocite	0.5–0.75	Granite (with magnetic minerals)	20–50 000
Dolomite	0.011	Gabbro	800–76 000
Iron (pure)	276 000	Basalt	500–182 000
Cobalt (pure)	204 000	Peridotite	95 500–196 000
Nickel (pure)	68 850	Average of various (acidic igneous)	40–82 000
Aluminum (pure)	0.0079	Average of various (basic igneous)	550–122 000
Diamagnetic			
Calcite	−0.0048	—	—
Quartz	−0.0058	—	—
Water	−0.009	—	—
Halite	−0.009	—	—
Kaolinite	−0.019	—	—
Alkali-feldspar	−0.005	—	—
Copper (pure)	−0.00108	—	—
Organic matter	−0.009	—	—
Plastic	−0.005	—	—

than low frequency MS (χ_{lf}). The phenomenon is thought to be caused by the presence of fine-grained particles in the soil. At low frequencies, almost all magnetic particles follow the direction of the applied alternating magnetic field, while at higher frequencies, the SP grains, which are typically less than ~20 nm in diameter, cannot be fully aligned with the alternating magnetic field and result in lower MS reading (Thompson and Oldfield 1986). Thus, the difference between low and high frequency MS can be an indicator of the presence of SP grains. This frequency effect is dependent on the specific frequency used in designing experimental instruments, and commonly used to qualitatively detect soil samples containing SP grains. Most companies tune their instruments to the frequency range of 1 to 20 kHz because the relaxation of SP minerals generally occurs in this range (Ustra et al. 2018). There are no specific values to be considered as low and high values for frequencies, so the best way is to normalize this difference to the lower frequency MS value to achieve a dimensionless quantity. By convention this quantity, shown by χ_{fd}, is referred to as the "percent frequency dependence of MS" or "percentage loss of susceptibility" (Maher 1986; Dearing et al. 1996) and is used to delineate soil grain sizes, defined as:

$$\chi_{fd} = 100 \times (\chi_{lf} - \chi_{hf})/\chi_{lf} \tag{3}$$

By measuring χ in three different frequencies and utilizing an inversion procedure, Ustra et al. (2018 and 2019) could calculate real χ_{lf} and χ_{hf}, that is, the values of χ in lowest and highest frequencies, as well as relaxation time (τ) for some soil samples. The lowest and highest frequencies, as well as the relaxation time, also vary for different soil samples. FD of MS plays an important role in soil studies, mostly to discriminate between lithogenic and pedogenic soil iron oxides, and is directly related to grain size. More explanation for this discrimination is presented in Section 4.1.

Values for MS are not only a frequency-dependent feature of materials but also a complex value.

This means that the measured magnetization has two components: one in-phase and another out-of-phase with the incident magnetic field (*H*). Studies show that out-of-phase MS can be used to distinguish the portion of magnetic grains greater than and less than ~20 nm, in diameter (Egli 2009; Chadima et al. 2010). The relationship between in-phase (IP) and out-of-phase (or quadrature-phase, QP) MS components at only one frequency was studied, in detail, by Hrouda et al. (2013) where they concluded that this relationship is highly correlated with χ_{fd} derived from MS values measured at two different frequencies. It means that χ_{fd} can be calculated by measuring MS, even at one frequency, as long as the measurement includes IP and QP MS components.

Thermal behavior of soil MS

In the last three decades, along with the study of soil MS in different frequencies, investigations have been conducted under continuous heating, up to 700 °C, followed by subsequent cooling. This method has become commonly used among soil scientists. The observed Curie temperatures, during these processes, are used to identify magnetic minerals in natural samples (Jordanova and Jordanova 2016). The cooling curve reveals changes in the mineral composition imposed by laboratory heating. Increases in MS, at temperatures above 420–450 °C, have been observed when studying the lacustrine deposits and loesses (Deng et al. 2005; Minyuk et al. 2011). This enhanced MS is due to the conversion of iron oxides in the soil from the weakly ferrimagnetic form, hematite, to a strongly ferrimagnetic form, magnetite, when the soil is heated, followed by re-oxidation of magnetite to maghemite, due to reoxidation during cool-down (Le Borgne 1955 and 1960). The form of the heating and cooling curves of MS vs. temperature (κ-T curves), as well as the observed peaks, are interpreted as various environmental processes. These processes include the neoformation of magnetite, and other pedogenic magnetic minerals, from iron bearing silicates or clay minerals (Liu et al. 2005), reactions of Fe minerals with organic matter (Hanesch et al. 2006), and time- and temperature-dependent cation ordering in magnesioferrites (Harrison and Putnis 1999) and titanomagnetites (Bowles et al. 2013). Continuous enhancement of χ_{fd} has also been reported by Owliaie et al. (2006), which attributed this phenomenon to the formation of fine-grained SP particles with high thermal stability from destruction of coarse-grained MD minerals. This approach is a sensitive tool for identifying the magnetic, and some other iron bearing, minerals which contain information about the origin and diagenesis of soils. Since the MS of heated samples must be measured under controlled conditions, the instrumentations for measuring MS in this case are laboratory-based instruments: typically the Bartington MS2W, or the AGICO KLY and MFK series. Natural or man-made fire can also enhance MS of materials at the soil surface. Soil MS can be significantly increased by exposing soils to high temperatures by burning and incorporating burned or other high susceptibility components into the soil matrix. Consequently, MS tools may be used to study archaeological sites where soil that has been exposed to anthropogenic sources of fire often has higher MS values than surrounding soils. In-field mapping of surface MS can provide maps to assist archaeologists to find ancient habitats of humanity (Dalan et al. 2017).

Measurement of Soil Magnetic Susceptibility

Two basic types of instrumentation are currently available to measure the MS of soils: those that employ a magnetic field or those that utilize EMI methods. In this basis, different companies have designed and produced MS sensors, which have different specifications like shape, size, and type of coils, operating frequency, and recording of measured components. Some of these instruments are handheld and can operate in the field, but some are stationary and need to be used in the laboratory. Here, we briefly explain the physics behind the two different methods, which have been mostly used in instruments to measure soil MS.

Instruments that use magnetic field for measuring MS

Consider a magnetic field having the intensity of H (units of Ampere/metre; A/m) passing through free space. In this case, the magnetic field induction, B, in the free space is $B = \mu_0 H$ (tesla, T) in which $\mu_0 = 4\pi \times 10^{-7}$ T. m/A is the magnetic permeability of free space. Magnetic permeability is the physical property of a material, which describes the degree of induced magnetism the material experiences under the influence of an external magnetic field. Now, assume that a specimen, with volume MS of κ, is exposed to the magnetic field of intensity H and magnetized as $M = \kappa H$. In this case, the specimen acts as a magnet and has its own magnetic field. The magnetic induction (B) is:

$$B = \mu_0 (H + M) \tag{4}$$

which can be expressed as $B = \mu H$ where $\mu = \mu_0(1 + \kappa)$ is the magnetic permeability of the specimen. Now, having μ_0 and measuring μ, the volume MS of the specimen can be simply calculated as:

$$\kappa = (\mu - \mu_0)/\mu_0 \tag{5}$$

All the instruments that employ a magnetic field for measuring MS use alternating currents and a kind of RLC circuit to measure μ, which includes a coil, having resistance R and inductance L, as an inductor, and a capacitor, having capacitance C. When the coil is in free space, the circuit has a known resonance frequency. When a specimen lies in the coil, the inductance of the inductor and in turn the resonance frequency of the circuit will shift. The difference in the resonance frequencies is then related to change in magnetic permeability of the specimen. Accordingly, by measuring the difference in resonance frequencies using electronic circuitry and analyzing it, the magnetic permeability inside the inductor, and then the MS of the specimen can be determined. This is a simple explanation of the physics behind MS measurements using magnetic field-based MS instruments. It is important to realize that the variation of μ is relatively small. Therefore, any thermally induced sensor drift, due to either variations of surrounding temperature or warming up by passing alternating currents through the sensor coil, needs to be eliminated. This elimination and correction is done by occasionally measuring a new "air" value (no specimen in place), to re-establish the μ_0 reference (Bartington Instruments, OM-0408/50).

Instruments that use magnetic fields for measuring soil MS were originally designed to operate in the laboratory as stationary instruments. Some of these instruments have the ability to measure magnetic hysteresis curves for soil or rock samples by measuring magnetization of the sample in various magnetic field intensities (e.g., AGICO MFK2, having magnetic field intensities from 2 to 700 A/m), while others can operate at different frequencies. For example, the Bartington MS2D operates at 465 and 4650 Hz, while the AGICO MFK and KLY series operate at 976, 3904, and 15 616 Hz. The ability to measure MS of soil or rock samples in different temperatures is also an option for some kinds of instruments. For example, the Bartington MS2W operates in the temperature range of −200 to +850 °C, and the AGICO MFK and KLY series equipped with CS4 and CSL sensors operate at the range of −192 to +700 °C. Similar instruments have been particularly designed to measure MS of thin layers of soil by inserting their sensor in a sample hole (e.g., Bartington MS2H, and SM-400 from ZH Instruments). Many attributes, other than just MS, can be measured using different types of magnetic field-based MS instruments, such as remanent magnetization, coercive force, or Curie temperature, which are important in rock magnetism and paleomagnetism. Since the Curie temperature is different for different ferromagnetic minerals, measuring remanent magnetization of the soil samples (or equivalent MS of soil samples) while varying temperatures can assist to determine various types of ferromagnetic minerals in a soil sample (Butler 1998). Nowadays, handheld magnetic-based MS sensors are available, which can be utilized directly in the field. The penetration depth of the magnetic signal is limited and, therefore, only small amounts of soil or rock samples can be analyzed due to small loops (or pick-up coils) that these kinds of instruments utilize as a magnetic inductor. The results, however, are very precise. Table 2 presents different types of current MS instruments, which employ magnetic fields to measure MS, and their applications in soil sciences. Although the operating frequencies of such sensors are different, which can be reflected in the measurements, some authors have utilized different types of these sensors using the same soil samples, compare measurements and discuss advantages and disadvantages in their studies (e.g., Lecoanet et al. 1999; Lee and Morris 2013; Deng and Smith 2016; Grison et al. 2017). In general, if MS of the soil surface, soil exposures, or thin soil layers or horizons is required (e.g., in studying soil pollution), then handheld sensors with small loops/coils (MS2E, MS2F, MS2K, SM-20, SM-30, and KT-10) are sufficient because collection of soil samples is not required. Handheld sensors with larger coils (e.g., MS2D and Multi Kappa) are less affected by locally accumulated magnetic minerals because a larger amount of soil contributes to the measured MS values. So, these MS readings are somewhat "apparent" values, rather than MS values recorded with smaller coil sensors. On the other hand, there is a balance between the time of measurement and the resolution of recordings in MS mapping. While the smaller coil instruments yield detailed information about the soil MS, many more points need to be measured, comparing to the case using larger coil, to map MS of the same area, which is costly and time-consuming. If the study of soil MS variations with frequency or temperature is needed, laboratory-based instruments are definitely preferred since the instruments are equipped with particular sensors to measure MS of soil samples at different frequencies, temperatures, or magnetic field intensities.

EMI instruments

EMI instruments were initially intended to measure electrical conductivity (EC) of soil. All EMI instruments have at least one transmitter coil and one receiver coil, which are tens to hundreds of centimetres apart. An alternating current passes through the transmitter coil and produces an alternating primary magnetic field. This magnetic field penetrates the ground surface and induces electromagnetic currents in the soil materials below in response to the EC and MS of the bulk soil. These currents in turn produce the secondary magnetic field. The aggregation of primary and secondary magnetic fields is then sensed by the receiver coil. The primary magnetic field is a real absolute quantity (or a real number), but due to nature of the induction phenomenon, the secondary magnetic field is a complex number containing in-phase (or real) and quadrature-phase (imaginary or out-of-phase) components. Although the study of the effects of EC and MS, on the secondary magnetic field in homogeneous or layered earth, is straightforward, and can be easily done, the separation of EC or MS contributions to the secondary magnetic field is difficult. While this difficulty occurs when using high frequency currents in the transmitter, there are some assumptions to estimate apparent electrical conductivity (ECa) and apparent magnetic susceptibility (MSa) at low frequencies. The "skin depth" of an EM field is the depth to which the amplitude of that EM field

Table 2. Current instruments[a] that use magnetic field for characterization of soil MS. The specifications of each instrument as well as their applications in soil sciences are also provided.

