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Pedogenic effect and the impact of erosion factors on topsoil magnetic susceptibility enhancement

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Abstract

The main aims of this study were to i) investigate the impact of erosion factors including land use, slope position, and lithology on magnetic susceptibility (MS) of soil, and ii) detecting the pedogenic effect on MS enhancement using simple methods, including median absolute deviation (MAD), topsoil-subsoil difference methods, MS magnitude and Dearing's model. Soil cores were sampled along five slope positions in two transects selected in forested and cultivated lands in a watershed located in north of Morocco. The results showed higher values of MS in the upperslopes in forested land due to soil stability, and lower ones in middleslopes and lowerslopes due to soil erosion. However, MS is higher in cultivated land in middleslopes due to soil deposition and it is lower in the upperslopes due to erosion. The results confirmed the pedogenic effect on MS. This is confirmed by i) enhanced Forster factor and low values of magnetic susceptibility background, ii) dominance of ultrafine super-paramagnetic/stable single-domain ferrimagnetic grains in almost all studied soils, and iii) absence of anomaly in MAD data set and pertinence of the results of MAD and topsoil-subsoil difference methods.

Keywords: Land use; Slope position; Magnetic susceptibility; Pedogenesis; MAD

1. Introduction

Soil conservation is an important challenge for sustainable agricultural activities. The stability of soil and its degradation are narrowly linked to the type of magnetic particles and their concentration in the soil. Lithogenic, pedogenic, and anthropogenic origins are the principal sources of magnetic minerals present in soils [Faleh *et al.*, 2003; Boyko *et al.*, 2004; Hanesch and Scholger, 2005; Fialova *et al.*, 2005; Hassouni and Bouhlassa, 2006; Yang *et al.*, 2007; Sadiki *et al.*, 2009; Bouhlassa and Choua, 2009; Grison *et al.*, 2017; Bouhsane and Bouhlassa, 2018]. Magnetic susceptibility (MS) depends principally on the concentration of grains of magnetic minerals, their mineralogy, and their size. In addition to diamagnetic and paramagnetic, the most important are ferrimagnetic soil minerals, e.g., magnetite or maghemite [Hendrickx *et al.*, 2005; Jordanova *et al.*, 2017]. These later are characterized by high magnetic susceptibility values even at low concentrations, and then control the magnetic properties of soil. Rocks and sediments have a wide range of magnetic susceptibility values due to their different kinds and amount of magnetic components [Karimi *et al.*, 2017]. In recent years, soil MS has developed as a rapid and inexpensive technique to analyze several soil sites and to monitor temporal changes in their environment [Petrovsky and Ellwood, 1999; Lu *et al.*, 2008]. MS can be used as a tracing tool for soil redistribution; it is considered as a reliable, fast, and economical method for measuring magnetic indexes in comparison with conventional approaches [Sadiki *et al.*, 2009; Liu *et al.*, 2015; Jordanova, 2017; Yu *et al.*, 2017; 2019; Ayoubi *et al.*, 2020]. It was employed as a tracer to estimate soil loss in a watershed located in central of Morocco, by its exploitation in developing models such as Tillage Homogenization (T-H) allowing to estimate the loss of depth after each erosion [Royall, 2004; Bouhlassa and Bouhsane, 2019; 2020; 2023]. The study established by Bouhlassa and Bouhsane [2023] confirm that MS could be used to trace and monitor soil erosion and deposition for different slope positions along cultivated and forested transects. Higher or lower values of magnetic susceptibility of soil also depends on its distribution along the slope. χ_{lf} is often lower in the upperslopes and middleslopes and higher in the lowerslopes in cultivated transects; the upperslopes and middleslopes represent the soil loss site, whereas the lower slopes are considered as the deposition site [Mokhtari Karchegani *et al.