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Modeling the response of a field probe for nondestructive measurements of the magnetic susceptibility of soils

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Abstract

Nondestructive volume magnetic susceptibility measurements (MS) from the surface do not provide information about the depth distribution of a magnetic material or about the amount of magnetic material. We have developed a model that can be used to predict the volume magnetic susceptibility from the surface for a given (known or hypothesized) stratification of the magnetic layers in the soil profile. The measurements were performed with the MS2D Bartington sensor. The antenna signal from the MS2D probe decreases rapidly with depth. We show that the relative decrease in MS depends not only on the concentration of the magnetic tracer, but also on the distribution of the magnetic tracer in the soil profile. The decrease in sensitivity was fitted with a double exponential function. The function was implemented in a newly developed MagHut model. The MagHut model is a tool that can be used for forward modeling of the volume magnetic susceptibility when the tracer distribution in the soil profile is known. The model was successfully calibrated and validated with the measured data and with data from the literature. The Nash–Sutcliffe coefficients for goodness of fit were above 0.99 in all cases. MagHut can help interpret MS mapping results or it can be used to optimize amount and placement of the magnetic tracer for soil erosion experiments. However, the MagHut tool is only limited to the top 10 cm of the soil profile and cannot replace, but only complement, the standard procedure of occasional soil profile sampling and laboratory mass MS measurements.

1 | INTRODUCTION

The various magnetic properties of soil and rock materials have been used in environmental studies for decades. Magnetism mapping is a popular technique for estimating soil contamination (Hanesch & Scholger, 2002; Petrovsky et al., 2004; Wang et al., 2018) and for assessing soil wind erosion (Ding et al., 2020; Ravi et al., 2019), water erosion (Guzmán, Vanderlinden et al., 2013; Jakšík et al., 2016; López-Vicente & Guzmán, 2021; Ventura et al., 2001), tillage erosion (Bouhlassa & Bouhsane, 2019; Fiener et al., 2018), or complex anthropogenic soil disturbance (Janas et al., 2022; Magiera et al., 2019).

Abbreviations: MS, magnetic susceptibility; MSκ, apparent volume magnetic susceptibility; MSκ_{norm}, normalized MSκ value; MSκ_{OBS}, measured volume magnetic susceptibility; MSχ, mass-specific magnetic susceptibility; MSχ_A, apparent mass-specific magnetic susceptibility.

Magnetic susceptibility (MS) is directly proportional to the amount of magnetic particles in the material (Thompson & Oldfield, 1986). Some materials, such as iron oxide Fe_3O_4 (hereafter referred to simply as magnetite), are highly magnetic. Other materials, such as quartz particles, organic matter, water or air, do not exhibit significant magnetic attraction. There are five types of magnetic behavior (ferromagnetic, ferrimagnetic, antiferromagnetic, paramagnetic, and diamagnetic). The measured MS is the sum of all these magnetic properties (Dearing, 1994). Magnetite, the most important magnetic substance in natural soils, belongs to the ferrimagnetic category.

Most natural soils have a low MS background. Guzmán et al. (2010) showed that magnetite powder adsorbs strongly to soil particles. Magnetite is widely commercially available, affordable, and environmentally safe. Its properties and its high MS allow it to be used as a tracer for monitoring soil erosion. The horizontal and vertical movement of the tracer can then be monitored by mapping the MS signature of the soil.

There are two widely used methods for measuring MS: (i) in a destructive manner, where the magnetic properties of loose material such as soil or rock flour can be accurately determined by measuring the mass-specific magnetic susceptibility (MSχ, $m^3 kg^{-1}$). In this case, the bulk density and the mass of the sample must be accurately known in order to calculate the amount of magnetite (Zawadzki et al., 2012); (ii) in situ, where the apparent magnetic volume susceptibility of the soil (MSκ, dimensionless) is measured with a surface loop probe (Kapička et al., 1997; Wojas, 2017). MSκ is usually measured in a dense grid on a bare soil surface—this procedure is called MS mapping. MSκ mapping provides qualitative information on the presence of magnetite and its areal distribution in the near-surface soil profile.

The Bartington MS2 susceptibility system (Bartington Instruments) is an instrument commonly used for MS monitoring. The system consists of a meter and interchangeable sensors. A laboratory MS2B single sample sensor with two frequencies for 10 cm^3 disturbed samples can be used to obtain MSχ. By sampling along a soil profile, the vertical magnetite distribution can be observed (Fiener et al., 2018; Kapička et al., 1997).

The MS2D field probe is considered a standard tool for MSκ monitoring of topsoil (Burguet et al., 2018; Guzmán et al., 2015; Guzmán, Quinton et al., 2013; Liu et al., 2018, 2020; López-Vicente & Guzmán, 2021; Zawadzki et al., 2012; Zubieta et al., 2021b). The circular MS2D sensor has an outer diameter of 208 mm, which provides a large effective measurement volume. The material volume from which the probe receives the signal is approximately 10,800 cm^3 (Lecoanet et al., 1999). The MSκ signal measured at the surface decreases exponentially with depth (Dearing, 1994). The MS2D measurement depth is approximately 150 mm, with 50% of the response coming from the top 15 mm, according to the manufacturer (Bartington Inc., 2022). The sensitivity tests conducted by various research teams on the probe have confirmed that it has a maximum measurement depth of 150 mm. These tests have also demonstrated the probe's high sensitivity for detecting magnetite in the topmost 20–30 mm of soil (Lecoanet et al., 1999; Liu et al., 2019; Zawadzki et al., 2012; Zubieta et al., 2021a).

Liu et al. (2019) showed that the relative decrease of the measured MSκ signal with depth does not depend only on the mass-specific susceptibility of the measured material and on the MS of the background soil. The relationship between the MSκ signal and depth is not significantly affected by other physical or chemical soil properties, nor by the soil water content (Liu et al., 2019; Maier et al., 2006). However, the MSκ signal decrease function depends on the spatial distribution of the magnetic tracer in the soil profile. Two extreme cases of magnetite distributions (Figure 1) that may be of interest for soil erosion research are:

Core Ideas

- Surface magnetic susceptibility (MS) mapping does not provide information about the depth distribution of a magnetic material.
- The decrease of the MS signal with depth was fitted with a double exponential function.
- The new MagHut model is able to simulate volume magnetic susceptibility based on the known tracer distribution in the soil.
- MagHut helps in the interpretation of MS measurements and in the planning of tracer experiments for soil erosion research.

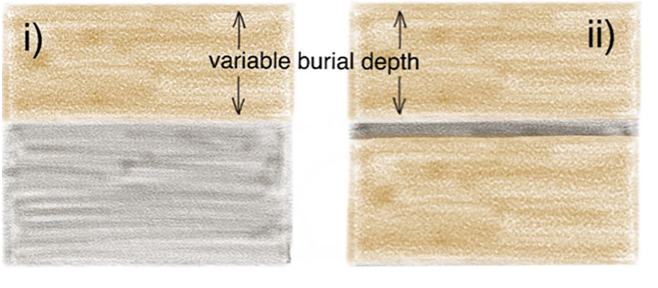

FIGURE 1 Two possible borderline scenarios for arranging magnetite tracers in the soil profile: (i) experimentally observed by Lecoanet et al. (1999) and (ii) experimentally observed by Liu et al. (2019). The brown color represents plain soil, and the gray color represents a magnetic layer.