Manufacturer	Model	Type	Oper. Freq. (Hz)	Sensitivity (SI)	Meas. Comp.	Oper. Temp. (°C)	Applications (references)
AGICO	KLY series	Lab	875	3×10^{-8}	IP, QP	−192 to +700	– Archaeology (Jordanova et al. 2001) – Environmental and soil pollution studies (Spiteri et al. 2005; Lu et al. 2007; Porsch et al. 2010; Birendra 2012; Dlouhá et al. 2013; Yurtseven-Sandker and Cioppa 2016; Canezaro 2018) – Soil organic matter (Yang et al. 2012) – Biochemistry (Sundman et al. 2017) – Soil erosion (Menshov et al. 2018)
	MFK series	Lab	976 3904 15 616	2×10^{-8} 6×10^{-8} 12×10^{-8}	IP, QP IP, QP IP, QP	−192 to +700	– Rock magnetism and palaeomagnetism research (Pokorný et al. 2011; Hrouda 2011; Jordanova and Jordanova 2016) – Environmental siences (Martin et al. 2018; Jordanova et al. 2019) – Soil sciences (Fleming et al. 2013; Grison et al. 2017) – Soil magnetism and mineral assemblage in the SP-SSD range (Hrouda 2011; Hrouda et al. 2013; Ohneiser et al. 2015; Liu et al. 2017; Ustra et al. 2018; Ustra et al. 2019) – Archaeology (Lowe et al. 2020) – Agriculture (Reyes et al. 2013)
Bartington	MS2B	Lab	465 4650	2×10^{-6} 2×10^{-6}	IP IP	Indoor temp.	– Identify soil drainage classes (e.g., de Jong et al. 2000, 2005; Owliaie et al. 2006; Blundell et al. 2009; Asgari et al. 2018; Gholamzadeh et al. 2019; Shirzaditabar and Heck 2021) – Study of soil forming processes or pedology (e.g., Singer et al. 1996; Sarmast et al. 2017) – Investigating the impact of land use and human activity on MS (e.g., Bouhsane and Bouhlassa 2018; Magiera et al. 2019) – Soil degradation (Sadiki et al. 2009; Łukasik et al. 2015; Jakšik et al. 2016) – Soil erosion (Ding et al. 2020) – Soil pollution (Yang et al. 2015; Liu et al. 2016; Rachwal et al. 2017; Wang et al. 2021) – Soil development (Grison et al. 2017)
	MS2C	Lab	565	2×10^{-6}	IP	Indoor temp.	– Archaeology (Fritz et al. 2011) – Lithology (Løvlie and Van Veen 1995) – Soil porosity (Keating et al. 2020) – Petrophysical studies (Potter et al. 2011)
	MS2D	Field	950 ± 60	—	IP	Outdoor temp.	– Soil erosion (Ventura et al. 2001; Liu et al. 2019) – Archaeology (Schmidt 2007) – Ecology (Grimley et al. 2008) – Pollution (Schibler et al. 2002; Boyko et al. 2004; Zawadzki et al. 2010, 2012; Boadi et al. 2014; Cao et al. 2015) – Agriculture (Quijano et al. 2014)
	MS2E	Lab, Field	2000	—	IP	Indoor & outdoor temp.	– Environmental pollutions (Kamaci and Uysal 2017) – Differentiate between clay types for road constructions (Asime et al. 2018)
	MS2F	Field	580	—	IP	Outdoor temp.	– Soil developments (Grison et al. 2011, 2015) – Land mine and UXO detection (van Dam et al. 2004) – Soil pollution (Wojas 2009) – Soil erosion (Ventura et al. 2001)
	MS2G	Lab	1300	—	IP	Indoor temp.	– Environmental studies (Bertrand et al. 2012) – Soil pollution (Akanbi and Nasamu 2020)
	MS2H	Field, Downhole	1300	10^{-5}	IP	Outdoor temp.	– Archaeology (Dalan 2006; Henry and Johnson 2012) – Environmental studies (Simms and Lobred 2011)
	MS2K	Lab, Field	930	—	IP	Indoor & outdoor temp.	– Archaeology (Dalan 2008; Dalan et al. 2017) – Paleomagnetic studies in the ocean (McKay et al. 2019; Reagan et al. 2015)
	MS2W	Lab	348	—	IP	−200 to +850	– Soil MS studies (Vasquez and Nami 2006; Ranganai et al. 2015; Alduraibi 2018) – Rock magnetism (Kristjansson et al. 2003)

Table 2. (*concluded*).

Manufacturer	Model	Type	Oper. Freq. (Hz)	Sensitivity (SI)	Meas. Comp.	Oper. Temp. (°C)	Applications (references)
GF Instruments	SM-20	Lab, Field	10 000	10^{-6}	IP	−10 to +60	– Geological investigations of bedrock mapping (Petersson et al. 2007) – Sinkhole detection (Mochales et al. 2007) – Piedmont stream water quality (Wegmann et al. 2012) – Pollution studies (Elhelou 2015) – Relationship between soil density and MS (Pueyo et al. 2020)
	MultiKappa	Field	—	10^{-6} to 10^{-4}	IP	−10 to +50	– Archaeology (Burks 2019)
Terraplus	KT-10	Lab, Field	10 000	10^{-6}	IP	−20 to +60	– Study of heavy metal contaminations (Shendi et al. 2013) – Geological investigations (Gettings and Bultman 2014) – Archaeology (Gibson 2017) – Mineral exploration (Naibert et al. 2020)
ZH Instruments	SM-30	Lab, Field	8000	10^{-7}	IP	−20 to +50	– Discriminate between rock types by measuring MS of rocks (Bleeker 2012; Lee and Morris 2013; Deng 2014) – Study of water level fluctuation zone (Zhu and He 2012) – MS measurements on pebbles of different shapes, sizes and lithologies (Gattacceca et al. 2004)
	SM-400	Field, Downhole	8000	10^{-6}	IP	Outdoor temp.	– Study of the influence of the soil electrical conductivity on MS measurements (Maier et al. 2006) – Vertical distribution study of MS of a soil column to map deposited dust or fly ash (Petrovsky et al. 2004; Cao et al. 2015)– Soil degradation (Magiera et al. 2019)

[a] Does not constitute endorsement of instruments.

reduces to 1/*e* of its value at the surface, where $e \approx 2.71$ is the base of the natural logarithm. When the ratio of the transmitter–receiver distance to the skin depth of the EM field is much less than unity, this is called a "Low Induction Number" (LIN) condition. The induction number is actually proportional to the product of frequency (f), EC (σ), and magnetic permeability (μ) of the medium. It has been shown that, when using low frequencies, the MSa and ECa are proportional to the in-phase and quadrature-phase of the secondary to primary magnetic field ratio, respectively (Keller and Frischknecht 1966; McNille 1980; Thiesson et al. 2014). In this case, the apparent MS of the soil is twice that of the in-phase component of the secondary to primary magnetic field ratio (EM38 manual 2002; Thiesson et al. 2014), as long as the measurements are done at the surface of the soil. Although these are just estimations of EC and MS of the medium, it is enough to map these properties to delineate areas of low and high EC or MS. The main advantage of using EMI methods is that the measurements can be easily and quickly done because no contact is needed between the instrument and the soil surface. The instruments can also be attached to a mobile vehicle to measure the data in the field such that a high volume of data, corresponding to an extensive area, can be collected in a fast and low-cost way.

EMI instruments, currently used for measuring soil MS, consist of one transmitter and one to six receivers in different separations and configurations. All EMI instruments are handheld and can be readily moved in the field. Since depth penetration of such EMI instruments depends on the distance between the transmitter and receiver, as well as the configuration of transmitter and receiver coils relative to the surface, each of the receivers senses the MS of the soil in a different way. The MS in these kinds of instruments measures the volume MS of the soil (i.e., MS of a volume of soil, for instance, 1 m × 1 m × 1 m, and referred to "apparent MS"). On this basis, EMI instruments are strictly for field use and are not able to measure the MS of soil as laboratory samples. EMI instruments can measure MS of a large area, in a short time to produce a detailed map of soil MS, which is one of the important applications of EMI instruments.

It is worth mentioning that the only way to determine the MS of different horizons or layers of soil in the field, with this type of measurements, is to invert the MS measurements. Considering the soil as a multilayered media, in which each layer has its own thickness and MS, one can mathematically calculate EMI response of the soil at the surface. This procedure is reversible so that given apparent MS measurements collected at the surface, the MS of soil layers can be calculated, as long as different configurations of transmitter and receiver have been used for measuring MS at the surface. When transmitter and corresponding receiver coils are in the same plane, which is horizontal referring to the soil surface, the configuration is called horizontal coplanar (HCP). If the plane is vertical, with respect to the soil surface, the configuration is called vertical coplanar (VCP). The configuration in which the transmitter coil is horizontal, relative to the surface, but the receiver coil is vertical, or vice versa, is called perpendicular (PERP) configuration. Table 3 presents different EMI instruments currently used for measuring soil MS and presents some of their applications in soil science. While some researchers may utilize only one of the EMI instruments (e.g., Bevan 1998; Bevan and Dalan 2003; McNeill 2012; Guillemoteau et al. 2016), other researchers have compared the apparent MS measurements utilizing different types of instruments over the same area of interest (e.g., Benech and Marmet 1999; Simpson et al. 2009; Simpson et al. 2010). Note that since the configuration and separation of transmitter and receiver coils, in different EMI instruments, affect the apparent MS measurements, so measurements from different types of such instruments are not completely comparable.

Applications of Soil MS in Soil Studies

Magnetic granulometry

The classical factors of soil formation (Jenny 1941), that is climate, soil organisms, relief, parent material, and time, have also been used to describe the formation of magnetic minerals in soil (Blundell et al. 2009). Although it seems unusual, micro-organisms can enhance soil MS through fermentation processes (Le Borgne 1955; Mullins 1977, Dearing et al. 1996). Abiotic aging of ferrihydrite to hematite, through the intermediate mineral hydromaghemite, has been found to be a major pathway of magnetic enhancement (Barrón et al. 2003; Torrent et al. 2006; Liu et al. 2008). After oxygen (O), silicon (Si), and aluminum (Al), iron (Fe) is the fourth major abundant element in earth's crust (Jordanova 2017). The abundance of atmospheric oxygen at the earth's surface leads to formation of iron oxides as stable magnetic minerals in nature. The type of iron oxides found in natural deposits, such as rocks, sediments, soils, and aerosols, is heavily influenced by their origin and environmental conditions under which they were formed. So, based on the origin of the magnetic iron oxide minerals, their formation can be classified as lithogenic (or primary) and pedogenic (or secondary). Lithogenic iron oxides are inherited directly from a parent rock. Thus, the mineralogical compositions of lithogenic minerals directly reflect the mineralogy of their parent rock. On this basis, soils developed on sedimentary rocks usually contain far fewer magnetic minerals than those soils developed on volcanic or intrusive parent rocks (Jordanova 2017). It has been found, however, that magnetic grains can be formed during the weathering of igneous or sedimentary rocks (Singer and Fine 1989; Vali et al. 1989; Hounslow and Maher 1996). Lithogenic iron oxides are usually coarse grained (≥20 nm), which contain SD and MD magnetic minerals

Table 3. Electromagnetic induction instruments[a] currently used for measuring soil MS, their specifications and applications in soil sciences.