*, 2011; Yu *et al.*, 2017; 2019; Bouhlassa and Bouhsane, 2023]. The background MS in undisturbed lands is generally uniform as such lands are characterized by the same parent materials and pedogenetic processes [Jordanova *et al.*, 2014]. The magnetic minerals in disturbed lands move along with the soil redistribution [Ding *et al.*, 2020]. The MS decreases at erosion sites and increases at deposition sites [Bouhlassa and Bouhsane., 2023]. Magnetic susceptibility could be used as an indicator for identifying polluted soils and to detect the degree of anthropogenic origin at large scale on the basis of the paramagnetic/diamagnetic versus ferromagnetic/ferrimagnetic contribution [Meena *et al.*, 2011]; it offers a rapid and cheap method to identify the pollution of soils by industrial contaminants that contribute to the soil magnetic susceptibility enhancement [Hay *et al.*, 1997; Wang *et al.*, 2000; Magiera *et al.*, 2000; 2002; Hanesh and Scholger, 2002; Ju *et al.*, 2004; Lu *et al.*, 2005; El Baghdadi *et al.*, 2011; Ayoubi *et al.*, 2014]. Many authors have reported that magnetic particles deposited in soils close to urban and industrial areas have higher magnetic susceptibility values and are generally characterized by a high magnetic signal [Wang *et al.*, 2000; Lu *et al.*, 2006; Kanu *et al.*, 2013]. Anthropogenic particles are usually found in the topsoil limited at 5 cm depth in undisturbed soils and in the plowed layer in cultivated lands [Hanesch and Scholger, 2002]. Many studies have shown that magnetic susceptibility enhancement in topsoil is caused by firing process [Le Borgne, 1960], pedological processes [Vadiunina and Babanin, 1972], lithologic contributions [Szuszkiewicz *et al.*, 2016; 2021; de Mello *et al.*, 2020; Grison *et al.*, 2021], climate effect [Tite and Linington, 1975; Magiera *et al.*, 2006]. The formation of secondary ferrimagnetic minerals during pedogenesis in the top layer of soil leads to higher magnetic susceptibility values, this enhancement could be used to distinguish topsoil from subsoil [Bouhlassa and Choua, 2009; Yu *et al.*, 2017; Bouhsane and Bouhlassa, 2018]. Maher *et al.* [2003] confirmed also that the topsoil magnetic susceptibility values are higher than those in the deeper soil horizons, which were attributed to the formation of pedogenic ferrimagnetic particles in the topsoil. The pedogenic magnetic fraction including ultrafine super-paramagnetic/stable single-domain (SP/SSD) ferrimagnetic grains is produced by weathering of the parent material and/or biological fermentation processes [Maher, 1986; Maher and Taylor, 1988; Dearing *et al.*, 1996b; Grison *et al.*, 2017]. Magnetic minerals produced during pedogenesis are the main contributors to the magnetic susceptibility enhancement, especially for soils developed on weakly magnetic substrates and preserved from pollution [Bouhsane and Bouhlassa, 2018]. The detection of the SP/SSD pedogenic magnetic fraction is often difficult for soils derived from strongly magnetic parent materials, where the SP/SSD signal is masked by lithological signals [Lu *et al.*, 2008; Jordanova *et al.*, 2016; Grison *et al.*, 2017; Szuszkiewicz *et al.*, 2021]. In this case, the effect of pedogenesis may be magnetically underestimated [Grison *et al.*, 2015; Ouyang *et al.*, 2015]. The coarser MD is produced anthropogenically in industrial areas, however finer SSD and SP grains are not necessarily produced due to the pollution [Meena *et al.*, 2011].

