MAGNETIC SUSCEPTIBILITY IN TOPSOILS AND BULK CORES OF CULTIVATED CALCISOLS

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Abstract

The magnetic susceptibility (MS) in soils is a fast and non-destructive technique that can be used to infer the concentration of magnetic minerals. The objective of this study was to analyze MS on topsoil and bulk core samples of cultivated Calcisols. Magnetic susceptibility was measured at two different frequencies to assess the variation of magnetic susceptibility when the frequency of the applied magnetic field changed. The low frequency values of mass-specific MS ranged between 16.0 and 57.6 $\times 10^{-8}$ m^3 kg^{-1}. High correlation coefficients were found between the MS in topsoil and bulk core samples (r = 0.94). In addition, magnetic susceptibility was measured in situ in the field to compare with the results obtained in the laboratory. The measurements of MS in the field varied from 10.0 to 48.0 $\times 10^{-5}$ SI. High correlation coefficients were found between MS in laboratory and field measurements (r = 0.88). The methodology applied in this study using a susceptibility meter and a dual frequency sensor for the laboratory measurements and a probe handle for the field measurements has proved to be useful for fast and reliable measurements of MS in the field.

Resumen

La medida de la susceptibilidad magnética (SM) en suelos es una técnica rápida y no destructiva que puede ser empleada para inferir la concentración de los minerales magnéticos. El objetivo de este estudio es medir la SM en muestras superficiales y en muestras de perfil completo en suelos Calcisoles cultivados. La susceptibilidad magnética se midió en dos frecuencias diferentes para analizar su variación cuando la frecuencia del campo magnético aplicado cambia. Los valores de susceptibilidad magnética medida a baja frecuencia varían entre 16.0 y 57.6 $\times 10^{-8}$ m^3 kg^{-1}. Los coeficientes de correlación entre las medidas de SM de las muestras superficiales y las de perfil completo son altos (r = 0.94). Además, la susceptibilidad magnética se midió en campo para compararla con las medidas de laboratorio. Las medidas en campo varían entre 10.0 y 48.0 $\times 10^{-5}$ SI. Los coeficientes de correlación entre las medidas de SM en el laboratorio y las de campo son altos (r = 0.88). La metodología aplicada en este estudio que utiliza un susceptibilímetro y un sensor dual para las medidas de laboratorio y un sensor portátil para las medidas de campo ha sido de utilidad para realizar medidas rápidas y fiables de SM en el campo.

Introduction

Soil magnetic susceptibility is used in a variety of environmental research such as anthropogenic pollution monitoring (Schibler et al, 2002, Chaparro et al., 2007), pedogenic processes related with magnetic minerals forming (Torrent et al., 2010) and soil degradation (Sadiki, et al., 2009). Volumetric MS (κ) is the ratio of the magnetization to the applied magnetic field (Mullins, 1977). The κ is a dimensionless parameter (10^{-5} SI). The mass-specific susceptibility is $\chi = \kappa/\rho$, where ρ is the density and the unit is 10^{-8} m^3 kg^{-1}.

Mass-specific susceptibility is a magnetic concentration-dependent parameter, and their values vary according to the nature of materials, i.e. diamagnetic (~ $-6\cdot\times10^{-9}$ m^3 kg^{-1}), paramagnetic (~ 10^{-6} m^3 kg^{-1}), antiferromagnetic (~ $6\text{-}7\cdot\times10^{-7}$ m^3 kg^{-1}), and ferrimagnetic materials (~ $0.5\text{-}5.6\cdot\times10^{-3}$ m^3 kg^{-1}).

Matherials and Methods

The soils, topsoil and bulk cores, were sampled in a cultivated area in northeast Spain (42º25'38.52''N; 1º13'14.04''W). The topsoil samples were collected with a 4 cm diameter manual core driller at 5 cm depth. The bulk core profile samples were collected using a 7 cm diameter automatic core driller at 30 – 50 cm depth. A total of 290 samples were sampled, air dried and stored at 4º C prior to the analyses.