(i) a thick homogeneous magnetic layer. The magnetic material may be covered by soil with significantly lower MSχ and with varying thickness. This scenario for different burial depths of the tracer was measured experimentally by Lecoanet et al. (1999);

(ii) a very thin magnetic layer (e.g., 1 mm), which can be surrounded by plain soil. Such a case was measured for different burial depths of tracers by Liu et al. (2019).

The surface-based monitoring technique has been shown to be very sensitive to the positioning of the surface probe and also to the distribution of magnetic material within the shallow soil profile. The measurements integrate signals from a relatively large volume of soil, so it is not apparent how deep the magnetically enhanced layer is (Petrovsky et al., 2004). Information on the MSκ measured at the surface can indicate the presence of a magnetic tracer in the shallow subsurface. However, a single value is not sufficient to determine the amount of tracer or its distribution. There are an infinite number of possible combinations of different magnetite distributions that give the same MSκ value. This limits the potential of nondestructive measurements of soil MS for quantitative studies unless researchers in the field develop a method to unambiguously standardize and interpret MSκ readings.

The aims of the study were as follows:

1. to create a model (MagHut) for forward modeling of volume MS;
2. to adjust and confirm the accuracy of the model using new and previously published data;
3. to make the model available to the public as a user-friendly tool that can be used to optimize the design of soil erosion experiments and improve the interpretation of MS mapping.

2 | MATERIALS AND METHODS

2.1 | Magnetic susceptibility monitoring

In order to create and calibrate the MagHut model, data of volume MS were collected for different magnetite concentrations and distributions in the soil profile. For this purpose, an experimental setup was designed and implemented (described in detail in section 2.6) consisting of several cardboard boxes filled with soil samples of different MS. Artificial soil profiles were created from these cardboard boxes and the volume MS was measured from the surface.

MS was measured using the Bartington MS2 Susceptibility System (Bartington Instruments). A laboratory MS2B single-sample dual-frequency sensor was used to monitor the MSχ of disturbed soil samples with different magnetite concentrations. The MSχ of air, and also the MSχ of the cardboard box that was used as a container for the soil samples during the experiments were considered as zero.

For MSκ monitoring, the MS2D field loop probe was used. The probe was attached to the MS2 electronic unit by a handle. In the following text, MSκ therefore refers to the readings with the MS2D probe. Each soil profile was measured in five replicates from five different spots on the soil surface. Care was taken to ensure that the probe had good contact with the surface. The probe was calibrated by setting the MSκ of the air to zero before each measurement.

2.2 | Magnetic susceptibility–depth relationship

The MSκ signal decreases with depth. The decrease functions of two magnetite distribution scenarios (Figure 1), published by Lecoanet et al. (1999) and by Liu et al. (2019), were digitized from the published figures using Grapher v. 19 software (Golden Software, LLC). The MSκ function was normalized so that the function represents the relative decrease in the signal (%) received by the antenna from different depths:

$$\mathrm{MS}\kappa_{\mathrm{norm}} = \frac{\mathrm{MS}\kappa_z}{\mathrm{MS}\kappa_{\max}} 100, \qquad (1)$$

where MSκ_{norm} (%) is the normalized MSκ value reflecting the percentage of signal amplification by a magnetite at a given depth, MSκ_z (-) is the apparent volume magnetic susceptibility of a material at a depth z, and MS$\kappa_{\max}$ (-) is the maximum theoretical volume magnetic susceptibility measured when the magnetite is at the soil surface.

The relationships of Lecoanet et al. (1999) and Liu et al. (2019) were parametrized using a double exponential decay model that allows an initial rapid decline followed by a slower decline to be fitted as follows:

$$\mathrm{MS}\kappa_{\mathrm{norm}} = P_{\mathrm{f}} e^{-K_f \times z} + P_{\mathrm{s}} e^{-K_s \times z}, \text{where } P_{\mathrm{s}} = 100 - P_f, \qquad (2)$$

where P_{f} and K_{f} are fitting coefficients for the fast exponential decay, P_{s} and K_{s} are fitting coefficients for the slow exponential decay, and z (mm) is the distance (depth) from the MS2D sensor to the magnetic layer or tracer. The maximum MSκ_{norm} was set to 100 (%), the plateau (the minimum possible value to which the function converges at infinity) was set to 0. GraphPad, v.8.4.3 (GraphPad Software) was used for parameter optimization. The fitted parameters for the data of Liu et al. (2019) and Lecoanet et al. (1999) are presented in Table 1, and the digitized data points and the fitted curves are shown in Figure 2.

TABLE 1 Fitted parameters of the double exponential decay functions.

	P_f	K_f	P_s	K_s
Lecoanet et al. (1999)	75.08	0.06126	24.92	0.02418
Liu et al. (2019)	38.25	0.17650	61.75	0.03964
This study	58.79	0.03719	41.21	0.16153

Equation (2) can be used to calculate the contribution of any slice in the soil profile to the measured MSκ. First, we divide the soil profile along its depth into n finite 1D elements (in the MagHut model, which is attached to this manuscript, there are 150 elements, each 1 mm thick). Since layers with a higher magnetite concentration contribute more to the MSκ, the magnetic properties must be specified for each element. In MagHut, the distribution of magnetic properties along the soil profile is expressed by a mass magnetic susceptibility MSχ (m^3 kg^{-1}) for each element. Then

$$\mathrm{MS}\chi_{A,i} = \frac{\mathrm{MS}\kappa_{\mathrm{norm},i}\mathrm{MS}\chi_i}{100}, \tag{3}$$

where MS$\chi_{A,i}$ is the apparent mass-specific magnetic susceptibility (m^3 kg^{-1}) of element i related to the position of the MS2D sensor (typically at soil surface), MS$\kappa_{\mathrm{norm},i}$ is the percentage of the signal received from element i, and MSχ_i is the mass magnetic susceptibility of element i, which needs to be specified as input. Based on the principle of superposition:

$$\mathrm{MS}\chi_{A_{\mathrm{TOT}}} = \sum_{i=0}^{n} S\chi_{A_i}, \tag{4}$$

where MS$\chi_{A_{\mathrm{TOT}}}$ is the total apparent mass-specific magnetic susceptibility across the soil profile, which the MS2D probe detects from the surface. MS$\chi_{A,i}$ (m^3 kg^{-1}) represents the vertical distribution of the magnetite in the soil profile.

When the bulk density of the soil and the relationship between MSχ and the magnetite concentration are known, the MagHut model can also calculate the mass distribution and the total mass of the magnetite in the soil profile.