Manufacturer	Model	Oper. Freq. (Hz)	No. of Receivers	Tx-Rx distance (m)	Configuration	Meas. Comp.	Applications (references)
GF Instruments	CMD Mini-Explorer	30 000	3[a]	0.320.711.18	HCP-VCP	ECa-MSa	– Archaeology (Bonsall et al. 2013; Benech et al. 2016) – Agriculture (Badewa 2017)
DUALEM	DUALEM-21S	9000	4	1 1.1 22.1	HCP-VCP PERP HCP-VCP PERP	ECa-MSa	– Delineate depth to clay mapping (Saey et al. 2009) – Archaeology (Simpson et al. 2009; Guillemoteau et al. 2016) – Soil MS mapping (Simpson et al. 2010)
Geonics	EM38	14 600	1	1	HCP-VCP	ECa-MSa	– Determination of MS of soil layers (Bevan and Dalan 2003; Simpson et al. 2010) – Archaeology (McNeill 2012; Simpson et al. 2009; Bavan 1998, 2000) – Identification of soil drainage classes (Shirzaditabar and Heck 2021)
GEOPHEX	GEM-2	30–93 000	1	1.66	HCP-VCP	ECa-MSa	– Geological, archaeological and environmental applications (Won et al. 1996; Huang and Won 2000; Won and Huang 2004) – Mapping magnetic viscosity and MS of soils (Simon et al. 2015)
GSSI (Geophysical Survey Systems, Inc.)	Profiler EMP-400	1000–16 000	1	1.22	HCP-VCP	ECa-MSa	– Mapping underground utilities (Rashed and Atef 2015)

[a] Does not constitute endorsement of instruments.

that preserve remnant magnetization. They are stable against demagnetizing factors, such as alternating field (AF) and thermal demagnetizations (Dunlop and Özdemir 1997), and due to their small surface to volume ratio, they are resistive to chemical weathering (Schaetzl and Anderson 2009). On the other hand, pedogenic iron oxides are formed during soil formation and development. They are much smaller in size and have low crystallinity compared with lithogenic iron oxides, which are the two most characteristic features of these pedogenic iron oxides (Cornell and Schwertmann 2003). Pedogenic magnetic minerals are ≤ 20 nm in diameter and, therefore, these minerals are called SP minerals. These SP minerals play an important role in soil magnetism. They cannot preserve remanent magnetization, but they possess high MS so that, in some cases, their contribution in soil MS is much higher than coarse-grain minerals (Dunlop and Özdemir 1997). On this basis, the measured MS in a single frequency (χ) cannot discriminate the portion of minerals with different grain sizes. The main method for separate lithogenic and pedogenic magnetic mineral contributions in soil MS is by measuring FD of soil MS, which is actually based on the fact that fine-grained magnetic minerals cannot follow high frequency magnetic field variations, and show less MS than when the low frequency magnetic field is used, that is, $\chi_{hf} < \chi_{lf}$ (Dearing et al. 1996). The difference between these two susceptibilities qualitatively reflects minerals with less than 20 nm in diameter. This phenomenon has motivated soil scientists to use FD of MS to discriminate soil grain sizes, sometimes known as "magnetic granulometry" (Dearing et al. 1996; Evans and Heller 2003; de Jong et al. 2005; Egli 2009; Chadima et al. 2010; Hrouda et al. 2013; Kodama 2013; Kodama et al. 2014). Magnetic granulometry is generally based on laboratory measurements of soil MS at different frequencies, which can be done using either Bartington MS2B or AGICO KLY and MFK series instruments. Since FD of MS is a dimensionless quantity derived from dividing the difference of low and high frequency MS measurements to low frequency MS, the low and high frequency measurements can be done as either mass-specific or volume MS.

Using physical and mathematical models, Hrouda (2011) has shown that FD of MS can be utilized to determine different soil grain sizes, but he also introduced a method to compensate the discrepancy of using different frequencies to calculate the FD of MS. Recently, Grison et al. (2017) used this method to detect pedogenic magnetic minerals in volcanic soils developed on basalt utilizing two different magnetic-based instruments, Bartington MS2D and AGICO MFK1-FA.

Detection of pollutants

Anthropogenic processes such as atmospheric deposition of fly ash from industrial emissions and motor vehicle exhaust, mining activities, irrigation with polluted or sewage water, or liquid slags from industrial activities may be detected in soil using MS instrumentation. These pollutants partly include some of magnetic iron oxides, which enhance the MS in the polluted area. As such, MS measurements can be used as a proxy to trace environmental pollutants. On the other hand, most of anthropogenic pollutant factors are related to heavy metals such as Al, Cd, Cr, Cu, Fe, Ni, Pb, and Zn. The existence of these heavy metals, in the soil, commonly results in enhancement of soil MS that can then be measured in the field or in the laboratory using soil samples. In fact, anthropogenic pollution results in a strong magnetic signature of the soil such that magnetic techniques, which are nondestructive, fast, and cost-effective, can be used to monitor these kinds of pollutants.

Numerous studies have reported positive relationships between soil MS and the contents of heavy metals in soil around roads or industrial sites (e.g., Kapička et al. 1999; Matzka and Maher 1999; Jordanova et al. 2003; Hu et al. 2007; El Baghdadi et al. 2012; Brempong et al. 2016; Orosun et al. 2020). In-field mapping of soil MS has also been utilized to monitor soil pollution resulted from industrial emissions (Hay et al. 1997; Heller et al. 1998; Hoffmann et al. 1999; Boyko et al. 2004; Duan et al. 2009). While the magnetic particles are well preserved in the topsoil of forest soils, cultivation of arable lands results in mixing the topsoil with high MS with underlying subsoil with low MS (Declercq et al. 2019). More recently, the soil MS has been used to detect heavy metal pollution in coastal areas (Tholkappian et al. 2019; Devanesan et al. 2020). The agricultural soil pollution can also be associated with the spread of heavy metals due to mining activities (Sheoran and Sheoran 2006). Mining wastes, produced by leaching ore bodies, are highly enriched in heavy metals that may penetrate nearby farming lands, groundwater, or streams. Dlouhá et al. (2013) utilized soil MS to investigate alluvial soils in river valleys contaminated by potentially toxic elements derived from mining and metallurgical industry. Hu et al. (2014) studied the effect of mining wastewater discharge on the quality in four representative paddy soils. The enhancement of soil MS signals around a tungsten mine is also reported to be linked to the contamination by arsenic (Ouyang et al. 2020). Unfortunately, EMI do not see applicability in all instances because the instruments are not sensitive to thin layers, containing fly ash or heavy metals for instance. They also cannot precisely measure MS of individual soil constituents; however, if the amount and special distribution of contamination are substantial, EMI techniques can help to delineate contaminated areas more accurately.

Impact of organic matter

Organic matter also affects soil MS. As a key indicator of soil quality (Owliaei et al. 2006), soil organic matter provides the energy needed for the reduction of iron from a hydroxide solution (Mullins 1977; Schwertmann et al. 1989; Bedard-Haughn 2011), which leads to formation of magnetite or maghemite and enhances the MS of the soil. Maher (1988) reported a positive correlation between MS and soil organic carbon content. Rijal et al. (2010 and 2012) observed enhancement of MS in hydrocarbon-contaminated soils and found a relationship between the amount of total nonpolar hydrocarbon (TNPH) and enhancement of soil MS. By studying the role of a kind of bacteria in the reduction of iron (hydr) oxides, Atekwana et al. (2014) observed correlation between zones with high concentrations of hydrocarbons and enhancement of MS and suggested the coupling of iron reduction with organic carbon oxidation in such zones. Zhang et al. (2013) observed an enhancement of low and high frequency MS in topsoil in farmland soils irrigated by sewage water. By comparing soil MS values of two adjacent agricultural sites, one irrigated by solely groundwater and other by sewage water, Yang et al. (2015) showed enhancements of MS and organic matter in the soils irrigated by sewage water and concluded that soil MS is significantly correlated with organic matter content. Another possibility for enhancing MS in soils irrigated by sewage water may be related to metals applied with the sewage water, which has not been addressed by Yang et al. (2015).

Almost all studies regarding the effect of organic matter on soil MS have been carried out by utilizing laboratory-based instruments, which use magnetic field for measuring soil MS. EMI instruments have not yet been used for studying the effect of organic matter on soil MS.

Delineation of drainage class

It has been suggested that the extremely reducing conditions, present in hydric soils, significantly enhance dissolution of soil ferrimagnetic minerals such as magnetite and maghemite (Maher 1986; Williams 1992). Since the MS of soils is mainly controlled by magnetite and maghemite concentrations (Mullins 1977; Maher 1986), MS values are typically very low in hydric, that is, poorly drained or gleyed, soils (Le Borgne 1955; Vadyunina and Babanin 1972; Yu et al. 1986). This phenomenon has widely been utilized by soil scientists to characterize soil drainage conditions (e.g., de Jong 2002; de Jong et al. 2005; Grimley et al. 2004 and 2008; Asgari et al. 2018; Gholamzadeh et al. 2019), which all have utilized the instruments that use magnetic fields to measure soil MS (Bartington MS2B and MS2D). Although measuring and (or) mapping of soil MS by utilizing EMI instruments can easily reveal drainage conditions of the soil, these kinds of instruments have rarely been used for discriminating soil drainage conditions (Shirzaditabar et al. 2021; Shirzaditabar and Heck 2021).

Paleo-environmental studies

The effect of climate, including temperature and rainfall, on soil MS has received a lot of attention because it is a proxy and a key factor in reconstructing past climate (e.g., Begét et al. 1990; Maher and Thompson 1991, 1992 and 1995; Geiss et al. 2008). By recording the MS of loess sequences in China, Maher and Thompson (1995) reported increasing MS with mean annual rainfall peaking at around 1500 mm, which was followed by decreasing MS to around 3000 mm. Singer et al. (1996) observed a similar behavior in increasing soil MS by annual precipitation of around 1000 mm in Kohala peninsula island, in Hawaii, with an associated decline of MS to around 2500 mm. They also reported enhancement of soil MS with increasing mean annual temperature, to a maximum of 18 °C, followed by a decrease. These researchers also reported enhancement of soil MS with time. More recently, by studying MS of loess soils in China and Europe, Jordanova and Jordanova (2021) also observed the influence of mean annual precipitation and temperature on MS of loess soils. All of these studies were done using laboratory-based instruments (Bartington MS2B and AGICO KLY and MFK series), because they require precise measurements of soil MS, which cannot be achieved by utilizing EMI instruments directly in the field.

Archaeology

Unnatural impacts of human activities on soil, as well as anthropogenic processes, have made the archaeological sites very complex environments. Therefore, combined multidisciplinary approaches are required to generate thorough reconstruction of these sites (Walkington 2010; Canti and Huisman 2015). Although chemical methods have been shown to be useful in archaeological studies (Pastor et al. 2016), geophysical methods are still the most important methods to detect archaeological sites (Gaffney 2008). These geophysical methods include EC measurements, to map conductivity (σ) changes in the soil, ground penetrating radar (GPR), to reveal detailed layering of the subsurface (mostly based on soil electrical permittivity, ε) and magnetometry, to disclose and map soil MS variations. While EC measurements are useful in archaeological investigations, moisture content of the soil can quickly affect EC values. On the other hand, it has been shown that MS is less affected by soil moisture (Maier et al. 2006), which suggests the soil MS as a reliable feature in archaeological studies. Indeed, many surveys in archaeological studies utilize soil MS to discover archaeological features (De Smedt et al. 2014; Fassbinder 2015). The early work of Le Borgne (1955) suggested that high temperatures produced by fires can cause enhancement in soil MS. In such circumstances, non-ferrimagnetic oxides, produced by weathering of the soil, are reduced to magnetite and maghemite. It has been also suggested that in poorly drained soils, dehydration of lepidocrocite, at temperatures between 275 °C and 400 °C, may cause formation of maghemite (Thompson and Oldfield 1986; Maher 1986). Fires may be produced either naturally or intentionally by humans. Inspired by this suggestion, the first attempts were done to explore archaeological sites (Aitken et al. 1958; Colani and Aitken 1966). Tite and Mullins (1971) confirmed that heating by fire has a strong impact on soil MS enhancement. Although iron tools, like swords, provide high magnetic signature, and can be easily detected using magnetic measurements, some human activities, like pottery production or metal workings. They also leave certain magnetic signatures behind in the landscape because of alteration of magnetic minerals in the soil or even distribution of waste pottery products. Evidence also shows that repetitive use of local fires, or intentional burning of a landscape, has left a distinctive magnetic trace on the soil (Linford 2005). Therefore, for the above-mentioned reasons, the most surveys in archaeological investigations nowadays use soil magnetic properties, especially MS, to reveal signatures from ancient civilizations (e.g., Bevan 2000; Bevan and Dalan 2003; Jordanova et al. 2001; Dalan 2006, 2008 and 2009; Sipmson et al. 2009; Bonsall et al. 2013; Benech et al. 2016; Heil and Schmidhalter 2017; Dalan et al. 2017; Gibson 2017; Lowe et al. 2020). Although using instruments that employ a magnetic field may be useful for archaeological investigations, EMI instruments are much more popular in such investigations because they are nonintrusive and have the ability to measure and map soil MS in a very fast and efficient way.