The principal aim of this study was to analyze the land use, slope position, and lithology effects on the magnetic susceptibility variation of soils sampled in cultivated and forested transects, and to establish the variation of inventory related to those factors. The secondary aim was to build and validate subsequently the determining method of pedogenic effect on the soil magnetic susceptibility enhancement.

2. Materials and methods

2.1 Description of the study site

The Mezguida catchment covers an area of 240 km^2; it constitutes a subcatchment of the Bouregreg basin, and is located at 33°4′48″ – 32°55′12″ N and 6°28′12″ – 6°13′12″ W Northeast in Morocco (Figure 1-a) [Bouhlassa and Bouhsane, 2023]. The study area is characterized by a Mediterranean climate; the temperature varies between 10 °C to 11 °C for the coldest month, and between 25° to 27° for the warmest one [Bouhlassa and Bouhsane, 2023]. The annual precipitations are about 396 mm/yr. The Mezguida watershed has a variable vegetation dominated by cultivated land. Forested areas, pure green oak, and matorrals represent a small part of the catchment (Figure 1-b). Schist, marl, limestone, and sandstone constitute the predominant lithologies in the watershed with the minor and distinct intrusion of red argil in some areas (Figure 1-c).

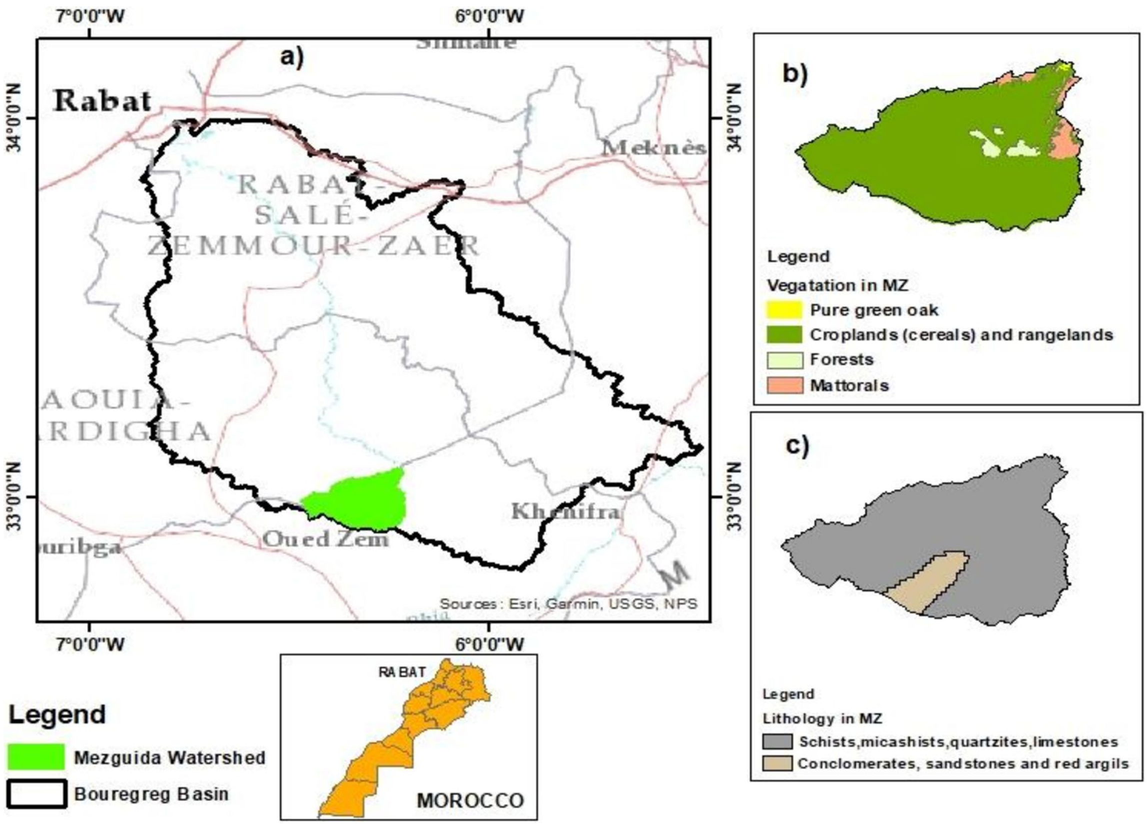

Figure 1. Geographical map of the study site.

2.2 Soil sampling and laboratory treatment

Two transects (MZ17) and (MZ13) were selected and sampled in forested and cultivated lands, respectively. MZ17 transect with 250 m in length starts at an altitude of 1000 m at point, 32°55′08 N, 06°18′55 W, and MZ13 with 200 m in length at an altitude of 1003 m at point, 32°55′30 N, 6°17′43 W. 17 soil cores were collected and chosen along MZ17 transect, and 13 soil cores in MZ13 transect in five slope positions including summit (SU), shoulder (SH), backslope (BS), footslope (FS), and toeslope (TS) (Table 1; Figure 2). The sampled soils of these two transects were developed on calcareous rock. Soil cores that may reach 30 cm in length depending on soil depth were collected at each slope position along the two transects, using a hand auger having 6 cm in diameter and 50 cm in length. Each core was divided into samples with layers of 5 cm, then these samples were stored in plastic bags. In total 109 soil samples collected at the 30 sampling sites. Each sample was oven-dried at 40 °C for eight hours and then sieved through a 1 mm plastic sieve.

Slope position MZ	Slope [°]	
	Cultivated transect (MZ13)	Forested transect (MZ17)
Summit	5	45
Shoulder	20	20
Backslope	10-30	20
Footslope	35	8
Toeslope	5	5

Table 1. Slope gradient (°) of different sampling sites.