2.3 | Volume magnetic susceptibility (MSκ) calculation

To construct the functional relationship between MSκ and MS$\chi_{\mathrm{A_TOT}}$, we constructed a total of 36 artificial soil profiles with various magnetic tracer quantities and distributions, see section 2.6 below. For each constructed soil profile, MSκ_{OBS} (measured volume magnetic susceptibility; the index denotes an observed value) was measured from the surface with the MS2D probe, and MS$\chi_{\mathrm{A_TOT}}$ was calculated simultaneously according to Equation (3). The relationship MSκ_{OBS}–MS$\chi_{\mathrm{A_TOT}}$ is linear. The slope of the regression curve a can be calculated as follows:

$$a = \frac{n\left(\mathrm{MS}\chi_{A_{\mathrm{TOT},i}} \cdot \mathrm{MS}\kappa_{\mathrm{OBS},i}\right) - \sum \mathrm{MS}\chi_{A_{\mathrm{TOT},i}} \sum \mathrm{MS}\kappa_{\mathrm{OBS},i}}{n\sum\left(\mathrm{MS}\chi_{A_{\mathrm{TOT},i}}\right)^2 - \left(\sum \mathrm{MS}\chi_{A_{\mathrm{TOT},i}}\right)^2}, \tag{5}$$

where n is the number of data points for the linear fit, and MS$\chi_{\mathrm{A_TOT,i}}$ and MS$\kappa_{\mathrm{OBS,i}}$ are individual data points. The volume specific magnetic susceptibility (MSκ) can then be predicted as follows:

$$MS\kappa = a\int_0^z \mathrm{MS}\chi_A(z)dz = a\mathrm{MS}\chi_{\mathrm{A\_TOT}} \tag{6}$$

Since the MSκ–MS$\chi_{\mathrm{A_TOT}}$ relationship is always linear and changes only slightly with different magnetite distributions (within a range given by Lecoanet et al. (1999) and Liu et al. (2019) functions in Figure 2), MSκ can be predicted for any soil profile stratification. Unfortunately, it is not possible to simulate the MSχ distribution based on MS$\kappa_{\mathrm{OBS},}$ because there are an infinite number of possible solutions (problem of equifinality).

The following sections describe the experimental work that led to the collection of MS$\chi_{\mathrm{A_TOT}}$ and MSκ_{OBS} data for the parametrization of the MSκ–MS$\chi_{\mathrm{A_TOT}}$ relationship.

2.4 | Magnetic tracer characteristics

Synthetic magnetic iron oxide pigment (97% Fe_3O_4), known as magnetite and commercially available as Bayferrox 318 M, was used as a magnetic tracer for the experiments. This black pigment, commonly used as a colorant for coatings or for cement, is light stable and weather and UV resistant. It comes in the form of a powder with predominantly spherical particles with an average size of 0.2 µm, maximum 40 µm. The usability of iron oxide pigment as a tracer for soil erosion studies was demonstrated by Guzmán et al. (2010).

2.5 | Soil properties

For the preparation of the different soil tracer mixtures, topsoil (0–10 cm) was taken from the La Conchuela olive plantation located in south–western Spain (37° 49′ 4.6″ N, 4° 53′ 45.6″ W), as a detailed characterization of the soil was already available. This soil is classified as Typic Haploxerert (Soil Survey Staff, 2010), the texture is silty clay with an average content of clay, silt, and sand of 48.6%, 44.3%, and 8.1% respectively, and the average organic matter content is 1.24%.

TABLE 2 Soil samples magnetic characteristics measured at soil bulk density of 1.13 g cm^{-3}.

	Plain topsoil La Conchuela	Soil sample A	Soil sample B	Soil sample C
Magnetite mass concentration (g kg^{-1} of soil)	0	24.3 (2.4%)	12.3 (1.2%)	6.0 (0.6%)
Mass magnetic susceptibility $MS\chi$ ($\times 10^{-6}$ m^3 kg^{-1})	0.27 ± 0.04	14.80 ± 0.38	7.65 ± 0.24	3.86 ± 0.08

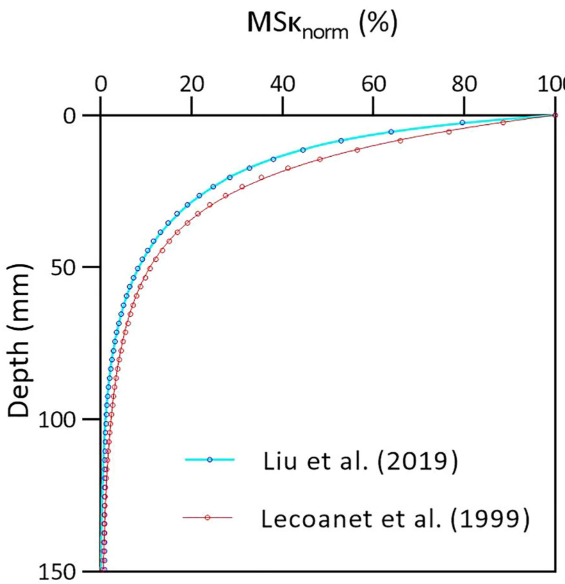

FIGURE 2 Normalized $MS\kappa$ ($MS\kappa_{norm}$) functions for two borderline ways of magnetic tracer distribution: (i) a thick magnetite layer (Lecoanet et al., 1999), and (ii) a thin magnetite layer (Liu et al., 2019) buried at variable depths. The dots represent the digitized data from the original manuscripts, and the lines represent the fitted functions.

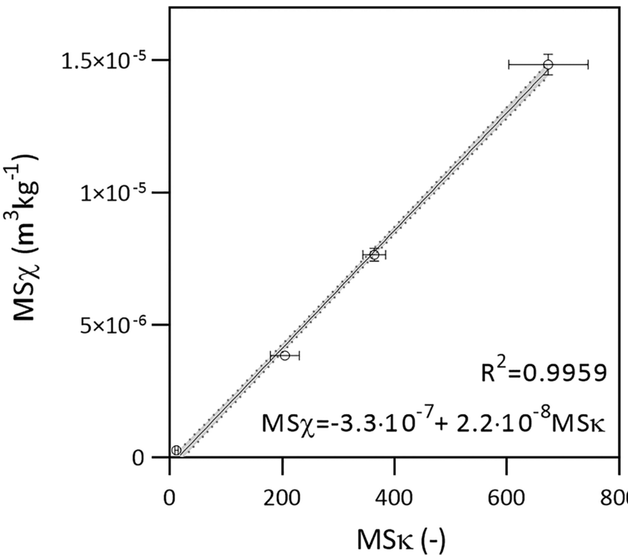

FIGURE 3 Linear relationship between the measured mass magnetic susceptibility ($MS\chi$) and the volume magnetic susceptibility ($MS\kappa$). The gray area around the linear trend line represents the area between the 95% confidence bands of the best-fit line, and the error bars represent the standard deviations of the measured $MS\chi$ and $MS\kappa$.

2.6 | Experimental setup

The air-dried soil was first crushed in a concrete mixer and then sieved on a 20-mm mesh, the organic fragments and roots were removed. Then the magnetite was added to the soil in order to prepare three mixtures with different concentrations. The mass concentration of magnetite in the soil was 0.6%, 1.2%, and 2.4%. The measured $MS\chi$ of the individual materials can be found in Table 2.

The soil–tracer mixture was lightly moistened during manual mixing to ensure binding and uniform distribution, after which the mixture was air-dried again. The apparent volume magnetic susceptibility ($MS\kappa$) of the materials was measured using the MS2D probe. The linear relationship between $MS\chi$ and $MS\kappa$ is shown in Figure 3.