Magnetic susceptibility was measured in the laboratory with a Bartington MS2 meter linked to a MS2B dual frequency sensor (Bartington Instruments Ltd.). The sensor operates with an alternating current producing an alternating magnetic field (80 A/m, Bartington Instruments Ltd., 2000). The MS2B dual frequency sensor is used with 10 ml sample containers. The sensor can be operated at two different frequencies, at low frequency 0.465 kHz (LF) and at high frequency 4.65 kHz (HF). Samples were measured at each frequency for studying the frequency dependence of susceptibility. The low frequency is usually selected when single frequency measurements are needed. In this study three measures of MS were taken from each sample and the average was done. The frequency dependence of magnetic susceptibility is expressed as percentage (χ_{FD}%):

$$\chi_{FD}\% = [(\chi_{LF} - \chi_{HF})/\ \chi_{LF}] \times 100$$

Magnetic susceptibility was measured in situ in the field (κis) using the MS2D probe handle. This probe handle has a mean diameter of 185 mm and operates on the same principle of the MS2B dual frequency sensor.

In the field, the sensor is placed on the soil surface. Before taking a reading it is necessary to remove any vegetation to avoid rough surfaces. The depth of response is 50% at 15 mm and 10% at 60 mm. Magnetic susceptibility was measured on the 145 sites corresponding to the samples for the laboratory measurements. Three measurements were taken at each site and the average of these measurements was done.

Results

The results of χ measured on topsoil samples in the laboratory are presented in Table 1. The MS values at low frequency (χ_{LF}) varied from 13.9 to 46.0 $\times10^{-8}$ m^3 kg^{-1} and the values of MS at high frequency (χ_{HF}) ranged between 12.7 and 41.0 $\times10^{-8}$ m^3 kg^{-1}.

Table 1. Descriptive statistics of the magnetic susceptibility in the topsoil samples.

Magnetic susceptibility [10^{-8} m^3 kg^{-1}]	n	mean	st.dev	median	variance
χ_{LF}	145	29.2	7.7	28.8	59.1
χ_{HF}	145	26.1	6.7	25.7	45.2

In the bulk core samples χ_{LF} values varied from 16.0 to 57.6 $\times10^{-8}$ m^3 kg^{-1} and χ_{HF} values ranged between 14.7 and 53.3 $\times10^{-8}$ m^3 kg^{-1} (Table 2). As expected, the values of MS at low frequency are always higher than at high frequency (Dearing, 1994).

Table 2. Descriptive statistics of the magnetic susceptibility in the bulk core samples.

Magnetic susceptibility [10^{-8} m^3 kg^{-1}]	n	mean	st.dev	median	variance
χ_{LF}	145	33.9	9.1	34.6	83.1
χ_{HF}	145	30.5	8.1	30.8	66.1

The values of low frequency MS in the bulk core samples are significantly different ($p > 99$ %) and slightly higher than in the topsoil samples. Values of MS in topsoil and bulk core samples are highly correlated (Figure 1). Similarly, the values of high frequency MS in the bulk core samples are significantly different ($p > 99$ %) and slightly higher than in the topsoil samples and also high correlation coefficients were found between these two groups of samples (Figure 1).