Soil erosion and degradation

As a natural phenomenon, soil erosion affects all types of landforms and the high level of land degradation in some geographical regions is a serious threat for sustainable agricultural activities (Bouhlassa and Bouhsane 2019). Soil erosion, in agriculture, is related to the removal and redistribution of topsoil, and sometimes subsoil, by natural forces, such as water and wind, or anthropogenically by tillage (Jordanova et al. 2014; Jakšík et al. 2016).

As a physical property of soil, MS has proved to be an effective tool in soil erosion and degradation studies. The distribution of ferrimagnetic minerals in soils has shown to be an indicator of soil degradation (Sadiki et al. 2009; Łukasik et al. 2015). Measuring soil MS for evaluation of soil redistribution along the slope in semi-arid regions was validated by Karchegani et al. (2011). Jordanova et al. (2011), in a detailed field and laboratory study showed that the magnetic methods are efficient in soil erosion assessment; even in a highly magnetic parent material, where they observed a significant amount of soil loss and related it to tillage practices. By measuring soil MS on a sloped site of agricultural land in the loess terrain, Kapička et al. (2013) observed the highest values of MS on flat up-slope areas, where the original top horizon remained, and the lowest values of MS on the steep side slopes, and attributed this to erosion on steep slopes. Results of studying MS of Chernozem soils, from an agricultural land, showed that tillage was the main cause of soil erosion on upper slopes (Jordanova et al. 2014). By analyzing the variation of soil MS in different soil profiles on forested, cultivated, and pasture lands, having the same lithology and climatic conditions but different land uses and slope gradients, Bouhlassa and Bouhsane (2019) found that MS decreases as $\chi_{\text{forested}} > \chi_{\text{pasture}} > \chi_{\text{cultivated}}$, and by observing positive correlation between χ_{lf} and χ_{fd}, they concluded that the loss of fine magnetic particles is associated to decrease in χ_{lf}. Highly correlated with the humus content and erosion index, MS is an indicator for identifying soil erosion rates and depths. Soil MS investigations, in addition to providing the benefit of rapid and low-cost measurements, allow for the formation of a dense grid of sampling and the identification of slope erosion structure (Menshov et al. 2018).

Since erosion affects topsoil more than subsoil, and the MS of soil must precisely be measured to be used in erosion studies, all instrumentations used for this case are laboratory instruments, mostly Bartington MS2B and AGICO KLY series, which are instruments that use magnetic fields for measuring MS. While EMI instruments have not yet been used for investigating soil erosion and degradation, the ability of measuring MS in different frequencies has made the laboratory instruments the only, and the most appropriate, option to be used in such studies.

Summary and Future Directions

The MS measurements in soils depend on grain sizes and the concentration of magnetic minerals. Measurements are also highly dependent on the instrument used to measure it. Almost all MS instruments that use magnetic fields to measure MS, utilize some kind of coil to pick up the returning magnetic signal from the soil and display or record the soil MS. The geometry of these coils, and electronics behind different MS instruments, affects the MS measurements. The coils of the MS instruments can excite certain amounts of soil to contribute to MS measurements. For example, a larger coil diameter is capable of influencing a larger volume of soil for the MS recordings (or more depth of investigation). The recorded MS in this case is a mean value of MS of the constituents within the volume of excited soil. Therefore, since the magnetic minerals are randomly distributed in the soil context, handheld instruments with larger coils have the advantage that their results are less affected by local accumulation of magnetic minerals and yield the mean MS of the soil.

The frequency in which the instrument operates also affects the measurement of soil MS. Due to relaxation of fine-grained magnetic minerals in the soil, MS recordings at higher frequencies are less than MS recordings at lower frequencies. This behavior is used to discriminate between lithogenic and pedogenic soil minerals. Furthermore, the FD of MS is a key factor to delineate soil drainage classes because intermittent water saturation and redox processes lead to formation of fine-grained magnetic minerals, which respond better to low frequency fields. The FD of MS can also be used in soil pollution studies where, for example, fine-grained fly ash from industry or motor vehicle exhausts are deposited on the soil surface. It should be noted that when the data are acquired using instruments with different operating frequencies over the same area, where the increases or decreases in MS over a profile or in a map are comparable, the individual values of soil MS, as well as percentage FD, are not the same over the same position. This means that the comparison between different types of instruments is meaningful only when they have the same design and geometry, and operate at the same frequency.

The ability to measure simultaneously out-of-phase components, as well as in-phase components, is the advantage of using some kinds of MS instruments, which use magnetic fields (e.g., AGICO KLY and MFK models). Using the in-phase and out-of-phase components in just one frequency is enough to calculate FD of MS of a sample. Some types of instruments have the capability to measure MS in a range of temperatures (AGICO KLY and MFK, Bartington MS2W), which can be used to reveal mineralogy of soil samples.

Contrary to instruments that use magnetic fields, the separation between transmitter and receiver in EMI instruments determines the amount of soil that contributes to the MS measurement. Therefore, MS values recorded by EMI instruments are essentially apparent values because they are mean values of MS based on a hemisphere of soil below the instrument, for example, 1 m diameter. Moreover, the sensitivity of EMI instruments to MS of the soil is different for different configurations. While the sign of apparent MS remains the same in VCP configuration mode, it changes from positive to negative, or vice versa, in HCP and perpendicular (PERP) configurations, because these two latter modes are sensitive to the distance from the magnetic layer (or magnetic horizon). Thus, mapping with EMI instruments may reveal negative apparent MS locations, especially when using HCP and PERP configurations, which are not necessarily the indication of diamagnetic zones. Although inversion methods can be utilized to recover MS of soil layers, or horizons, from apparent MS measurements taken from EMI instruments, these methods have limited accuracy when they are given limited input data. The best results are achieved if data from various configurations, and possibly different heights above surface, are used as input data.

The great advantage of EMI instruments against those that use magnetic fields is their high speed of recording. This is because the EMI instruments does not need to contact the earth's surface and the signal can be sensed by receiver coil of instrument even it is suspended above the soil surface. So, if the objective of MS measurements is to map the MS variations in a certain area, for instance in archaeological or agricultural studies, the EMI instrument is preferred because the measurements can be done quickly, and the resulting MS map reveals high and low MS zones. On the other hand, if grain size or mineralogy of the soil is desired, instruments that use just magnetic fields are preferred, especially laboratory instruments which have the ability to measure FD or out-of-phase components of MS.

This review showed that both kinds of MS instruments have been widely used in soil science; however, they cannot be simply interchanged with each other because they use different methods for measuring soil MS. Limitations of designing handheld EMI instruments to operate at low frequencies for laboratory measurements, or vice versa, have limited comparison. Moreover, the lack of available three-dimensional, and even one-dimensional, inversion software for calculating MS of different segments of soil has deterred soil scientists from utilizing EMI instruments widely in their research. Therefore, designing new instruments to be used in the field and (or) laboratory that are able to operate for a range of frequencies, and comparison of the results of applying both kinds of instruments in the same area, might be a future work to see which kind of instrument can find better status among soil scientists.

Funding

This research was supported by NSERC-Engage grant awarded to the second author.

Acknowledgements

The authors would like to thank the editor, Dr. James Warren, and two anonymous reviewers for their helpful remarks as well as thorough and detailed editing recommendations for improving the article.

References

Aitken, M.J., Webster, G., and Reeds, A. 1958. Magnetic Prospecting, Antiquity. **32**: 270–271.

Akanbi, E.S., and Nasamu, E.J. 2020. Magnetic pollution of soil samples at some industrial sites in Jos Metropolis, Plateau State, Nigeria, J. Appl. Sci. Environ. Manage. **24**: 193–196, doi:10.4314/jasem.v24i2.1

Alduraibi, S. 2018. Characterisation and Spatial Variability of the Magnetic and Electrical Resistivity Geophysical Properties of the Soils of Counties Kildare and Wicklow, Eastern Ireland, Ph.D. thesis, Maynooth University.

Asgari, N., Ayoubi, S., and Dematte, J.A.M. 2018. Soil drainage assessment by magnetic susceptibility measures in western Iran. Geoderma Reg. **13**: 35–42. doi:10.1016/j.geodrs.2018.03.003

Asime, O., Don Lawson, C., and Chidiebere, O.A. 2018. Clay typing for sustainable road constructions in some parts of Niger delta using magnetic susceptibility signature technique. Int. J. Chem. Chem. Proces. **4**(3).

Atekwana, E.A., Mewafy, F.M., Abdel Aal, G., Werkema, D.D., Jr., Revil, A., and Slater, L.D. 2014. High-resolution magnetic susceptibility measurements for investigating magnetic mineral formation during microbial mediated iron reduction. J. Geophys. Res. Biogeosci. **119**: 80–94. doi:10.1002/2013JG002414

Badewa, E.A. 2017. Apparent Electrical Conductivity Mapping in managed Podzols using Multi-coil and Multi-frequency EMI sensor measurements, M.Sc. thesis, Memorial University.

Barrón, V., Torrent, J., and de Grave, E. 2003. Hydromaghemite, an intermediate in the hydrothermal transformation of 2-line ferrihydrite into hematite. Am. Mineral. **88**: 1679–1688. doi:10.2138/am-2003-11-1207

Bartington Instruments, Operation Manual for MS2 Magnetic Susceptibility System, OM-0408/50.

Bedard-Haughn, A. 2011. Gleysolic soils of Canada: genesis, distribution, and classification. Can. J. Soil Sci. **91**: 763–779. doi:10.4141/cjss10030

Begét, J.E., Stone, D.B., and Hawkins, D.B. 1990. Paleoclimatic forcing of magnetic susceptibility variations in Alaskan loess during the late Quaternary. Geology, **18**: 40–43. doi:10.1130/0091-7613(1990)018b0040

Benech, C., and Marmet, E. 1999. Optimum depth of investigation and conductivity response rejection of the different electromagnetic devices measuring apparent magnetic susceptibility. Archaeol. Prospec. **6**: 31–45, doi:10.1002/(SICI)1099-0763(199903)6:1<31::AID-ARP112>3.0.CO;2-N.

Benech, C., Lombard, P., Rejiba, F., and Tabbagh, A. 2016. Demonstrating the contribution of dielectric permittivity to the in-phase EMI response of soils: example from an archaeological site in Bahrain, Near Surf. Geophys. **14**: 337–344, doi:10.3997/1873-0604.2016023

Bertrand, S., Hughen, K.A., Sepúlveda, J., and Pantoja, S. 2012. Geochemistry of surface sediments from the fjords of Northern Chilean Patagonia (44-47°S): Spatial variability and implications for paleoclimate reconstructions. Geochim. Cosmochim. Acta. **76**: 125–146. doi:10.1016/j.gca.2011.10.028

Bevan, B.W. 1998. Geophysical Exploration for Archaeology: an Introduction to Geophysical Exploration, U.S. National Park Service Publications and Papers, 91. [Online]. Available from https://digitalcommons.unl.edu/natlpark/91

Bevan, B.W. 2000. A Geophysical Survey at Malvern Hill, doi:10.13140/rg.2.2.10895.79520

Bevan, B.W., and Dalan, R.A. 2003. Magnetic Susceptibility Sounding, Geosight, doi:10.13140/rg.2.2.10891.28962

Birendra, S. 2012. Effects of metal pollutants on magnetic and chemical properties of soils and plant biomass: experimental studies in Environmental Magnetism, Electronic Theses and Dissertations, 5405. [Online]. Available from https://scholar.uwindsor.ca/etd/5405

Bleeker, W. 2012. The use of hand-held MS meters in the field: an invaluable tool in regional studies of dyke swarms: geological Survey of Canada, Open File 7139, poster. doi:10.4095/291403

Blundell, A., Dearing, J.A., Boyle, J.F., and Hannam, J.A. 2009. Controlling factors for the spatial variability of soil magnetic susceptibility across England and Wales. Earth Sci. Rev. **95**: 158–188, doi:10.1016/j.earscirev.2009.05.0 01

Boadi, B., Preko, K., and Amekudzi, L.K. 2014. Implications of soil magnetic susceptibility measurements from the waste site deposit of Independence Hall, Kwame Nkrumah University of Science and Technology (K. N. U. S. T), Kumasi. Int. J. Sci. Res. Publ. **4**: 5.