The same mass (7 kg) of soil or soil-tracer mixture was packed into the carton boxes with external dimensions of 60 × 50 × 2.7 cm^3, and the cardboard wall thickness was 0.3 cm. The resulting bulk density of the material (without the carton) was 1.13 g cm^{-3}. The soil was loosely and evenly distributed in the carton boxes so that the height of the material layer was constant and there were no air gaps between the soil and the carton. The boxes were closed and sealed for manipulation and measurements.

The artificial soil profiles were made from seven stacked cardboard boxes (Figure 4). Four cartons were filled with normal (without magnetite) soil and three cartons were filled with soil–tracer mixtures of varying concentrations. Of the 36 scenarios, 25 soil profiles were used for calibration of the $MS\kappa$-$MS\chi_{A\_TOT}$ function, and 11 scenarios were used for subsequent validation of the relationship. The data set for the validation was selected in such a way that the measured $MS\kappa$ values were evenly distributed over the entire recorded range.

In this manuscript, when describing the artificial soil profiles, we denote plain soil with the letter S, cardboard (paper) with P, air with G, soils with a mass concentration of 2.4% magnetite with A, soils with 1.2% magnetite with B, and soils with 0.6% magnetite with C.

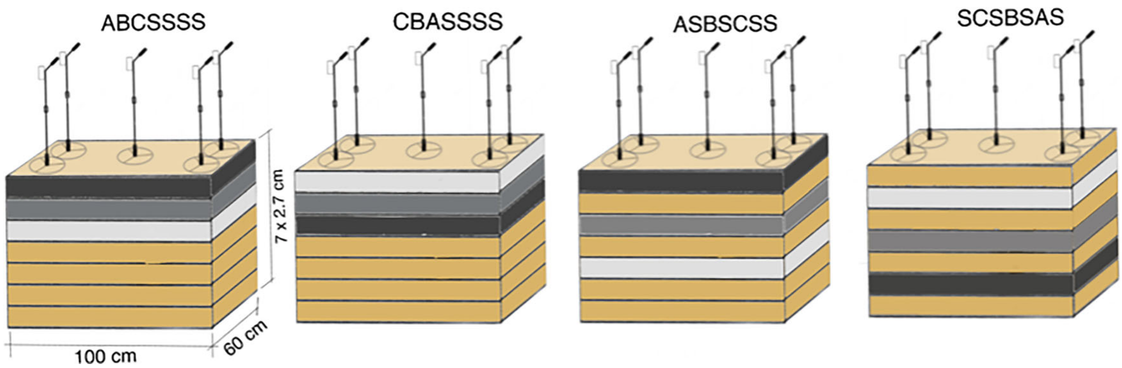

FIGURE 4 Examples of stacking scenarios for four different tracer distributions in the soil profile (the codes above each soil profile explain the nomenclature used in this manuscript). Each scenario was measured five times on different spots of the box. For every scenario, the average and the standard deviation of the volume magnetic susceptibility was calculated. A total of 36 combinations of different material distributions were constructed. A stands for soil with a magnetite concentration of 2.4%, B stands for soil with a magnetite concentration of 1.2%, C stands for soil with a magnetite concentration of 0.6%, and S stands for plain soil.

For each configuration of the soil profile, we measured additional scenarios by raising the field probe above the surface of the box. The probe was raised 2.5, 5, and 7.5 cm into the air. The exact height was maintained by placing 2.5-cm-thick incompressible polyethylene foam blocks between the soil sample and the probe. The MSχ of the PE foam was zero. This allowed us to simulate the coverage of the soil surface with magnetically inert material, such as organic residues. All scenarios selected for validation and calibration are accessible from a data repository (Zumr et al., 2022).

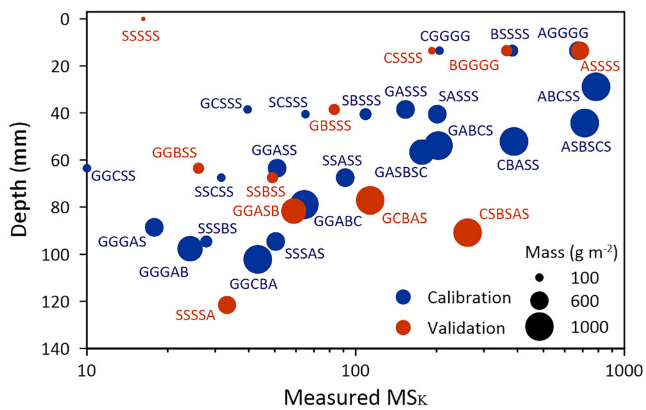

FIGURE 5 Measured volume magnetic susceptibility (MSκ) of 36 artificially created soil profiles. The blue bubbles represent measurements used to fit the coefficients of the model. The red bubbles were used for validation. The values shown are averages of five replicates. The depth represents the centroids of the magnetite distributions, and the size of the bubble reflects the mass of magnetite per square meter of the soil profile. Only the first five layers are listed in the labels. A stands for soil with a magnetite concentration of 2.4%, B stands for soil with a magnetite concentration of 1.2%, C stands for soil with a magnetite concentration of 0.6%, S stands for plain soil, and G stands for air.

3 | RESULTS

3.1 | Volume magnetic susceptibility (MSκ) monitoring

The measured values of the volume MS of all constructed soil profiles used for the calibration and validation of the MagHut model are shown in Figure 5. The highest measured values were present when the magnetite was in high concentration near the surface (in Figure 5, measurements starting with the layer A). In contrast, the lowest values were obtained for soil profiles with little magnetite or with deeply buried magnetite.

Plotting the position of the magnetite in soil on a scatter plot is difficult because the tracer was spread out over a large depth. Therefore, in Figure 5, the centroids of the magnetite tracer positions are plotted on the vertical axis. For example, in the ASBSC scenario, the average depth (the centroid of the tracer)is 44 cm, although some of the tracer was also present near the surface. This means that the data points do not perfectly follow the exponential decay pattern. The measurement data, on the basis of Figure 5 was created, are available via a data repository (Zumr et al., 20222).