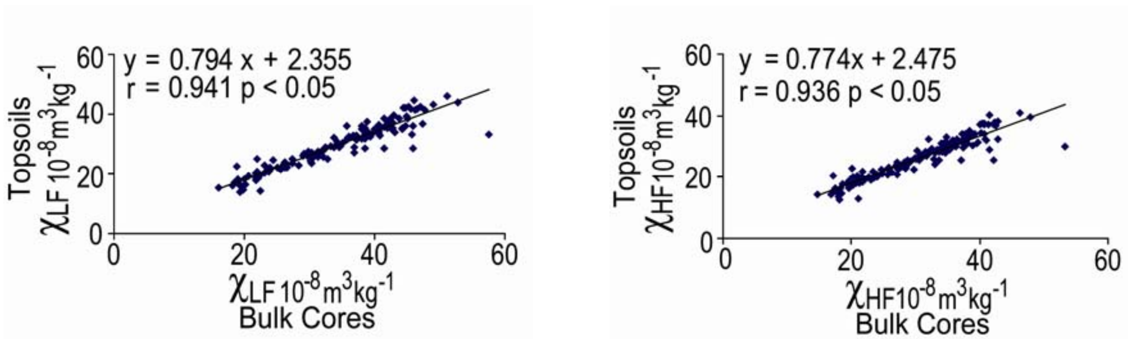

Figure 1. Linear regressions between low frequency and high frequency in bulk core and topsoil samples.

The MS measurements at two different frequencies are used to detect the presence of ultrafine <0.03μm superparamagnetic minerals (SP). When SP minerals are present in a soil sample the values of MS at high frequency are slightly lower than values of MS measured at low frequency. If there are not SP minerals the two measurements are identical (Dearing, 1994).
There is a slight difference between χ_{LF} and χ_{HF} values measured in the laboratory ($\Delta\chi = \chi_{LF} - \chi_{HF}$) which indicates the presence of SP minerals in the Calcisols (Table 3). The values of $\Delta\chi$ in the topsoil samples ranged between 0.9 and 5.0 $\times 10^{-8}$ m^3 kg^{-1} and the values of $\Delta\chi$ for the bulk core samples varied from 1.1 to 6.1 $\times 10^{-8}$ m^3 kg^{-1}.

Table 3. Descriptive statistics of $\Delta\chi$ values in topsoil and bulk core samples.

Magnetic susceptibility $[10^{-8} m^3 kg^{-1}]$	n	sample	mean	st.dev	median	variance
$\Delta\chi$	145	topsoils	3.2	1.0	3.2	1.0
$\Delta\chi$	145	bulk cores	3.4	1.1	3.5	1.1

Figure 2 relates the χ_{LF} and χ_{HF} values in the topsoil and bulk core samples. In both cases the correlation coefficients are highly significant. Similarly to what $\Delta\chi$ values suggest the slope different from 1 and the small and positive intercept in the regression reflects the presence of SP minerals.

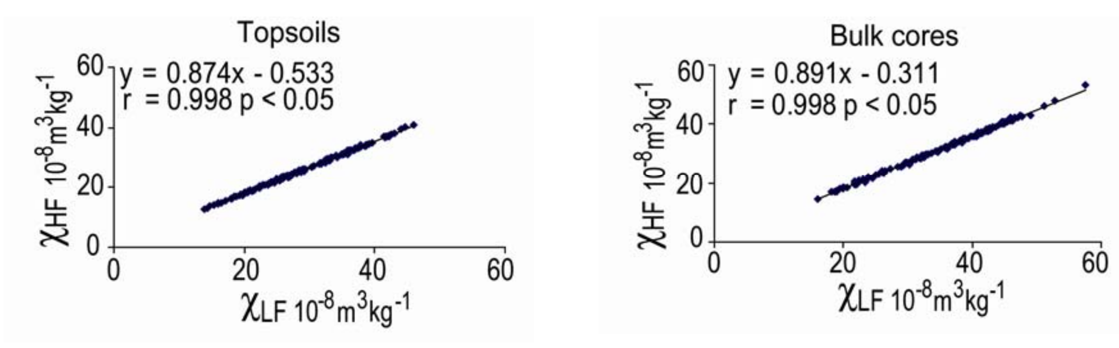

Figure 2. Linear regressions between low frequency and high frequency magnetic susceptibility in topsoil and bulk core samples.