Bonsall, J., Fry, R., Gaffney, C., Armit, I., Beck, A., and Gaffney, V. 2013. Assessment of the CMD mini-explorer, a new low-frequency multi-coil electromagnetic device, for archaeological investigations. Archaeol. Prospect. **20**: 219–231. doi:10.1002/arp.1458

Bouhlassa, S., and Bouhsane, N. 2019. Assessment of areal water and tillage erosion using magnetic susceptibility: the approach and its application in Moroccan watershed. Environ. Sci. Pollut. Res. **26**: 25452–25466. doi:10.1007/s11356-019-05510-6

Bouhsane, N., and Bouhlassa, S. 2018. Assessing Magnetic Susceptibility Profiles of Topsoils under Different Occupations. Int. J. Geophys., Article ID 9481405, 8 pages, doi:10.1155/2018/9481405

Bowles, J.A., Jackson, M.J., Berquó, T.S., Sølheid, P.A., and Gee, J.S. 2013. Inferred time- and temperature-dependent cation ordering in natural titanomagnetites. Nat. Commun. **4**: 1916. doi:10.1038/ncomms2938

Boyko, T., Scholger, R., and Stanjek, H., and , MAGPROX Team. 2004. Topsoil magnetic susceptibility mapping as a tool for pollution monitoring: repeatability of in situ measurements. J. Appl. Geophys. **55**: 249–259. doi:10.1016/j.jappgeo.2004.01.002.

Brempong, F., Mariam, Q., and Preko, K. 2016. The use of magnetic susceptibility measurements to determine pollution of agricultural soils in road proximity. Afr. J. Environ. Sci. Technol. **10**: 263–271. doi:10.5897/ajest2015.2058.

Burks, J. 2019. Village life in the Middle Ohio Valley, USA: geophysical survey and anomaly testing. J. Bonsall, ed. “New global perspectives on archaeological prospection”, The 13th ICAP and the importance of Archaeological Prospection, 28 Aug.–1 Sep. 2019, Sligo, Ireland.

Butler, R.F. 1998. Paleomagnetism: magnetic domains to geologic terranes. Electronic edition, Blackwell Science Inc.

Canezaro, M.E. 2018. Magnetic susceptibility and XRF analysis of soils from baton rouge, Louisiana: correlation and implications for heavy metal pollution, University of Louisiana at Lafayette.

Canti, M., and Huisman, D.J. 2015. Scientific advances in geoarchaeology during the last twenty years. J. Archaeol. Sci. **56**: 96–108. doi:10.1016/j.jas.2015.02.024.

Cao, L., Appel, E., Rösler, W., and Magiera, T. 2015. Efficiency of stepwise magnetic-chemical site assessment for fly ash derived heavy metal pollution. Geophys. J. Int. **203**: 767–775. doi:10.1093/gji/ggv318.

Carmichael, R.S. 1989. Practical Handbook of Physical Properties of Rocks and Minerals. CRC Press.

Chadima, M., Kadlec, J., Hrouda, F., and Šlechta, S. 2010. Frequency dependence of magnetic susceptibility of weakly magnetic sediments: implications for magnetic granulometry. Travaux Geophys. **39**: 11.

Colani, C., and Aitken, M.J. 1966. Utilization of magnetic viscosity effects in soils for archaeological prospection. Nature, **212**: 1446–1447. doi:10.1038/2121446a0

Cornell, R., and Schwertmann, U. 2003. The iron oxides. Structure, properties, reactions, occurrence and uses. Weinheim, New York.

Dalan, R.A. 2006. A geophysical approach to buried site detection using down-hole susceptibility and soil magnetic techniques, Archaeol. Prospect. **13**: 182–206. doi:10.1002/arp.278

Dalan, R.A. 2008. A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: recent developments and prospects. Archaeol. Prospect. **15**: 1–31. doi:10.1002/arp.323

Dalan, R.A. 2009. Probing the surface: Adding depth and detail to surface geophysical surveys using down-hole susceptibility measurements. Archeo. Sci. **33**: 283–285. doi:10.4000/archeosciences.1711.

Dalan, R.A., Sturdevant, J., Wallace, R., Schneider, B., and De Vore, S. 2017. Cutbank geophysics: a new method for expanding magnetic investigations to the subsurface using magnetic susceptibility testing at an Awatixa Hidatsa Village, North Dakota. Remote Sens. **9**: 112. doi:10.3390/rs9020112

Dearing, J. 1999. Environmental magnetic susceptibility Using the Bartington MS2 systems. 2nd ed, OM3836/9.

Dearing, J.A., Dann, R.J.L., Hay, K., Lees, J.A., Loveland, P.J., Maher, B.A., and O’Grady, K. 1996. Frequency-dependent susceptibility measurements of environmental materials. Geophys. J. Int. **124**: 228–240. doi:10.1111/j.1365-246x.1996.tb06366.x

Debye, P.J.W. 1929. Polar molecules, The Chemical Catalog Company, Inc. New York, USA.

Declercq, Y., Samson, R., Castanheiro, A., Spassov, S., Tack, F.M.G., Van De Vijver, E., and De Smedt, P. 2019. Evaluating the potential of topsoil magnetic pollution mapping across different land use classes. Sci. Total Environ. **685**: 345–356. doi:10.1016/j.scitotenv.2019.05.379.

de Jong, E. 2002. Magnetic susceptibility of Gleysolic and Chernozemic soils in Saskatchewan. Can. J. Soil Sci. **82**: 191–199. doi:10.4141/s01-019

de Jong, E., Heck, R.J., and Ponomarenko, E.V. 2005. Magnetic susceptibility of soil separates of Gleysolic and Chernozemic soils. Can. J. Soil Sci. **85**: 233–244. doi:10.4141/s04-034

de Jong, E., Pennock, D.J., and Nestor, P.A. 2000. Magnetic susceptibility of soils in different slope positions in Saskatchewan, Canada. Catena, **40**: 291–305. doi:10.1016/s0341-8162(00)00080-1

Deng, D.N. 2014. A comparative study of hand-held MS instruments, M.Sc. thesis, Earth Sciences Department, Laurentian University, Canada.

Deng, C., Vidic, N.J., Verosub, K.L., Singer, M.J., Liu, Q., Shaw, J., and Zhu, R. 2005. Mineral magnetic variation of the Jiaodao Chinese Loess/Paleosol Sequence and its bearing on long-term climatic variability. J. Geophys. Res. **110**: B03103. doi:10.1029/2004jb003451

Deng, D.N., and Smith, R.S. 2016. A comparison of magnetic susceptibility meters using samples from the Thompson Nickel Belt, Canada. Preview, **184**: 41–44. doi:10.1071/pvv2016n184p41.

De Smedt, P., Saey, T., Meerschman, E., De Reu, J., De Clercq, W., and Van Meirvenne, M. 2014. Comparing Apparent Magnetic Susceptibility Measurements of a Multi-receiver EMI Sensor with Topsoil and Profile Magnetic Susceptibility Data over Weak Magnetic Anomalies. Archaeol. Prospect. **21**: 103–112. doi:10.1002/arp.1467

Devanesan, E., Chandrasekaran, A., Sivakumar, S., Freny Joy, K.M., Najam, L.A., and Ravisankar, R. 2020. Magnetic susceptibility as proxy for heavy metal pollution detection in sediment. Iran, J. Sci. Technol. Trans. Sci. **44**: 875–888. doi:10.1007/s40995-020-00865-9

Ding, Z., Zhang, Z., Li, Y., Zhang, L., and Zhang, K. 2020. Characteristics of magnetic susceptibility on cropland and pastureland slopes in an area influenced by both wind and water erosion and implications for soil redistribution patterns. Soil Tillage Res. **199**: 104568. doi:10.1016/j.still.2019.104568.

Dlouhá, Š., Petrovský, E., Kapička, A., Borůvka, L., Ash, C., and Drábek, O. 2013. Investigation of polluted alluvial soils by magnetic susceptibility methods: a case study of the Litavka River. Soil Water Res. **8**: 151–157. doi:10.17221/14/2013-swr

Duan, X.M., Hu, S.Y., Yan, H.T., Blaha, U., Roesler, W., Appel, E., and Sun, W.H. 2009. Relationship between magnetic parameters and heavy element contents of arable soil around a steel company, Nanjing. Sci. China Earth Sci. **53**: 411–418. doi:10.1007/s11430-009-0165-1

Dunlop, D., and Özdemir, Ö. 1997. Rock magnetism. Fundamentals and frontiers. D. Edwards, ed. Cambridge studies in magnetism. Cambridge University Press.

Dzyaloshinsky, I. 1958. A thermodynamic theory of "weak" ferromagnetism of antiferromagnetics. J. Phys. Chem. Solids, **4**: 241–255. doi:10.1016/0022-3697(58)90076-3

Egli, R. 2009. Magnetic susceptibility measurements as a function of temperature and frequency I: inversion theory. Geophys. J. Int. **177**: 395–420. doi:10.1111/j.1365-246x.2009.04081.x

El Baghdadi, M., Barakat, A., Sajieddin, M., and Nadem, S. 2012. Heavy metal pollution and soil of Beni Mellal City (Morocco). Environ. Earth Sci. **66**: 141–155. doi:10.1007/s12665-011-1215-5

Elhelou, O. 2015. Magnetic susceptibility mapping of fly ash in soil samples near a coal-burning power plant in pointe Coupee Parish, Louisiana, M.Sc. thesis, University of Louisiana at Lafayette, Louisiana, USA.

EM38 Ground Conductivity Meter Operating Manual. 2002. Geonics limited, Mississauga, Canada.

Evans, M.E., and Heller, F. 2003. Environmental magnetism: principles and applications of enviromagnetics, Academic Press, San Diego, USA.

Fassbinder, J. 2015. Seeing beneath the farmland, steppe and desert soil: magnetic prospecting and soil magnetism. J. Archaeol. Sci. **56**: 85–95. doi:10.1016/j.jas.2015.02.023.

Fleming, E.J., Stevenson, C.T.E., and Petronis, M.S. 2013. New insights into the deformation of a Middle Pleistocene glaciotectonised sequence in Norfolk, England through magnetic and structural analysis. Proc. Geol. Assoc. **124**: 834–854. doi:10.1016/j.pgeola.2012.11.004.

Fritz, B.G., McFarland, D., Hertz, W., and Gamey, J. 2011. Application of Magnetic and Geotechnical Methods for Archaeological Site Investigations, Pacific Northwest National Laboratory, SERDP Project RC-1697. doi:10.21236/ada551819

Gaffney, C. 2008. Detecting trends in the prediction of the buried past: a review of geophysical techniques in archaeology. Archaeometry, **50**: 313–336. doi:10.1111/j.1475-4754.2008.00388.x.

Gattacceca, J., Eisenlohr, P., and Rochette, P. 2004. Calibration of in situ MS measurements, Geophys. J. Int. **158**: 42–49. doi:10.1111/j.1365-246x.2004.02297.x

Geiss, C.E., Egli, R., and Zanner, C.W. 2008. Direct estimates of pedogenic magnetite as a tool to reconstruct past climates from buried soils. J. Geophys. Res. **113**: B11102. doi:10.1029/2008jb005669

Gettings, M.E., and Bultman, M.W. 2014. Magnetic susceptibility data for some exposed bedrock in the western conterminous United States: U.S. Geological Survey Data Series 804. doi:10.3133/ds804

Gholamzadeh, M., Ayoubi, S., and Sheikhi Shahrivar, F. 2019. Using magnetic susceptibility measurements to differentiate soil drainage classes in central Iran, Stud. Geophys. Geod. **63**: 465–484. doi:10.1007/s11200-018-0679-0

Gibson, T. 2017. Near surface magnetic assessment on the FM Ranch Campsite (EfPk-1). Archaeol. Surv. Alberta Occas. Paper **37**: 82–93.

Grimley, D.A., Arruda, N.K., and Bramstedt, M.W. 2004. Using magnetic susceptibility to facilitate more rapid, reproducible and precise delineation of hydric soils in the Midwestern USA. Catena, **58**: 183–213. doi:10.1016/j.catena.2004.03.001.

Grimley, D.A., Wang, J.S., Liebert, D.A., and Dawson, J.O. 2008. Soil magnetic susceptibility: a quantitative proxy of soil drainage for use in ecological restoration. Restor. Ecol. **16**: 657–667. doi:10.1111/j.1526-100x.2008.00479.x.