3.2 | Apparent mass magnetic susceptibility (MSχ_A) calculation

The apparent mass magnetic susceptibility distributions MSχ_A within the soil profiles were calculated for all 36 measured scenarios. Examples of three differently constructed soil profiles are shown in Figure 6. The MSχ_A distribution decreases exponentially according to the functions in Equation (2) and Table 1. The MSχ_A scale is proportional to the mass of magnetite in each layer. The gaps between

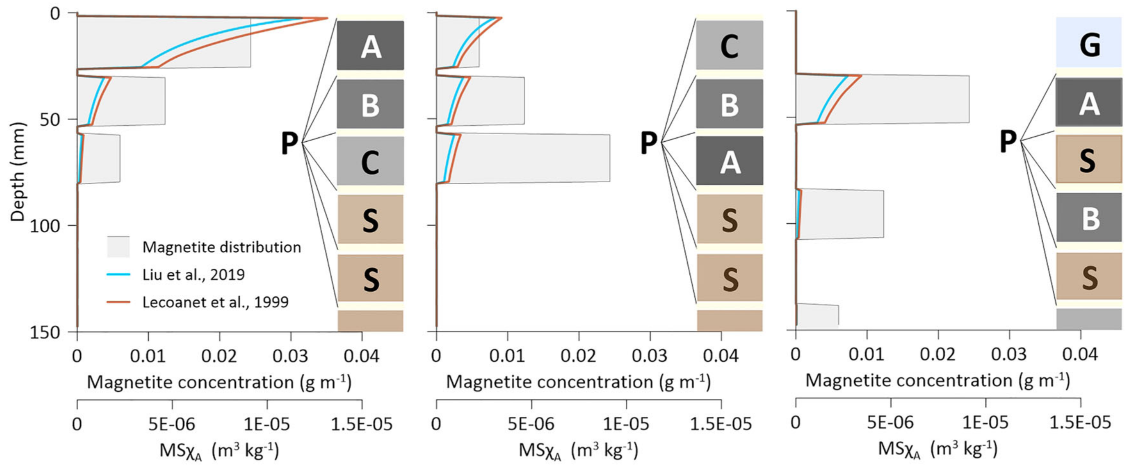

FIGURE 6 Apparent mass magnetic susceptibility ($MS\chi_A$) profiles (calculated by Liu et al. (2019) and by Lecoanet et al. (1999) from empirical data using Equation (3) for three examples of magnetic tracer distributions. The boxes on the right of each scenario show the composition of the soil profile, where P stands for cardboard, A stands for soil with a magnetite concentration of 2.4%, B stands for soil with a magnetite concentration of 1.2%, C stands for soil with a magnetite concentration of 0.6%, S stands for plain soil, and G stands for air.

the magnetite layers represent the carton boxes with zero MS.

The Figure 6 shows the $MS\chi_A$ distribution calculated according to both the Lecoanet et al. (1999) function and the Liu et al. (2019) function. The values are higher for the Lecoanet et al. (1999) relation, especially in the near-surface region. The highest calculated total apparent mass magnetic susceptibility $MS\chi_{A\_TOT}$ of 2.22 10^{-4} m^3 kg^{-1} (according to Lecoanet et al., 1999) or 1.79 10^{-4} m^3 kg^{-1} (Liu et al., 2019) was calculated for the ABCSS scenario. This is the scenario with the highest amount of tracer accumulating closest to the surface (Figure 5). A scenario with plain soil (SSSSS) leads to $MS\chi_{A\_TOT}$ of 5.07 10^{-6} m^3 kg^{-1} for Lecoanet et al. (1999) and 4.03 10^{-6} m^3 kg^{-1} for Liu et al. (2019). It should be remembered that $MS\chi_{A\_TOT}$ has no clear physical meaning, as it is related to the antenna sensitivity pattern of the field probe.

3.3 | $MS\chi_{A\_TOT}$–$MS\kappa$ regression relationship

The simulated mass magnetic susceptibility $MS\chi_{A\_TOT}$ and the observed volume magnetic susceptibility $MS\kappa_{OBS}$ for 21 selected soil profile scenarios are plotted on the left in Figure 7. The points in the graph represent the arithmetic $MS\kappa_{OBS}$ averages of five measurements for each scenario. The $MS\kappa$ standard deviation varied between 2 (for low readings) and 80 (for high readings). On average, the deviation was 13.8% of the mean measured values.

The data points were fitted with linear trend lines according to Equations (5) and (6) as follows:

For Liu et al. (2019):

$$MS\kappa = 4.43 \times 10^6 \, MS\chi_{A\_TOT}, \text{with} \, R^2 = 0.9711 \tag{7}$$

For Lecoanet et al. (1999):

$$MS\kappa = 3.62 \times 10^6 \, MS\chi_{A\_TOT}, \text{with} \, R^2 = 0.9755, \tag{8}$$

where $MS\chi_{A\_TOT}$ was calculated for each scenario according to Equation (4) and $MS\kappa$ is the predicted (simulated) volume specific magnetic susceptibility. The slopes of the resulting trend lines are statistically different with $p = 0.0004$.

In general, the $MS\chi_{A\_TOT}$–$MS\kappa$ regression relation can be constructed in a similar way for all additionally measured data with any tracer arrangement. The results will lie within the limits defined by the curves of Liu et al. (2019) and Lecoanet et al. (1999).

The validation of the model was carried out using 11 independent scenarios (Figure 7, right). The comparison of the simulated and $MS\kappa_{OBS}$ shows very good agreement in the entire tested range. The Nash–Sutcliffe coefficients for goodness of fit were 0.994 for the Liu et al. (2019) function and 0.993 for the Lecoanet et al. (1999) function, and the coefficients of determination were 0.992 and 0.990, respectively.

3.4 | MagHut—Support tool for estimating the volume magnetic susceptibility

Complementary to this manuscript, there is a Microsoft Excel spreadsheet with implemented MagHut model (compatible and tested with MS Office 2019 and newer versions) that

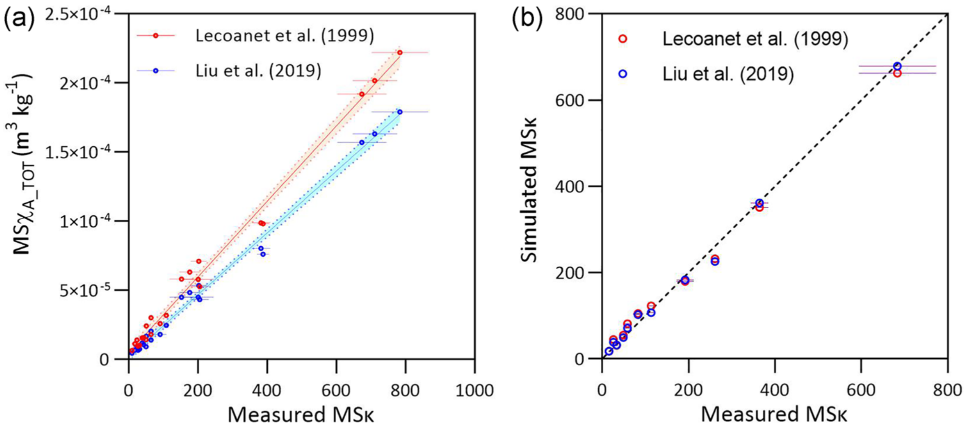

FIGURE 7 Left: Calculated mass magnetic susceptibility ($MS\chi_{A\_TOT}$) for the Lecoanet et al. (1999) and Liu et al. (2019) functions compared to the measured volume magnetic susceptibility ($MS\kappa_{OBS}$). Twenty-five calibration scenarios were fitted with linear regression functions. Right: Validation of the model on 11 selected scenarios showing a comparison between simulated MSκ values and measured $MS\kappa_{OBS}$ values. The error bars represent the standard deviations of the measured MSκ.

calculates the volume magnetic susceptibility of a soil profile based on an arbitrarily defined amount and distribution of a magnetic tracer in the soil (available in a repository, see Zumr et al., 2023). The MagHut model aims to offer a practical tool for forward modeling of volume magnetic susceptibility. The model was created to be versatile, simple to parametrize, and easy to implement.