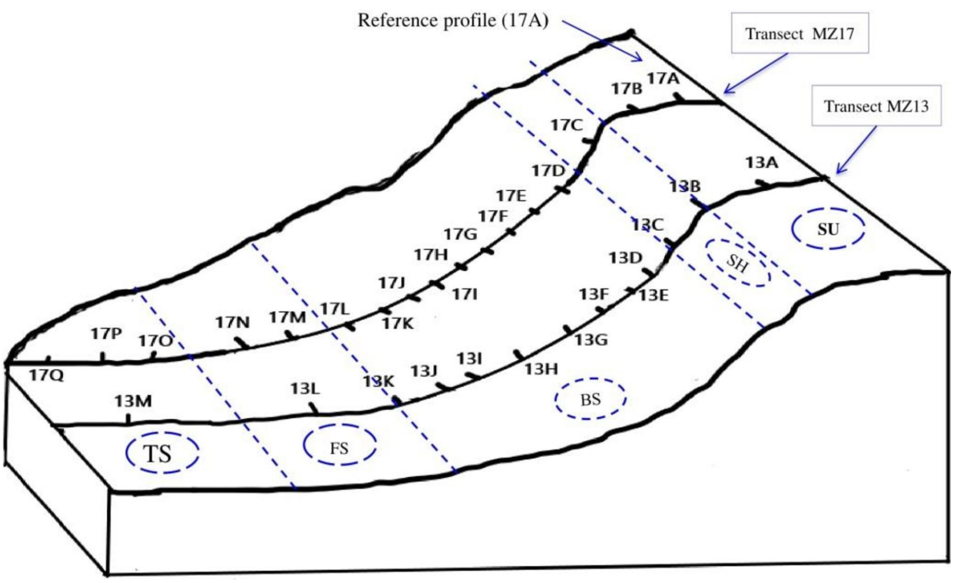

Figure 2. Simplified representation of geomorphological slopes along the MZ17 and MZ13 735 transects. (SU: summit; SH: shoulder; BS: backslope; FS: footslope; and TS: toeslope) 736 [Bouhlassa and Bouhsane, 2023].

2.3 Magnetic measurements

Magnetic measurements of our samples were performed in the laboratory of Radiochemistry and Nuclear Chemistry of Faculty of Sciences, Rabat, Morocco. Samples in 10 cm^3 cylindrical boxes were submitted to magnetic susceptibility measurements using a Bartington magnetic susceptibility meter (MS2) and a dual-frequency sensor (MS2B) (Bartington Instruments Ltd., Witney, Oxon, UK). Mass specific magnetic susceptibility (χ) is defined as the ratio between the produced magnetization and the applied magnetic field, it is considered one of the easiest to measure magnetic parameters of soil [Mullins, 1977; Thompson and Oldfield, 1986; Moukhchane *et al.*, 1998; Evans and Heller, 2003]. MS is either expressed per unit volume (volume-specific susceptibility, κ) or per unit mass (mass-specific susceptibility, χ). The ratio of soil mass in the cylindrical box to the volume of the container leads to the bulk density (ρ) of each sample. The calculation of the mass-specific magnetic susceptibility value helps in comparing samples with different density values from different soil horizons. The volume-specific magnetic susceptibility (κ) was measured at two different frequencies: low frequency (0.47 kHz; κ_{lf}) and high frequency (4.7 kHz; κ_{hf}). Mass-specific low-frequency magnetic susceptibility (χ_{lf}) is defined by the following equation:

$$\chi_{lf} = \frac{\kappa_{lf}}{\rho} \quad [10^{-8}\ m^3 kg^{-1}]$$

The frequency dependent susceptibility is either expressed as a percentage loss of susceptibility (χ_{fd}%), this later depends on the nature and size of the magnetic grains [Dearing, 1994]. It is expressed by the following equation:

$$\chi_{fd}\ \% = \frac{\chi_{lf} - \chi_{hf}}{\chi_{lf}} \times 100\ [\%]$$

or as a relative loss of susceptibility expressed by the following expression:

$$\chi_{fd} = \chi_{lf} - \chi_{hf} \quad [10^{-8}\ m^3 kg^{-1}]$$

where χ_{hf} is the mass-specific high-frequency magnetic susceptibility.