Grison, H., Petrovský, E., Jordanova, N., and Kapička, A. 2011. Strongly magnetic soil developed on a non-magnetic rock basement: a case study from NW Bulgaria. Stud. Geophys. Geod. **55**: 697–716. doi:10.1007/s11200-009-0489-5

Grison, H., Petrovský, E., Kapička, A., and Hanzlikova, H. 2017. Detection of the pedogenic magnetic fraction in volcanic soils developed on basalts using frequency-dependent magnetic susceptibility: comparison of two instruments. Geophys. J. Int. **209**: 654–660. doi:10.1093/gji/ggx037

Grison, H., Petrovský, E., Stejskalova, S., and Kapička, A. 2015. Magnetic and geochemical characterization of Andosols developed on basalts in the Massif Central, France. Geochem. Geophys. Geosyst. **16**: 1348–1363. doi:10.1002/2015GC005716

Guillemoteau, J., Simon, F.X., Lück, E., and Tronicke, J. 2016. 1D sequential inversion of portable multi-configuration electromagnetic induction data. Near Surf. Geophys. **14**: 423–432. doi:10.3997/1873-0604.2016029

Hanesch, M., Stanjek, H., and Petersen, N. 2006. Thermomagnetic measurements of soil iron minerals: the role of organic carbon. Geophys. J. Int. **165**: 53–61. doi:10.1111/j.1365-246x.2006.02933.x

Harrison, R.J., and Putnis, A. 1999. Determination of the mechanism of cation ordering in magnesioferrite ($MgFe_2O_4$) from the time- and temperature-dependence of magnetic susceptibility. Phys. Chem. Miner. **26**: 322–332. doi:10.1007/s002690050192

Hay, K.L., Dearing, J.A., Baban, S.M.J., and Loveland, P. 1997. A preliminary attempt to identify atmospherically-derived pollution particles in English topsoils from magnetic susceptibility measurements. Phys. Chem. Earth, **22**: 207–210. doi:10.1016/s0079-1946(97)00104-3.

Heil, K., and Schmidhalter, U. 2017. The Application of EM38: Determination of Soil Parameters, Selection of Soil Sampling Points and Use in Agriculture and Archaeology. Sensors, **17**: 2540. doi:10.3390/s17112540.

Heller, F., Strzyszcz, Z., and Magiera, T. 1998. Magnetic record of industrial pollution in forest soils of Upper Silesia, Poland. J. Geophys. Res. Solid Earth, **103**: 17767–17774. doi:10.1029/98jb01667.

Henry, E.R., and Johnson, J.K. 2012. Geophysical Investigations at Feltus Mounds (22Je568), Jefferson County, MS, Mississippi Department of Archives and History Reports, University of Mississippi, USA.

Hoffmann, V., Knab, M., and Appel, E. 1999. Magnetic susceptibility mapping of roadside pollution. J. Geochem. Explor. **66**: 313–326. doi:10.1016/s0375-6742(99)00014-x.

Hounslow, M.W., and Maher, B.A. 1996. Quantitative extraction and analysis of carriers of magnetization in sediments, Geophys. J. Int. **124**: 57–74. doi:10.1111/j.1365-246x.1996.tb06352.x

Hrouda, F. 2011. Models of frequency-dependent susceptibility of rocks and soils revisited and broadened, Geophys. J. Int. **187**: 1259–1269. doi:10.1111/ j.1365-246X.2011.05227.x

Hrouda, F., Pokorný, J., Ježek, J., and Chadima, M. 2013. Out-of-phase magnetic susceptibility of rocks and soils: a rapid tool for magnetic granulometry, Geophys. J. Int. **194**: 170–181. doi:10.1093/gji/ggt097

Hu, X.F., Jiang, Y., Shu, Y., Hu, X., Liu, L., and Luo, F. 2014. Effects of mining wastewater discharges on heavy metal pollution and soil enzyme activity of the paddy fields. J. Geochem. Explor. **147**: 139–150. doi:10.1016/j.gexplo.2014.08.001

Hu, X.F., Su, Y., Ye, R., Li, X.Q., and Zhang, G.L. 2007. Magnetic properties of the urban soils in Shanghai and their environmental implications. Catena, **70**: 428–436. doi:10.1016/j.catena.2006.11.010.

Huang, H., and Won, I.J. 2000. Conductivity and Susceptibility Mapping Using Broadband Electromagnetic Sensors. J. Environ. Eng. Geophys. **5**: 31–41. doi:10.4133/jeeg5.4.31

Jackson, M., Moskowitz, B., Rosenbaum, J., and Kissel, C. 1998. Field-dependence of AC susceptibility in titanomagnetites. Earth Planet. Sci. Lett. **157**: 129–139. doi:10.1016/s0012-821x(98)00032-6

Jakšik, O., Kodešová, R., Kapička, A., Klement, A., Fér, M., and Nikodem, A. 2016. Using Magnetic Susceptibility mapping for assessing soil degradation due to water erosion, Soil Water Res. **11**: 105–113. doi:10.17221/233/2015-SWR

Jenny, H. 1941. Factors of soil formation: a system of quantitative pedology. McGraw-Hill, New-York, USA.

Jordanova, N. 2017. Soil magnetism. Applications in pedology, environmental science and agriculture,. Academic Press, Elsevier, Amsterdam. p. 446

Jordanova, N., and Jordanova, D. 2016. Rock-magnetic and geochemical characteristics of relict Vertisols-signs of past climate and recent pedogenic development. Geophys. J. Int. **205**: 1437–1454. doi:10.1093/gji/ggw067

Jordanova, D., and Jordanova, N. 2016. Thermomagnetic behavior of magnetic susceptibility-heating rate and sample size effects. Front. Earth Sci. **3**: 90. doi:10.3389/feart.2015.00090

Jordanova, D., and Jordanova, N. 2021. Updating the significance and paleoclimate implications of magnetic susceptibility of Holocene loessic soils. Geoderma, **391**: 114982. doi:10.1016/j.geoderma.2021.114982.

Jordanova, D., Jordanova, N., and Petrov, P. 2014. Pattern of cumulative soil erosion and redistribution pinpointed through magnetic signature of Chernozem soils. Catena, **120**: 46–56. doi:10.1016/j.catena.2014.03.020

Jordanova, D., Jordanova, N., Atanasova, A., Tsacheva, T., and Petrov, P. 2011. Soil tillage erosion by using magnetism of soils - A case study from Bulgaria. Environ. Monit. Assess. **183**: 381–394. doi:10.1007/s10661-011-1927-8

Jordanova, N., Jordanova, D., and Barrón, V. 2019. Wildfire severity: environmental effects revealed by soil magnetic properties, Land Degrad. Dev. **30**: 2226–2242. doi:10.1002/ldr.3411

Jordanova, N., Petrovský, E., Kovacheva, M., and Jordanova, D. 2001. Factors determining magnetic enhancement of burnt clay from archaeological sites. J. Archaeol. Sci. **28**: 1137–1148. doi:10.1006/jasc.2000.0645

Jordanova, N.V., Jordanova, D.V., Veneva, L., Yorova, K., and Petrovský, E. 2003. Magnetic response of soils and vegetation to heavy metal pollution–A case study. Environ. Sci. Technol. **37**: 4417–4424. doi:10.1021/es0200645.

Kamaci, Z., and Uysal, G. 2017. Pollution determined by using magnetic susceptibility measurements: a case study from İzmir-AliağaZ. Acta Phys. Pol. A **132**: 3. doi:10.12693/APhysPolA.132.487

Kapička A., Dlouhá S., Grison H., Jakšík O., Petrovský E., and Kodešová R. 2013. Magnetic properties of soils - A basis for erosion study at agricultural land in Southern Moravia.SGEM2013 Conference Proceedings, 577–584. doi:10.5593/SGEM2013/BC3/S13.013.

Kapička, A., Petrovský, E., Ustjak, S., and Macháčkovác, K. 1999. Proxy mapping of fly-ash pollution of soils around a coal-burning power plant: a case study in the Czech Republic. J. Geochem. Explor. **66**: 291–297. doi:10.1016/s0375-6742(99)00008-4.

Karchegani, P.M., Ayoubi, S., Lu, S.G., and Honarju, N. 2011. Use of magnetic measures to assess soil redistribution following deforestation in hilly region. J. Appl. Geophys. **75**: 227–236. doi:10.1016/j.jappgeo.2011.07.017

Keating, K., Walsh, D.O., and Grunewald, E. 2020. The effect of magnetic susceptibility and magnetic field strength on porosity estimates determined from low-field nuclear magnetic resonance. J. Appl. Geophys. **179**: 104096. doi:10.1016/j.jappgeo.2020.104096.

Keller, G.W., and Frischknecht, F.C. 1966. Electrical methods in geophysical prospecting, Pergamon Press.

Kodama, K. 2013. Application of broadband alternating current magnetic susceptibility to the characterization of magnetic nanoparticles in natural materials. J. geophys. Res. **118**: 1–12. doi:10.1029/2012JB009502.

Kodama, K., An, Z., Chang, H., and Qiang, X. 2014. Quantification of magnetic nanoparticles with broad-band-frequency magnetic susceptibility measurements: a case study of an upper loess/palaeosol succession at Luochuan, Chinese Loess Plateau. Geophy. J. Inter. **199**: 767–783. doi:10.1093/gji/ggu299.

Kristjansson, L., Hardarson, B.S., and Audunsson, H. 2003. A detailed palaeomagnetic study of the oldest (≈15 Myr) lava sequences in Northwest Iceland. Geophys. J. Int. **155**: 991–1005. doi:10.1111/j.1365-246x.2003.02111.x

Le Borgne, E. 1960. Influence du feu sur les propriétés magnétiques du sol et sur celles du schiste et du granite. Ann. Geophys. **16**: 159–195.

Le Borgne, E. 1955. Susceptibilite magnetique anomale du sol superficial. Ann. Geophys. **11**: 399–419.

Lecoanet, H., Lévêque, F., and Segura, S. 1999. Magnetic susceptibility in environmental applications: comparison of field probes. Phys. Earth Planet. Inter. **115**: 191–204. doi:10.1016/s0031-9201(99)00066-7.

Lee, M.D., and Morris, W.A. 2013. Comparison of magnetic-susceptibility meters using rock samples from the Wopmay Orogen, Northwest Territories, Geological Survey of Canada Technical Note 5. doi:10.4095/292739

Linford, N. 2005. Archaeological applications of naturally occurring nanomagnets. J. Phys. Conf. Ser. **17**: 127–144. doi:10.1088/1742-6596/17/1/019

Liu, D., Ma, J., Sun, Y., and Li, Y. 2016. Spatial distribution of soil magnetic susceptibility and correlation with heavy metal pollution in Kaifeng City, China. Catena, **139**: 53–60. doi:10.1016/j.catena.2015.11.004.

Liu, L., Zhang, K., Fu, S., Liu, B., Huang, M., Zhang, Z., Zhang, F., and Yu, Y. 2019. Rapid magnetic susceptibility measurement for obtaining superficial soil layer thickness and its erosion monitoring implications. Geoderma, **351**: 163–173. doi:10.1016/j.geoderma.2019.05.030

Liu, Q., Barrón, V., Torrent, J., Eeckhout, S.G., and Deng, C. 2008. Magnetism of intermediate hydromaghemite in the transformation of 2-line ferrihydrite into hematite and its paleoenvironmental implications. J. Geophys. Res. **113**: B01103.doi:10.1029/2007JB005207.