The following briefly explains the process of setting up and running the MagHut model. The 15 cm deep soil profile is approximated by 150 elements, each 1 mm thick. The user can theoretically subdivide the soil profile into any number of elements and extend the profile depth. It has been demonstrated that a soil profile depth of 15 cm is sufficient to extend beyond the range of depths at which the MS2D antenna is sensitive. For each element, information about the material properties (the mass or the MS of the material) must be defined.

The user can choose between two functions for the decrease in MS (as shown in Figure 2) based on the expected tracer distribution. The function of Liu et al. (2019) is suitable for scenarios where a thin magnetic layer is expected, while the function of Lecoanet et al. (1999) is more suitable for thick magnetic layers or for a quasi-homogeneous tracer distribution (see Figure 1). The implementation of alternative decline functions based on user-obtained data is possible. An example of such a function, derived from the data presented in this study, is demonstrated in the accompanying MagHut spreadsheet. This function may also prove useful in situations where the distribution of magnetite is uncertain and does not strictly follow the scenarios depicted on Figure 1.

The MagHut tool first calculates the apparent mass magnetic susceptibility $MS\chi_{A\_TOT}$ as an integral of the mass magnetic susceptibility of each element. Then, based on the regression $MS\chi_{A\_TOT}$–MSκ, the volume magnetic susceptibility MSκ is calculated. Subsequently, the tracer distribution in the soil profile and the shape of the MS response ($MS\chi_{A\_TOT}$) are plotted to obtain qualitative and visual information on the effects of tracer distribution on the MSκ measurement (similarly as shown on Figure 6).

4 | DISCUSSION

It has been shown that the simulated values of the volume magnetic susceptibility (MSκ) values for the Lecoanet et al. (1999) and Liu et al. (2019) relationships differ by up to 15%, depending on the magnetite distribution in the soil profile (higher values are obtained with the Lecoanet function). Since both the Liu et al. (2019) relationship and the Lecoanet et al. (1999) relationship were derived for extreme scenarios (a thin magnetic layer for Liu and a thick homogeneous profile for Lecoanet), the real volume magnetic susceptibility will fall within the range between the simulated values in most cases.

It should be noted that the MS2D field probe was not designed as a laboratory precision device. Zubieta et al. (2021b) state that a difference in measured relative MS of less than 6% is due to systematic measurement errors. The spatial variability of apparently homogeneous soil profiles can differ by an order of magnitude (Zubieta et al., 2021a). In our study, the standard deviation of repeated Measured volume magnetic susceptibility measurements of the same profiles was in the range of 5%–20%. Therefore, the difference between the Liu et al. (2019) and Lecoanet et al. (1999) functions is smaller than the uncertainty associated with most MS2D surveys.

4.1 | Volume magnetic susceptibility–depth relationship

As mentioned earlier, it is well known that the MS2D probe antenna signal decreases exponentially with depth (e.g., Dearing, 1994; Lecoanet et al., 1999; Liu et al., 2019; Petrovsky et al., 2004). We have shown that a double exponential function, which allows for a faster decline near the surface, fits the measured data better than a single exponential function. Our experimental data also follow the double exponential trend line.

A comparison of the decrease function of Liu et al. (2019) and Lecoanet et al. (1999) shows that the antenna signal decreases faster in the case of a thin magnetic layer in the soil than in the case of a thick magnetic layer. This conclusion is intuitive, because the faster decrease in the case of the thin magnetic layer is dictated by the shape and the volume that the MS2D probe can detect (Dearing, 1994). It can be shown (as we demonstrate in part in the following discussion) that any magnetite distribution in a soil profile will have a similar decay function with increasing burial depth. When plotted, the decay function lies within the range delineated by the Liu et al. (2019) and Lecoanet et al. (1999) functions shown in Figure 2.

4.2 | Validation of the MagHut model with data from other experimental studies

There are only a small number of studies in which the authors present information on both the measured MSκ from the surface and the magnetite distribution in the soil profile. The amount of magnetite in the soil profile is usually low (especially in studies related to soil contamination by fly ash), and is therefore not useful for validating MagHut. We therefore used the data from our experiment and checked whether they fit the range given by the models of Lecoanet et al. (1999) and Liu et al. (2019) (see Figure 7, left).

To do this, we constructed a new MSχ_{A_TOT}–MSκ decay function based on the measured experimental data. The fitted parameters of the double-exponential function (Equation 2) are listed in Table 1. The decay function can be plotted in the MagHut model, which includes the optimized parameters. The gradient of the MSχ_{A_TOT}–MSκ decay of 3.87 10^6 is within the range observed for the same regression by Lecoanet et al. (1999) and by Liu et al. (2019) (see Equations 7 and 8). It should be emphasized that the function from this study is specific to the given setup, but it can mimic well a heterogeneous spatial distribution of magnetite concentration in soils and can therefore be used in situations where the distribution of the magnetite tracer is unknown or uncertain. A similar analysis was carried out for the dataset published by Zubieta et al. (2021a). They measured MS in a total of 28 soil profiles. Each profile contained a 5 mm thick layer with different magnetite concentrations. The magnetite was buried at depths of 0–10 cm. Since the authors only published relative values of MS, the absolute MS values were first recalculated. The

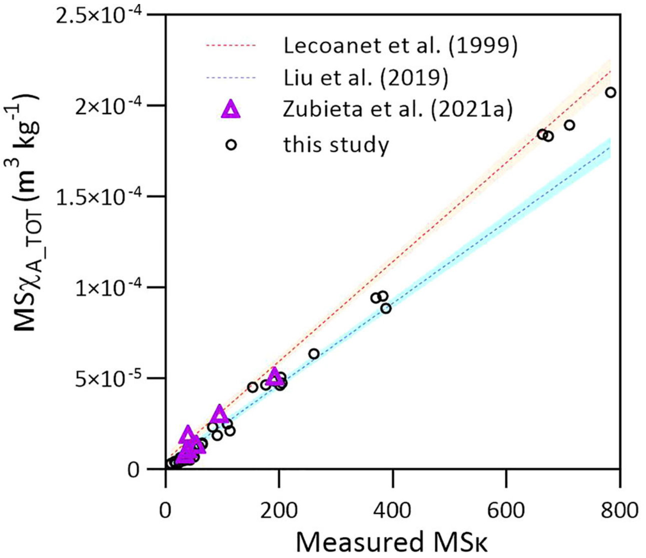

FIGURE 8 Measured volume magnetic susceptibility (MSκ) and simulated apparent mass magnetic susceptibility (MSχ_{A_TOT}) for the experimental data of this study and the data of Zubieta et al. (2021a). The data points fit the theoretical range delineated by the Liu et al. (2019) and Lecoanet et al. (1999) functions.

mass magnetic susceptibility of soils with different magnetite concentrations was calculated according to Equation (3).

The measured mass magnetic susceptibility and the simulated values of MSχ_{A_TOT} for the data of this study and for the data of Zubieta et al. (2021a) are shown in Figure 8. For the Zubieta et al. data, only the five highest values were plotted, as the remaining data points were very close to zero. All simulated values, as suspected, fit well within the range delineated by the curves of Lecoanet et al. (1999) and Liu et al. (2019).