The parameter F_c% introduced by Forster *et al.* [1994] offers the possibility to identify pedogenesis and discriminate the anthropogenic fallout of magnetic particles, it is defined as follows [Faleh *et al.*, 2003]:

$$Fc\ \% = \frac{\chi_{lf} - \chi_{hf}}{\chi_{lf} - \chi_{b}} \times 100\ [\%]$$

where χ_b is the magnetic susceptibility background associated to paramagnetic and coarse ferrimagnetic grains, it is independent of the inherited magnetic minerals and it expresses the magnitude of pedogenesis [Faleh *et al.*, 2003]. The χ_b value is obtained by the intersection of the χ_{lf} axis, where χ_{fd} is zero.

2.4 Data analysis

Statistical analysis was performed on the data using XLSTAT [Addinsoft, 2018] to determine parametric statistics such as the mean, minimum, and maximum values, coefficient of variation (CV), and standard deviation (SD) [Wendroth *et al.*, 1997]. These descriptive statistics were used to define the degree of dispersion and deviation of the data. The coefficient of variation (CV) is related to the variability in magnetic susceptibility and soil properties.

2.5 Detection of anomalous values of magnetic susceptibility

2.5.1 Topsoil-subsoil difference method

The fallout anthropogenic magnetic particles accumulate in the upper layer of the soil, from where they contribute to an increase of magnetic susceptibility of topsoil. Generally, this layer is limited to the uppermost 5 cm [Kapička *et al.*, 2001]. Consequently, a higher value of magnetic susceptibility in the topsoil relating to the subsoil is attributed to an anthropogenic anomaly. Hanesh *et al.* [2002] suggest that if the susceptibility difference exceeds $20 \times 10^{-8}\ m^3kg^{-1}$, it is anthropogenic anomaly and pedogenic anomaly if it is below $20 \times 10^{-8}\ m^3kg^{-1}$.

The determination of magnetic susceptibility of topsoil and subsoil in cultivated and forested lands is based on the following definitions:

$$\chi_{lf}(\text{topsoil})(\text{forested}) = \chi_{lf}(0-5\text{ cm}); \quad \chi_{lf}(\text{subsoil})(\text{forested}) = \chi_{lf}(20-25\text{ cm})$$

$$\chi_{lf}(\text{topsoil})(\text{cultivated}) = \frac{\sum \chi_{lf}(0-20\text{ cm})}{4}; \quad \chi_{lf}(\text{subsoil})(\text{fore\ \ sted}) = \chi_{lf}(>20\text{ cm})$$

2.5.2 Median absolute deviation method

The median absolute deviation (MAD) is defined as the median of the absolute deviation from the data's median [Tukey, 1977]. The median value $\pm$ 2MAD defines a barrier that separates outliers and extremes from a population. Although the MAD method is considered to define more anomalous or outlier values than the topsoil-subsoil difference, it is elaborated for the detection of magnetic pollution [Hanesh *et al.*, 2007]. If the average magnetic susceptibility of the core falls within the range of $\chi_{lf}(\text{Median}) \pm 2\text{MAD}$, then the improvement of the magnetic susceptibility in the samples of the studied soils is related to the pedogenic effect and it is no longer an anthropogenic effect.

Where:

$$\chi_{lf}(\text{Minimum}) = \chi_{lf}(\text{Median}) - 2\chi_{lf}(\text{MAD})$$

$$\chi_{lf}(\text{Maximum}) = \chi_{lf}(\text{Median}) + 2\chi_{lf}(\text{MAD})$$

2.6 Theoretical model of Dearing [1999a]

Dearing [1999] suggests a theoretical model based on the classification of magnetic samples depending on their χ_{fd}% values, he classifies the samples into four classes:

- $\chi_{fd}\% < 2\%$: SP concentration < 10% and virtually there is no SP grains, presence of MD grains.
- $2\% < \chi_{fd}\% < 10\%$: there is a mixture of SP and coarser non-SP grains (SSD).
- $10\% < \chi_{fd}\% < 14\%$: SP concentration > 75% and nearly all grains are SP.
- $\chi_{fd}\% > 14\%$: which indicates rare values, inexact measurements, weak samples, or contamination during measurement