Liu, Q., Deng, C., Yu, Y., Torrent, J., Jackson, M.J., Banerjee, S.K., and Zhu, R. 2005. Temperature dependence of magnetic susceptibility in an argon environment: implications for pedogenesis of Chinese loess/palaeosols. Geophys. J. Int. **161**: 102–112. doi:10.1111/j.1365-246x.2005.02564.x

Liu, Z., Ma, J., Wei, G., Liu, Q., Jiang, Z., Ding, X., et al. 2017. Magnetism of a red soil core derived from basalt, northern Hainan Island, China: volcanic ash versus pedogenesis. J. Geophys. Res. Solid Earth, **122**: 1677–1696. doi:10.1002/2016JB013834

Lovley, D.R., Stolz, J.F., Nord, G.L., and Phillips, E.J.P. 1987. Anaerobic production of magnetite by a dissimilatory iron-reducing microorganism. Nature, **330**: 252–254. doi:10.1038/330252a0

Løvlie, R., and Van Veen, P. 1995. Magnetic susceptibility of a 180 m sediment core: reliability of incremental sampling and evidence for a relationship between susceptibility and gamma activity. Geol. Soc. London, Special Publ. **98**: 259–266. doi:10.1144/gsl.sp.1995.098.01.16

Lowe, K.M., Arthure, S., Wallis, L.A., and Feinberg, J. 2020. Geophysical and archaeological investigations of Baker's Flat, a nineteenth century historic Irish site in South Australia. Archaeol. Anthropol. Scie. **12**: 33. doi:10.1007/s12520-019-01003-2

Lu, S.G., Bai, S.Q., and Xue, Q.F. 2007. Magnetic properties as indicators of heavy metals pollution in urban topsoils: a case study from the city of Luoyang, China. Geophys. J. Int. **171**: 568–580. doi:10.1111/j.1365-246X.2007.03545.x

Łukasik, A., Szuszkiewicz, M., and Magiera, T. 2015. Impact of artifacts on topsoil magnetic susceptibility enhancement in urban parks of the Upper Silesian conurbation datasets. J. Soils Sediments, **15**: 1836–1846. doi:10.1007/s11368-014-0966-5

Lukshin, A.A., Rumyantseva, T.I., and Kovrigo, V.P. 1968. Magnetic susceptibility of the principal soil types in the Udmuit Association. Soviet Soil Sci. **3**: 88–93.

Magiera, T., Łukasik, A., Zawadzki, J., and Rösler, W. 2019. Magnetic susceptibility as indicator of anthropogenic disturbances in forest topsoil: a review of magnetic studies carried out in Central European forests. Ecol. Indic. **106**: 105518. doi:10.1016/j.ecolind.2019.105518

Maher, B.A., and Taylor, R.M. 1988. Formation of ultrafine-grained magnetite in soils. Nature, **336**: 368–370. doi:10.1038/336368a0

Maher, B.A., and Thompson, R. 1992. Paleoclimatic significance of the mineral magnetic record of the Chinese Loess and Paleosols. Quat. Res. **37**: 155–170. doi:10.1016/0033-5894(92)90079-x

Maher, B.A., and Thompson, R. 1995. Paleorainfall reconstructions from pedogenic magnetic susceptibility variations in the Chinese Loess and Paleosols. Quat. Res. **44**: 383–391. doi:10.1006/qres.1995.1083

Maher, B.A. 1986. Characterisation of soils by mineral magnetic measurements. Phys. Earth Planet. Inter. **42**: 76–92. doi:10.1016/s0031-9201(86)80010-3

Maher, B.A. 1988. Magnetic properties of some synthetic sub-micron magnetites. Geophys. J. Int. **94**: 83–96. doi:10.1111/j.1365-246x.1988.tb03429.x

Maher, B.A., and Thompson, R. 1991. Mineral magnetic record of the Chinese loess and paleosols. Geology, **19**: 3–6. doi:10.1130/0091-7613(1991)019b0003

Maier, G., Scholger, R., and Schön, J. 2006. The influence of soil moisture on magnetic susceptibility measurements. J. Appl. Geophys. **59**: 162–175. doi:10.1016/j.jappgeo.2005.10.001

Martin, A.P., Ohneiser, C., Turnbull, R.E., Strong, D.T., and Demler, S. 2018. Soil magnetic susceptibility mapping as a pollution and provenance tool: an example from southern New Zealand. Geophys. J. Int., **212**: 1225–1236. doi:10.1093/gji/ggx484

Matzka, J., and Maher, B. 1999, Magnetic biomonitoring of roadside tree leaves: identification of spatial and temporal variations in vehicle-derived particulates. Atmos. Environ. **33**: 4565–4569. doi:10.1016/s1352-2310(99)00229-0

Maxbauer, D.P., Feinberg, J.M., and Fox, D.L. 2016. Magnetic mineral assemblages in soils and paleosols as the basis for paleoprecipitation proxies: a review of magnetic methods and challenges. Earth Sci. Rev. **155**: 28–48. doi:10.1016/j.earscirev.2016.01.014

McKay, R.M., De Santis, L., Kulhanek, D.K., Browne, I.M., Shevenell, A.E., and Expedition 374 Scientists. 2019. Expedition 374 Methods, Marine Science Faculty Publications: 667. doi:10.14379/iodp.proc.374.102.2019

McNeill, D.J. 1980. Electromagnetic terrain conductivity measurement at low induction numbers, Technical Note TN-6, Geonics Ltd., Mississauga, ON, Canada.

McNeill, D.J. 2012. Archaeological Mapping Using the Geonics EM38B to Map Terrain Magnetic Susceptibility (With Selected Case Histories), Geonics Limited Technical Note TN-35.

Menshov, O., Kruglov, O., Vyzhva, S., Nazarok, P., Pereira, P., and Pastushenko, T. 2018. Magnetic methods in tracing soil erosion, Kharkov Region, Ukraine. Stud. Geophys. Geod. **62**: 681–696. doi:10.1007/s11200-018-0803-1

Minyuk, P.S., Subbotnikova, T.V., and Plyashkevich, A.A. 2011. Measurements of thermal magnetic susceptibility of Hematite and Goethite. Phys. Solid Earth, **47**: 762–774. doi:10.1134/s1069351311080052

Mochales, T., Pueyo, E.L., Casas, A.M., and Soriano, M.A. 2007. Magnetic prospection as an efficient tool for doline detection: a case study in the central Ebro Basin (northern Spain). M. Parise, and J. Gunn, eds. Natural and anthropogenic hazards in Karst areas: recognition, analysis and mitigation, Geological Society of London, Special Publications. 279: 73–84. doi:10.1144/SP279.7

Mullins, C.E., and Tite, M.S. 1973. Magnetic viscosity, quadrature susceptibility, and frequency dependence of susceptibility in single-domain assemblies of magnetite and maghemite. J. Geophys. Res. **78**: 804–809. doi:10.1029/jb078i005p00804

Mullins, C.E. 1977. Magnetic susceptibility of the soil and its significance in soil science—a review. J. Soil Sci. **28**: 223–246. doi:10.1111/j.1365-2389.1977.tb02232.x

Naibert, T.J., Twelker, E., Wypych, A., Athey, J.E., Newberry, R.J., Lopez, J.A., et al. 2020. Field station locations and magnetic susceptibility data collected in 2019 for the Eastern Tanacross Project, Tanacross and Nabesna quadrangles, Alaska, Alaska Division of Geological & Geophysical Surveys Raw Data File 2019-9, 2 p. doi:10.14509/30268

Ohneiser, C., Wilson, G.S., and Cox, S.C. 2015. Characterisation of magnetic minerals from southern Victoria Land, Antarctica. N. Z. J. Geol. Geophys. **58**: 52–65. doi:10.1080/00288306.2014.990044

Orosun, M.M., Oniku, S.A., Peter, A., Orosun, R.O., Salawu, N.B., and Hitler, L. 2020. Magnetic susceptibility measurement and heavy metal pollution at an automobile station in Ilorin, North-Central Nigeria. Environ. Res. Commun. **2**: 015001. doi:10.1088/2515-7620/ab636a

Ouyang, T., Li, M., Appel, E., Tang, Z., Peng, S., Li, S., and Zhu, Z. 2020. Magnetic response of Arsenic pollution in a slag covered soil profile close to an abandoned tungsten mine, southern China. Sci. Rep. **10**: 4357. doi:10.1038/s41598-020-61411-6

Owliaie, H.R., Heck, R.J., and Abtahi, A. 2006. The magnetic susceptibility of soils in Kohgilouye. Iran. Can. J. Soil Sci. **86**: 97–107. doi:10.4141/s05-003.

Parasnis, D.S. 1986. Principles of applied geophysics. Chapman & Hall.

Pastor, A., Gallello, G., Cervera, M.L., and de la Guardia, M. 2016. Mineral soil composition interfacing archaeology and chemistry. TrAC Trend. Anal. Chem. **78**: 48–59. doi:10.1016/j.trac.2015.07.019.

Petersson, J., Skogsmo, G., Vestgård, J., Albrecht, J., Hedenström, A., and Gustavsson, J. 2007. Forsmark site investigation: bedrock mapping and magnetic susceptibility measurements, Quaternary investigations and GPR measurements in trench AFM001265, SKB P-06-136 report, Swedish Nuclear Fuel and Waste Management Co.

Petrovský, E., Hulka, Z., and Kapička, A. 2004. A new tool for in situ measurements of the vertical distribution of magnetic susceptibility in soils as basis for mapping deposited dust. Environ. Technol. **25**: 1021–1029. doi:10.1080/09593332508618391

Pokorný, J., Pokorný, P., Suza, P., and Hrouda, F. 2011. A multifunction Kappabridge for high precision measurement of the AMS and the variations of magnetic susceptibility with field, temperature and frequency. Earth's Mag. Inter. **1**: 292–301. IAGA Special Sopron Book Series. doi:10.1007/978-94-007-0323-0_20

Porsch, K., Dippon, U., Rijal, M.L., Appel, E., and Kappler, A. 2010. In-situ magnetic susceptibility measurements as a tool to follow geomicrobiological transformation of fe minerals. Environ. Sci. Technol. **44**: 3846–3852. doi:10.1021/es903954u

Potter, D.K., Ali, A., Imhmed, S.A.A., and Schleifer, N. 2011. Quantifying the effects of core cleaning, core flooding and fines migration using sensitive magnetic techniques: implications for permeability determination and formation damage. Petrophysics, **52**: 444–451.

Pueyo, E.L., Román-Berdiel, M.T., Ayala, C., Loi, F., Soto, R., Beamud, E., et al. 2020. Density and magnetic susceptibility relationships in non-magnetic granites; a “wildcard” for modeling potential fields geophysical data, EGU General Assembly 2020. EGU2020-8736. doi:10.5194/egusphere-egu2020-8736

Quijano, L., Chaparro, M.A.E., Marié, D.C., Gaspar, L., and Navas, A. 2014. Relevant magnetic and soil parameters as potential indicators of soil conservation status of Mediterranean agroecosystems. Geophys. J. Int. **198**: 1805–1817. doi:10.1093/gji/ggu239

Rachwał, M., Kardel, K., Magiera, T., and Bens, O. 2017. Application of magnetic susceptibility in assessment of heavy metal contamination of Saxonian soil (Germany) caused by industrial dust deposition. Geoderma, **295**: 10–21. doi:10.1016/j.geoderma.2017.02.007

Ranganai, R.T., Moidaki, M., and King, J.G. 2015. Magnetic susceptibility of soils from eastern Botswana: a reconnaissance survey and potential applications. J. Geograph. Geol. **4**: 45–64. doi:10.5539/jgg.v7n4p45

Rashed, M., and Atef, A. 2015. Mapping underground utilities within conductive soil using multi-frequency electromagnetic induction and ground penetrating radar. Arab. J. Geosci. **8**: 2341–2346. doi:10.1007/s12517-014-1358-2

Reagan, M.K., Pearce, J.A., and Petronotis, K., and , the Expedition 352 Scientists. 2015. Expedition 352 methods. Proc. Int. Ocean Dis. Prog. **352**. doi:10.14379/iodp.proc.352.102.2015

Reyes, B.A., Carrancho, A., Gogichaishvili, A., Quintana, P., Bautista, F., Morales, J., and Faust, B. 2013. Influence of agricultural burning on magnetic properties in Maya Milpas. Latinmag Letters. 3: 1-4, Proceedings Montevideo, Uruguay.

Reynolds, J.M. 2011. An introduction to applied and environmental geophysics, 2nd edn. Wiley-Blackwell, New York.