4.3 | Limitations and effectiveness of the MagHut model

The MagHut model, developed to provide a simple tool for volume magnetic susceptibility estimation, is inherently limited by its focus on a forward modeling approach. This means that, unlike geophysical inversion modeling, it is unable to determine the true tracer distribution, in terms of both concentration and depth, from a single surface measurement. The problem of nonuniqueness, a well-known issue with this type of modeling (Lyu et al., 2021), means that the model is only able to calculate the volume magnetic susceptibility based on a known magnetic tracer distribution. In the current study, only soils with minimal ferrous material content have been tested. However, it is important to note that the presence of ferrous materials in soils can significantly influence MS measurements (Alekseev, 2011).

A similar modeling approach has been applied to other geophysical methods such as electrical resistivity tomography (e.g., Melouah & Hichem, 2021) to interpret field measurements and improve understanding of subsurface properties. The procedure involves comparing the modeled values with the measured values and adjusting the parameters of the model until a reasonable agreement between the modeled and measured values is achieved. A good agreement is an indication that the model is a realistic representation of the actual situation in the subsurface.

The effectiveness of the MagHut model depends on a basic understanding of the properties of the magnetic tracer and its position in the soil profile. Therefore, the use of this approach requires prior knowledge of the test site to improve the understanding of both the tracer and the soil movement during experimental monitoring of soil erosion processes.

A typical application of the MagHut model is to conduct soil erosion tests, especially at sites where erosion rates need to be monitored. The MagHut model can be used to optimize the test design, that is, the concentration of magnetic tracers and its initial distribution across different depths in the soil profile. The measured value of MS can then be directly converted into tracer depth, which is a key parameter for understanding soil erosion rates (Guzman et al., 2010). The advantage of using a magnetite tracer and mapping MS is its simplicity and speed compared to conventional soil sampling methods. Therefore, the MagHut model can be used to improve the understanding of the soil erosion process and increase the accuracy of erosion rate measurements.

A limitation of the MagHut model is that it has only been trained with data obtained with the MS2D Bartington probe. So if another probe were used, the model would need to be recalibrated, implying that using a different probe would require model recalibration. However, the model has been shown to be able to accurately simulate the distribution of magnetic tracers, as shown by a coefficient of determination of about 0.99 when the tracer is in the top 10 cm of the soil profile.

5 | CONCLUSIONS

MS mapping is a very popular tool for monitoring soil erosion processes at the field scale, mainly because of its simplicity and its noninvasive nature. However, measurements from the surface do not provide information about the depth distribution of a magnetic material, nor about its quantity. Therefore, due to the problem of nonuniqueness, the same response can be obtained with very different magnetic stratification of the soil profile. That is, a low concentration of a magnetic tracer at the surface can result in the same measured value of volume magnetic susceptibility as a layer with a high magnetic concentration that lies just below the surface. The ambiguity of the measured MS, which has also been shown in this study, is the main drawback of the method.

We have presented the new MagHut model, which is able to calculate the volume magnetic susceptibility based on a defined distribution of magnetic material in the soil profile. The model is based on regression relationships between the MSκ_{OBS} and the distance to the magnetic tracer. The model has been successfully calibrated and validated with newly measured data and also with previously published data sets. For simplicity and general accessibility, the MagHut model is programmed as an MS Excel spreadsheet.

Although the MagHut model is not able to calculate the amount and the spatial distribution of magnetite when only a single value of volume magnetic susceptibility is measured, it still offers practical advantages. The use of forward modeling can help interpret field survey results, improve understanding of the distribution of magnetite in the subsurface and optimize the design of soil erosion experiments. The position of the magnetic layer is often known, and its quantity can be estimated with the help of MagHut. Conversely, if the amount of tracer in the subsurface is known, an estimate of its distribution can be made. Nevertheless, standard soil coring and laboratory measurements of the mass magnetic susceptibility along the soil profile are still required when prior knowledge of the distribution of magnetic tracers is poor or when the magnetite is deeply buried.

AUTHOR CONTRIBUTIONS

David Zumr: Conceptualization; investigation; software; writing—original draft. **Tailin Li**: Data curation; formal analysis; validation. **José A. Gómez**: Conceptualization; methodology; resources; writing—review and editing. **Gema Guzmán**: Conceptualization; methodology; investigation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The MagHut model and the data that support the findings of this study are openly available in Zenodo repository at https://doi.org/10.5281/zenodo.7297158 and https://doi.org/10.5281/zenodo.8079166.

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REFERENCES

Alekseev, A. (2011). Magnetic properties of soils. In J. Gliński , J. Horabik , & J. Lipiec (Eds.), *Encyclopedia of agrophysics* (pp. 436–439). Springer. https://doi.org/10.1007/978-90-481-3585-1_86

Bartington Inc. (2022). *Operation manual for MS2 magnetic susceptibility system*. Bartington Inc. https://Bartingtondownloads.Com/Wp-Content/Uploads/OM0408.Pdf

Bouhlassa, S., & Bouhsane, N. (2019). Assessment of areal water and tillage erosion using magnetic susceptibility: The approach and its application in Moroccan watershed. *Environmental Science and Pollution Research*, *26*(25), 25452–25466. https://doi.org/10.1007/s11356-019-05510-6

Burguet, M., Guzmán, G., de Luna, E., Taguas, E. V., & Gómez, J. A. (2018). Evaluation of disruption of sediment connectivity and herbicide transport across a slope by grass strips using a magnetic iron oxide tracer. *Soil and Tillage Research*, *180*, 268–281. https://doi.org/10.1016/j.still.2018.02.014

Dearing, J. (1994). *Environmental magnetic susceptibility: Using the Bartington MS2 system*. Chi Publishing.

Ding, Z., Zhang, Z., Li, Y., Zhang, L., & 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 and Tillage Research*, *199*, 104568. https://doi.org/10.1016/j.still.2019.104568

Fiener, P., Wilken, F., Aldana-Jague, E., Deumlich, D., Gómez, J. A., Guzmán, G., Hardy, R. A., Quinton, J. N., Sommer, M., van Oost, K., & Wexler, R. (2018). Uncertainties in assessing tillage erosion—How appropriate are our measuring techniques? *Geomorphology*, *304*, 214–225. https://doi.org/10.1016/j.geomorph.2017.12.031

Guzmán, G., Barrón, V., & Gómez, J. A. (2010). Evaluation of magnetic iron oxides as sediment tracers in water erosion experiments. *Catena*, *82*(2), 126–133. https://doi.org/10.1016/j.catena.2010.05.011

Guzmán, G., Laguna, A., Cañasveras, J. C., Boulal, H., Barrón, V., Gómez-Macpherson, H., Giráldez, J. V., & Gómez, J. A. (2015). Study of sediment movement in an irrigated maize-cotton system combining rainfall simulations, sediment tracers and soil erosion models. *Journal of Hydrology*, *524*, 227–242. https://doi.org/10.1016/j.jhydrol.2015.02.033