3. Results and discussions

3.1 Statistical characteristics of soil magnetic properties (χ_{lf}, χ_{fd}%)

The magnetic susceptibility values mainly reflect the content of ferrimagnetic minerals; it determines the total magnetism of the sample [Mullins *et al.*, 1977; Yu *et al.*, 2017; 2019]. Thus, χ_{lf} variation in soil profile can indicate the transformation in situ of oxy-hydroxide of iron and the formation of secondary ferrimagnetic minerals, which is closely related to soil development processes and geographic environment. Table 2 gives the statistical data of magnetic susceptibilities (χ_{lf}, χ_{fd}%) for cores collected in forested (MZ17 transect) and cultivated (MZ13 transect) lands. The value of mass specific-magnetic susceptibility χ_{lf} ranges between 4×10^{-8} m^{3}kg^{-1} to 215×10^{-8} m^{3}kg^{-1} with a mean value of 84×10^{-8} m^{3}kg^{-1} for the cultivated land, and it varies between 0.6×10^{-8} m^{3}kg^{-1} and 231×10^{-8} m^{3}kg^{-1}, with a mean of 73.5×10^{-8} m^{3}kg^{-1} for the forested land. Frequency-dependent magnetic susceptibility percentage χ_{fd}% values varied between 0% and 10.7%, with an average of 7.6% for the cultivated land, and between 0% and 13.2% with a mean value of 8% for the forested land. Figure 3-a-b gives the box plot for χ_{lf} and χ_{fd}% showing that the two means of χ_{lf} and χ_{fd}% in the MZ17 and MZ13 transects are close, and their values vary approximately in the same range of magnitude. This indicates that the ferrimagnetic minerals and their amounts in soil from the two types of land use are closely equivalent on average. However, significant differences could be found in the maximum, coefficient of variation and median of χ_{lf} in the two land uses. These results suggest that χ_{lf} values could be linked to land use.

Land use in MZ	Variable	Depth [cm]	N Total	Min	Mean	S.D	C.V%	Max	Median
Forested Transect MZ17	χ_{lf}	0-25	102	0.6	71.3	53.1	74	231.1	63
	χ_{fd}%	0-25	102	0	8	2.1	24	13.2	8.4
Cultivated Transect MZ13	χ_{lf}	0-25	78	4	83.4	48.7	57	215	87
	χ_{fd}%	0-25	78	0	7.6	2.5	32	10.7	8
χ_{lf} in 10^{-8} m^{3}kg^{-1}, χ_{fd} in %, S.D: is the deviation and C.V is the coefficient of variation.									

Table 2. Descriptive statistics for χ_{lf} (10^{-8} m^{3}kg^{-1}) and χ_{fd} (%) in cultivated and forested lands. (χ_{lf}: mass-specific low-frequency magnetic susceptibility; χ_{fd}%: Frequency-dependent magnetic susceptibility percentage).