Rijal, M.L., Appel, E., Petrovský, E., and Blaha, U. 2010. Change of magnetic properties due to fluctuations of hydrocarbon contaminated groundwater in unconsolidated sediments. Environ. Pollut. **158**: 1756–1762. doi:10.1016/j.envpol.2009.11.012

Rijal, M.L., Porsch, K., Appel, E., and Kappler, A. 2012. Magnetic signature of hydrocarbon-contaminated soils and sediments at the former oil field Hänigsen, Germany. Stud. Geophys. Geod. **56**: 889–908. doi:10.1007/s11200-010-0040-8

Sadiki, A., Faleh, A., Navas, A., and Bouhlassa, S. 2009. Using magnetic susceptibility to assess soil degradation in the Eastern Rif, Morocco. Earth Surf. Process. Landf., **34**: 2057–2069. doi:10.1002/esp.1891

Saey, T., Simpson, D., Vermeersch, H., Cockx, L., and Meirvenne, M.V. 2009. Comparing the EM38DD and DUALEM-21S sensors for depth-to-clay mapping. Soil Sci. Soc. Am. J., **73**: 7–12. doi:10.2136/sssaj2008.0079

Sarmast, M., Farpoor, M.H., and Esfandiarpour Boroujeni, I. 2017. Magnetic susceptibility of soils along a lithotoposequence in southeast Iran. Catena, **156**: 252–262. doi:10.1016/j.catena.2017.04.019

Schaetzl, R., and Anderson, A. 2009. Soils: genesis and geomorphology. Cambridge University Press, UK.

Schibler, L., Boyko, T., Ferdyn, M., Gajda, B., Höll, S., Jordanova, N., et al . 2002. Topsoil magnetic susceptibility mapping: data reproducibility and compatibility, measurement strategy. Stud. Geophys. Geod. **46**: 43–57. doi:10.1023/a:1019885532390

Schmidt, A. 2007. Archaeology, magnetic methods. Pages 23–31 in D. Gubbins and E. Herrero-Bervera, eds. Encyclopedia of geomagnetism and paleomagnetism. Encyclopedia of Earth Sciences Series. Springer, Heidelberg, New York.

Schwertmann, U. 1988. Occurrence and formation of iron oxides in various pedoenvironments. Iron Soils Clay Miner., **217**: 267–308. doi:10.1007/978-94-009-4007-9_11

Schwertmann, U., and Taylor, R.M. 1989. Iron oxides. Pages 379–438 inG.B. Dixon and S.B. Weed, eds., Minerals in soil environment. Madison, WI: SSSA.

Shendi, E.H., Attia, T.E., and Shehata, M.A. 2013. Magnetic susceptibility as an indicator to heavy metal contamination of the urban top soil in Port Said city and surroundings, Egypt, IOSR J. Environ. Sci. Toxicol. Food Technol. (IOSR-JESTFT) **6**: 47–55. doi:10.9790/2402-0654755

Sheoran, A.S., and Sheoran, V. 2006. Heavy metal removal mechanism of acid mine drainage in wetlands: a critical review. Miner. Eng. **19**: 105–116. doi:10.1016/j.mineng.2005.08.006

Shirzaditabar, F., and Heck, R.J. 2021. Characterization of soil drainage using electromagnetic induction measurement of soil magnetic susceptibility. Catena, **207**: 105671. doi:10.1016/j.catena.2021.105671

Shirzaditabar, F., Heck, R.J, and Catalano, M. 2021. Delineation of soil drainage class by electromagnetically measurements of soil magnetic susceptibility, EGU General Assembly 2021, EGU21-9232. doi:10.5194/egusphere-egu21-9232

Simms, J.E., and Lobred, A.R. 2011. Application of Magnetic Susceptibility for Wetlands Delineation. J. Environ. Eng. Geophys., **16**: 105–114. doi:10.2113/jeeg16.3.105

Simon, F.X., Sarris, A., Thiesson, J., and Tabbagh, A. 2015. Mapping of quadrature magnetic susceptibility/magnetic viscosity of soils by using multi-frequency EMI. J. Appl. Geophys., **120**: 36–47. doi:10.1016/j.jappgeo.2015.06.007

Simpson, D., Van Meirvenne, M., Luck, E., Rühlmann, J., Saey, T., and Bourgeois, J. 2010. Sensitivity of multi-coil frequency domain electromagnetic induction sensors to map soil magnetic susceptibility. Eur. J. Soil Sci., **61**: 46–478. doi:10.1111/j.1365-2389.2010.01261.x

Simpson, D., Van Meirvenne, M., Saey, T., Vermeersch, H., Bourgeois, J., Lehouck, A., et al. 2009. Evaluating the multiple coil configurations of the EM38DD and DUALEM-21S sensors to detect archaeological anomalies. Archaeol. Prospect. **16**: 91–102. doi:10.1002/arp.349

Singer, M.J., and Fine, P. 1989. Pedogenic factors affecting magnetic susceptibility of northern California soils. Soil Sci. Soc. Am. J. **53**: 1119–1127. doi:10.2136/sssaj1989.03615995005300040023x

Singer, M.J., Verosub, K.L., Fine, P., and TenPas, J. 1996. A conceptual model for the enhancement of magnetic susceptibility in soils. Quat. Int. **34**–**36**: 243–248. doi:10.1016/1040-6182(95)00089-5

Spiteri, C., Kalinski, V., Rösler, W., Hoffmann, V., and Appel, E. 2005. Magnetic screening of a pollution hotspot in the Lausitz area, Eastern Germany: correlation analysis between magnetic proxies and heavy metal contamination in soils. Environ. Geol. **49**: 1–9. doi:10.1007/s00254-005-1271-9

Sundman, A., Byrne, J.M., Bauer, I., Menguy, N., and Kappler, A. 2017. Interactions between magnetite and humic substances: redox reactions and dissolution processes. Geochem. Trans. **18**: 6. doi:10.1186/s12932-017-0044-1

Thiesson, J., Kessouri, P., Schamper, C., and Tabbagh, A. 2014. Calibration of frequency-domain electromagnetic devices used in near-surface surveying. Near Surf. Geophys., **12**: 481–491. doi:10.3997/1873-0604.2014012

Tholkappian, M., Chandrasekaran, A., Harikrishnan, N., Devanesan, E., Ganeshand, D., and Ravisankar, R. 2019. Application of magnetic susceptibility in source identification of heavy metal pollution in sediments of Chennai Coast, Tamilnadu using multivariate statistical analysis. J. Rad. Nucl. Appl. **4**: 15–23. doi:10.18576/jrna/040102

Thompson, R., and Oldfield, F. 1986. Environmental magnetism, Allen & Unwin, London, UK.

Tite, M.S., and Mullins, C.E. 1971. Enhancement of the magnetic susceptibility of soils on archaeological sites. Archaeometry, **13**: 209–219. doi:10.1111/j.1475-4754.1971.tb00043.x

Tite, M.S., and Linington, R.E. 1975. Effect of climate on the magnetic susceptibility of soils. Nature **256**: 565–566. doi:10.1038/256565a0

Torrent, J., Barrón, V., and Liu, Q. 2006. Magnetic enhancement is linked to and precedes hematite formation in aerobic soil. Geophys. Res. Lett. **33**: L0240I. doi:10.1029/2005gl024818

Ustra, A., Mendonça, C.A., Leite, A., Jaqueto, P., and Novello, V.P. 2019. Low field frequency dependent magnetic susceptibility inversion. Comput. Geosci. **133**: 104326. doi:10.1016/j.cageo.2019.104326

Ustra, A., Mendonça, C.A., Leite, A., Jovane, L., and Trindade, R.I.F. 2018. Quantitative interpretation of the magnetic susceptibility frequency dependence. Geophys. J. Int. **213**: 805–814. doi:10.1093/gji/ggy007

Vadyunina, A.F., and Babanin, V.F. 1972. Magnetic susceptibility of some soil s in the U.S.S.R. Soviet Soil Sci. **4**: 588–599.

Vali, H., von Dobenck, T., Amarantidis, G., Forster, O., Mortenani, G., Bachmann, L., and Petersen, N. 1989. Biogenic and lithogenic magnetic minerals in Atlantic and Pacific deep sea sediments and their paleomagnetic significance. Geol. Rundsch. **78**: 753–764. doi:10.1007/bf01829320

van Dam, R.L., Hendrickx, J.M.H., Harrison, B., Borchers, B., Norman, D.I., Ndur, S., et al. 2004. Spatial variability of magnetic soil properties. R.S. Harmon, J.T. Broach and J.H. Holloway, Jr., eds., Detection and remediation technologies for mines and minelike targets IX, SPIE, Orlando, FL.

Vasquez, C.A., and Nami, H.G. 2006. Rock magnetic study of fluvial Holocene soil from Buenos Aires province (Argentina). Earth Planets Space, **58**: 1381–1387. doi:10.1186/bf03352634

Ventura, E., Nearing, M.A., and Norton, L.D. 2001. Developing a magnetic tracer to study soil erosion. Catena, **43**: 277–291. doi:10.1016/s0341-8162(00)00149-1.

Walkington, H. 2010. Soil science applications in archaeological contexts: A review of key challenges. Earth-Science Rev. **103**: 122–134. doi:10.1016/j.earscirev.2010.09.002.

Wang, B., Zhang, X., Zhao, Y., Zhang, M., and Jia, J. 2021. Spatial and temporal distribution of pollution based on magnetic analysis of soil and atmospheric Dustfall in Baiyin City, Northwestern China. Int. J. Environ. Res. Public Health **18**: 1681. doi:10.3390/ijerph18041681

Wegmann, K.W., Lewis, R.Q., and Hunt, M.C. 2012. Historic mill ponds and piedmont stream water quality: making the connection near Raleigh, North Carolina. M.C. Eppes and M.J. Bartholomew, eds., From the blue ridge to the coastal plain: field excursions in the southeastern United States. Geological Society of America Field Guide, 29: 93–121. doi:10.1130/2012.0029(03)

Williams, M. 1992. Evidence for the dissolution of magnetite in recent Scottish peats. Quat. Res., **37**: 171–182. doi:10.1016/0033-5894(92)90080-3

Wojas, A. 2009. Magnetic Susceptibility of Soils, Including Iron Oxides of Anthropogenic and Natural Origin - Measurements Using the Bartington Instrument, II International Interdisciplinary Technical Conference of Young Scientists. 20–22 May 2009, Poznań, Poland.

Won, I.J., and Huang, H. 2004. Magnetometers and electro-magnetometers. Lead. Edge **23**: 448–451. doi:10.1190/1.1756834

Won, I.J., Keiswetter, D.A., Fields, G.R.A., and Sutton, L.C. 1996. GEM-2: a new multifrequency electromagnetic sensor. J. Environ. Eng. Geophys. **1**: 129–138. doi:10.4133/jeeg1.2.129

Yang, P.G., Yang, M., Mao, R.Z., and Byrne, J.M. 2015. Impact of long-term irrigation with treated sewage on soil magnetic susceptibility and organic matter content in North China. Bull. Environ. Contam. Toxicol. **95**: 102–107. doi:10.1007/s00128-015-1562-0

Yang, T., Liu, Q., Zeng, Q., and Chan, L. 2012. Relationship between magnetic properties and heavy metals of urban soils with different soil types and environmental settings: implications for magnetic mapping. Environ. Earth Sci. **66**: 409–420. doi:10.1007/s12665-011-1248-9

Yu, J., Zhan, S., Wu, L., and Chu, T. 1986. The magnetic susceptibility of the soils in subtropical and tropical China. Acta Pedol. Sin. **23**: 50–56.

Yurtseven-Sandker, A., and Cioppa, M.Y. 2016. Tracking the historical traces of soil pollution from an iron-sintering plant by using magnetic susceptibility in Wawa, Ontario, Canada. Water Air Soil Pollut. **227**: 434. doi:10.1007/s11270-016-3140-4

Zawadzki, J., Fabijańczyk, P., Magiera, T., and Strzyszcz, Z. 2010. Study of litter influence on magnetic susceptibility measurements of urban forest topsoils using the MS2D sensor. Environ. Earth Sci. **61**: 223–230. doi:10.1007/s12665-009-0336-6

Zawadzki, J., Magiera, T., Fabijańczyk, P., and Kusza, G. 2012. Geostatistical 3-dimensional integration of measurements of soil magnetic susceptibility, Environ. Monit. Assess. **184**: 3267–3278. doi:10.1007/s10661-011-2187-3

Zhang, C.X., Appel, E., and Qiao, Q.Q. 2013. Heavy metal pollution in farmland irrigated with river water near a steel plant-magnetic and geochemical signature. Geophys. J. Int. **192**: 963–974. doi:10.1093/gji/ggs079

Zhu, H., and He, X. 2012. Soil magnetic susceptibility changes with immerging depth in the three gorges reservoir area, World Automation Congress Proceedings, Puerto Vallarta, Mexico, 1–5.

Published by Canadian Science Publishing