Guzmán, G., Quinton, J. N., Nearing, M. A., Mabit, L., & Gómez, J. A. (2013). Sediment tracers in water erosion studies: Current approaches and challenges. *Journal of Soils and Sediments*, *13*(4), 816–833. https://doi.org/10.1007/s11368-013-0659-5

Guzmán, G., Vanderlinden, K., Giráldez, J. V., & Gómez, J. A. (2013). Assessment of spatial variability in water erosion rates in an olive orchard at plot scale using a magnetic iron oxide tracer. *Soil Science Society of America Journal*, *77*(2), 350–361. https://doi.org/10.2136/sssaj2012.0219

Hanesch, M., & Scholger, R. (2002). Mapping of heavy metal loadings in soils by means of magnetic susceptibility measurements. *Environmental Geology*, *42*(8), 857–870. https://doi.org/10.1007/s00254-002-0604-1

Jakšík, O., Kodešová, R., Kapička, A., Klement, A., Fér, M., & Nikodem, A. (2016). Using magnetic susceptibility mapping for assessing soil degradation due to water erosion. *Soil and Water Research*, *11*(2), 105–113. https://doi.org/10.17221/233/2015-SWR

Janas, S., Magiera, T., & Szumiata, T. (2022). Susceptometer in soil magnetic susceptibility studies. *Metrology and Measurement Systems*, *29*(1), 127–142. https://doi.org/10.24425/mms.2022.138550

Kapička, A., Petrovský, E., & Jordanova, N. (1997). Comparison of in-situ field measurements of soil magnetic susceptibility with laboratory data. *Studia Geophysica et Geodaetica*, *41*(4), 391–395. https://doi.org/10.1023/A:1023363502016

Lecoanet, H., Lévêque, F., & Segura, S. (1999). Magnetic susceptibility in environmental applications: Comparison of field probes. *Physics of the Earth and Planetary Interiors*, *115*(3–4), 191–204. https://doi.org/10.1016/S0031-9201(99)00066-7

Liu, L., Huang, M., Zhang, K., Zhang, Z., & Yu, Y. (2018). Preliminary experiments to assess the effectiveness of magnetite powder as an erosion tracer on the Loess Plateau. *Geoderma*, *310*, 249–256. https://doi.org/10.1016/j.geoderma.2017.09.024

Liu, L., Liu, H., Fu, S., Zhang, K., Wen, M., Yu, Y., & Huang, M. (2020). Feasibility of magnetite powder as an erosion tracer for main soils across China. *Journal of Soils and Sediments*, *20*(4), 2207–2216. https://doi.org/10.1007/s11368-020-02574-7

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

López-Vicente, M., & Guzmán, G. (2021). Measuring soil erosion and sediment connectivity at distinct scales. In J. Rodrigo-Comino (Ed.), *Precipitation* (pp. 287–326). Elsevier. https://doi.org/10.1016/b978-0-12-822699-5.00011-2

Lyu, C., Capdeville, Y., Al-Attar, D., & Zhao, L. (2021). Intrinsic non-uniqueness of the acoustic full waveform inverse problem. *Geophysical Journal International*, *226*(2), 795–802. https://doi.org/10.1093/gji/ggab134

Magiera, T., Łukasik, A., Zawadzki, J., & Rösler, W. (2019). Magnetic susceptibility as indicator of anthropogenic disturbances in forest topsoil: A review of magnetic studies carried out in Central European forests. *Ecological Indicators*, *106*, 105518. https://doi.org/10.1016/j.ecolind.2019.105518

Maier, G., Scholger, R., & Schön, J. (2006). The influence of soil moisture on magnetic susceptibility measurements. *Journal of Applied Geophysics*, *59*(2), 162–175. https://doi.org/10.1016/j.jappgeo.2005.10.001

Melouah, O., & Hichem, Z. (2021). Utility of forward and inverse modeling in 2D electric tomography for Hydrogeologic studies. *Applied Water Science*, *11*(15), https://doi.org/10.1007/s13201-020-01347-4

Petrovsky, E., Hulka, Z., & Kapicka, A. (2004). A new tool for in situ measurements of the vertical distribution of magnetic susceptibility in soils as basis for mapping deposited dust. *Environmental Technology*, *25*(9), 1021–1029. https://doi.org/10.1080/09593332508618391

Ravi, S., Gonzales, H. B., Buynevich, I. V., Li, J., Sankey, J. B., Dukes, D., & Wang, G. (2019). On the development of a magnetic susceptibility-based tracer for aeolian sediment transport research. *Earth Surface Processes and Landforms*, *44*(2), 672–678. https://doi.org/10.1002/esp.4536

Soil Survey Staff. (2010). *Keys to soil taxonomy* (11th ed.). USDA-Natural Resources Conservation Service.

Thompson, R., & Oldfield, F. (1986). *Environmental magnetism*. Springer. https://doi.org/10.1007/978-94-011-8036-8

Ventura, E., Nearing, M. A., & Norton, L. D. (2001). Developing a magnetic tracer to study soil erosion. *Catena*, *43*(4), 277–291. https://doi.org/10.1016/S0341-8162(00)00149-1

Wang, G., Liu, Y., Chen, J., Ren, F., Chen, Y., Ye, F., & Zhang, W. (2018). Magnetic evidence for heavy metal pollution of topsoil in Shanghai, China. *Frontiers of Earth Science*, *12*(1), 125–133. https://doi.org/10.1007/s11707-017-0624-5

Wojas, A. (2017). The magnetic susceptibility of soils in Krakow, southern Poland. *Acta Geophysica*, *65*(3), 453–463. https://doi.org/10.1007/S11600-017-0041-X/FIGURES/6

Zawadzki, J., Magiera, T., Fabijańczyk, P., & Kusza, G. (2012). Geostatistical 3-dimensional integration of measurements of soil magnetic susceptibility. *Environmental Monitoring and Assessment*, *184*(5), 3267–3278. https://doi.org/10.1007/s10661-011-2187-3

Zubieta, E., Larrasoaña, J. C., Aldaz, A., Casalí, J., & Giménez, R. (2021a). Assessment of magnetite as a magnetic tracer for sediments in the study of ephemeral gully erosion: Conditioning factors of magnetic susceptibility. *Earth Surface Processes and Landforms*, *46*(6), 1103–1110. https://doi.org/10.1002/esp.5074

Zubieta, E., Larrasoaña, J. C., Aldaz, A., Casalí, J., & Giménez, R. (2021b). Assessment of magnetite as a sediment tracer in the study of ephemeral gully erosion: Application and distribution in the soil. *Earth Surface Processes and Landforms*, *46*(7), 1419–1427. https://doi.org/10.1002/esp.5111

Zumr, D., Li, T., Gómez, J., & Guzmán, G. (2022). *Measured magnetic susceptibility data for different magnetite tracer stacking scenarios*. Zenodo. https://doi.org/10.5281/zenodo.7297158

Zumr, D., Li, T., Gómez, J., & Guzmán, G. (2023). *MagHut model—Modeling tool to simulate volume magnetic susceptibility based on the known tracer distribution in the soil (1.0)*. Zenodo. https://doi.org/10.5281/zenodo.8079166

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