Figure 3 compares the $\Delta\chi$ and χ_{LF} values in the topsoil and bulk core samples. An increase in magnetic susceptibility at low frequency appears to be related with the increase in the difference between the measures of MS at low and high frequency. According to Foster et al. (1994) such linear correlation indicates that with increasing magnitude the susceptibility is more controlled by the contribution from the fine pedogenic magnetic fraction.

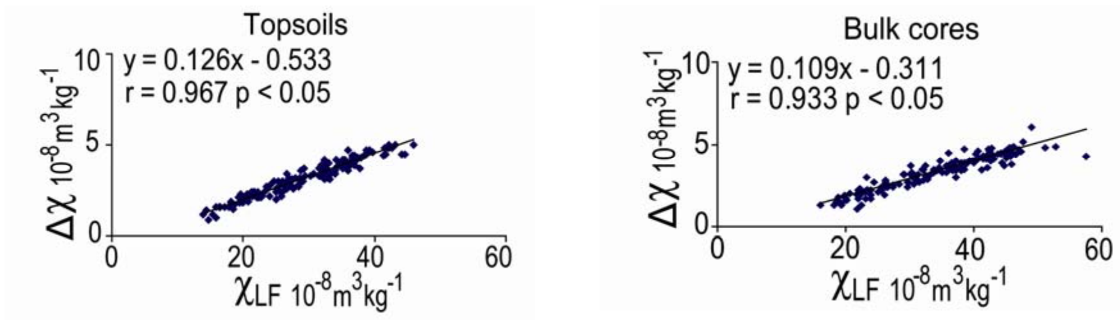

Figure 3. Linear regressions between $\Delta\chi$ values and low frequency magnetic susceptibility in topsoil and bulk core samples.

The variations in the frequency dependence (χ_{FD}%) are commonly due to the variable content of superparamagnetic grains (Forster et al., 1994). The χ_{FD}% values in the topsoil samples varied from 6.1 to 13.1 % and in the bulk core samples ranged between 5.0 and 13.3 % (Table 4).

Table 4. Descriptive statistics of the frequency dependence of magnetic susceptibility values.

Frequency dependence %	n	sample	mean	st.dev	median	variance
χ_{FD}%	145	topsoils	10.6	1.1	10.8	1.3
χ_{FD}%	145	bulk cores	9.9	1.3	10.0	1.6

According to Dearing (1994) it is possible to obtain semi-quantitative estimates by relating the percentage of the frequency dependence MS and the concentration of SP grains. Dearing establishes that the values of χ_{FD} ranging between 2.0 and 10.0% are considered as medium values. This range is interpreted as an admixture of SP and coarser non-SP grains, or < 0.005 μm SP grains. The values of χ_{FD} ranging between 10 and 14% are considered high values. Samples within this range can be interpreted as soils where virtually all iron components are SP grains (>75%).
In the topsoils the percentage of soil samples with high values of χ_{FD} (73 %) was significantly higher than that of medium χ_{FD} values (27 %) (Table 5). The Anova test indicates that means of high and medium values were significantly different.

Table 5. Descriptive statistics of the ranges of frequency dependence in topsoils according to Dearing (1994).

χ_{FD}	n	mean	st.dev	median	variance	min	max
Medium values (2-10 %)	39	9.2	0.9	9.4	0.8	6.1	10.0
High values (10-14 %)	106	11.2	0.7	11.1	0.4	10.0	13.1

In the bulk cores around 51 % of the samples are within the range of 2 to 10 % whereas the remaining 49 % are included in the range of 10 to 14 % (Table 6). The Anova test indicates that means of high and medium values are also significantly different.

Table 6. Descriptive statistics of the ranges of frequency dependence in bulk cores according to Dearing (1994).

χ_{FD}	n	mean	st.dev	median	variance	min	max
Medium values (2-10 %)	74	8.9	1.0	9.3	1.0	5.0	10.0
High values (10-14 %)	71	10.8	0.7	10.6	0.5	10.0	13.3

The means of the medium values of χ_{FD} are not significantly different in the topsoils and the bulk cores but means of high values of χ_{FD} are higher and significantly different in the topsoils than in bulk core samples (Figure 4) suggesting that topsoils have higher concentrations of SP minerals than bulk core samples.

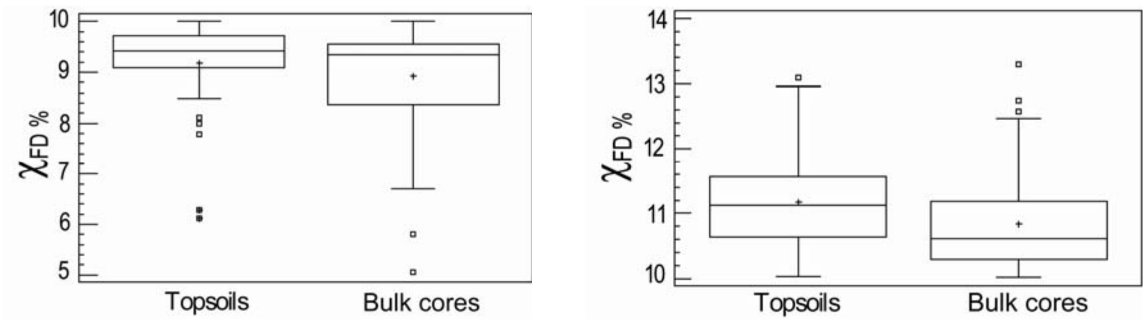

Figure 4. Box-plots of $\chi_{FD\,\%}$ in topsoil and bulk core samples (Medium values: 2 - 10%, high values: 10.0 - 14.0%).

Results of magnetic susceptibility in the field were corrected for smooth surfaces (Bartington Instruments Ltd., 2000). In addition, the values of low frequency susceptibility measured in the laboratory for topsoil samples were also expressed as volumetric values (κ) (Lecoanet et al. 1999) (Table 7). The linear regression between κ and κis showed high and significant correlation (Figure 5).

Table 7. Descriptive statistics of magnetic susceptibility in topsoils and in the field.

Magnetic susceptibility [10^{-5} SI]	n	sample	mean	st.dev	median	variance	min	max
κ	145	topsoils	40.4	11.8	38.9	139.6	18.7	65.9
κis	145	field	32.5	10.7	32.7	113.7	13.3	64.0

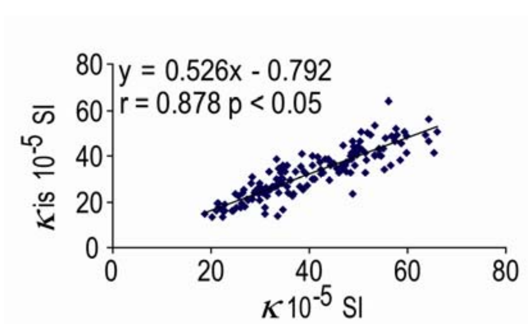

Figure 5. Linear regression between κ measured in the field and in the laboratory.

Conclusions

The measures of magnetic susceptibility are slightly and significantly higher in the bulk cores than in the topsoil samples and their values are highly correlated. Iron components in topsoil layers contribute relatively more to bulk MS than the bulk profile.
The difference between the values of high and low frequency MS indicates the presence of SP minerals in the cultivated Calcisols. The values of frequency dependence susceptibility range between 6.12 and 13.09% in the topsoil and 5-13.30% in the bulk core samples which are medium to high values of frequency dependence. The percentage of topsoil samples included within the range of frequency dependence is higher (74%) than in the bulk core samples (51%) suggesting a relatively high content of superparamagnetic minerals in topsoils. The field measurements of κis correlated well with the measurements in the laboratory (κ), therefore it is possible to use the MS2D probe for a fast screening on the contents of magnetic minerals in cultivated soils.

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