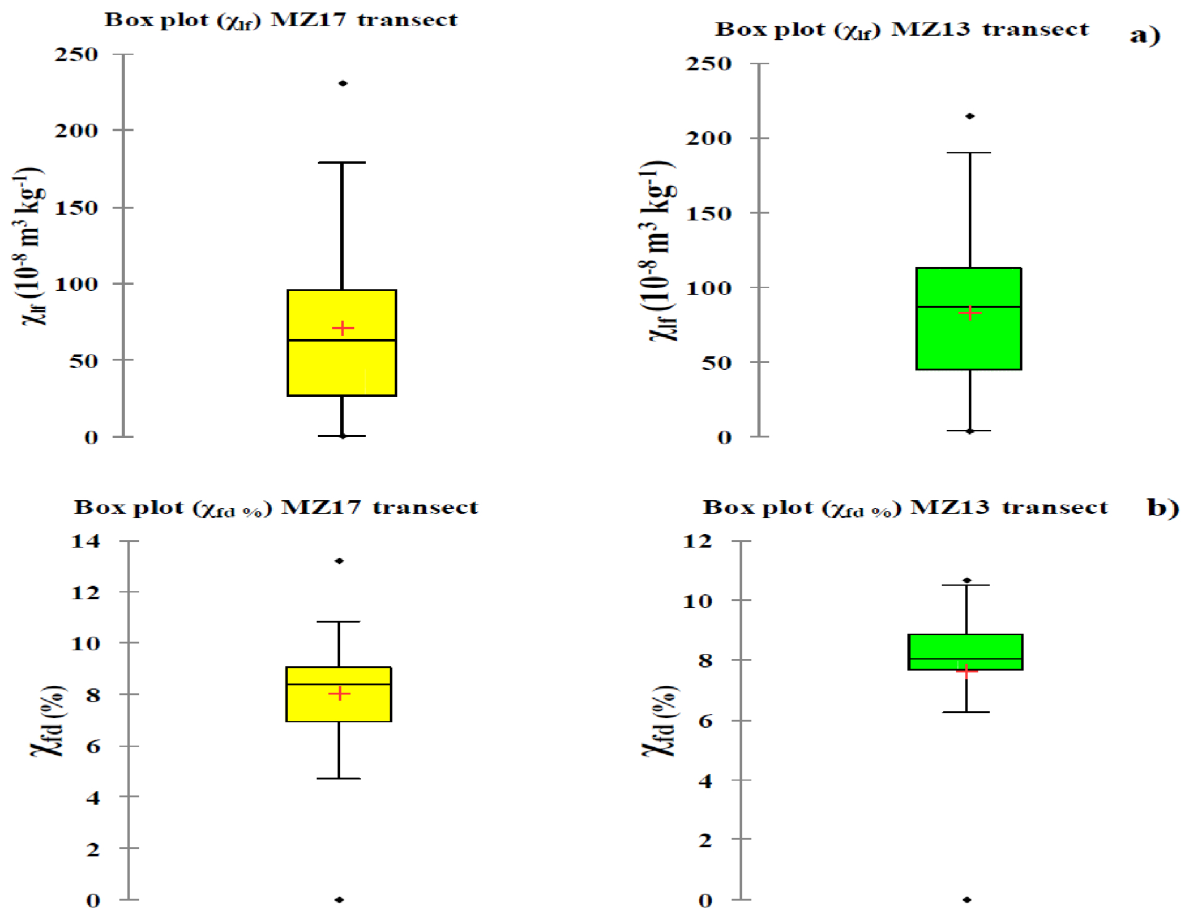

Figure 3. Box plot showing a statistical data of magnetic susceptibility (χlf, χfd%) in the MZ13 and MZ17 transects. (χlf: mass-specific low-frequency magnetic susceptibility; χfd%: Frequency-dependent magnetic susceptibility percentage).

3.2 Impact of land use, slope position, and lithology on the magnetic susceptibility of soil in the MZ17 and MZ13 transects

3.2.1 Land use and slope position effects on the soil magnetic susceptibility χ_{lf}

Figure 4 shows the variation of average values of magnetic susceptibility of soil along forested and cultivated transects in five slope positions including summit (SU), shoulder (SH), backslope (BS), footslope (FS), and toeslope (TS). In the forested land (MZ17 transect), the mean of magnetic susceptibility at the summit, shoulder, backslope, footslope, and toeslope are 138×10^{-8} m^3kg^{-1}, 21×10^{-8} m^3kg^{-1}, 73.5×10^{-8} m^3kg^{-1}, 72×10^{-8} m^3kg^{-1}, and 31.5×10^{-8} m^3kg^{-1} respectively. These results show that the magnetic susceptibility values varied with the slope position in the forested transect (MZ17) in the following order: $\chi_{lf}(SU) > \chi_{lf}(BS) > \chi_{lf}(FS) > \chi_{lf}(TS) > \chi_{lf}(SH)$. The mean values of χ_{lf} in the summit, backslope, and footslope seem higher compared to those of the shoulder and toeslope positions. These later are easily affected by erosion and are considered as an unstable positions in comparison to the other positions in the forested transect. The summit position located in the upper part of the forested transect is characterized by a stability due to the high vegetation cover protecting soils against erosion. The stability of soils in such position favors pedogenic processes conducing to the enhanced magnetic susceptibility. The lower value of magnetic susceptibility in the shoulder position is due to erosion of fine particles from this position to be deposited in the backslope and footslope.

Mokhtari Karchegani *et al.* [2011] reported that magnetic susceptibility of soil in the shoulder in the forested transect is lower compared to the values recorded in the upperslopes even under a natural protected environment, suggesting that this position was in unstable conditions and was affected by erosion. The mean value of magnetic susceptibility in the toeslope is lower compared to backslope and footslope, it's also easily affected by erosion. But the highest rates of soil erosion is occurred in the SH position, and the lowest one is produced in TS position [Sac *et al.*, 2008; Abbaszadeh Afshar *et al.*, 2010]. This is confirmed by the lower values of SH in comparison to the TS position. An opposed behavior is observed in the cultivated transect (MZ13) where the averages of magnetic susceptibility of sampled cores in the summit (SU), shoulder (SH), backslope (BS), footslope (FS), and toeslope (TS)

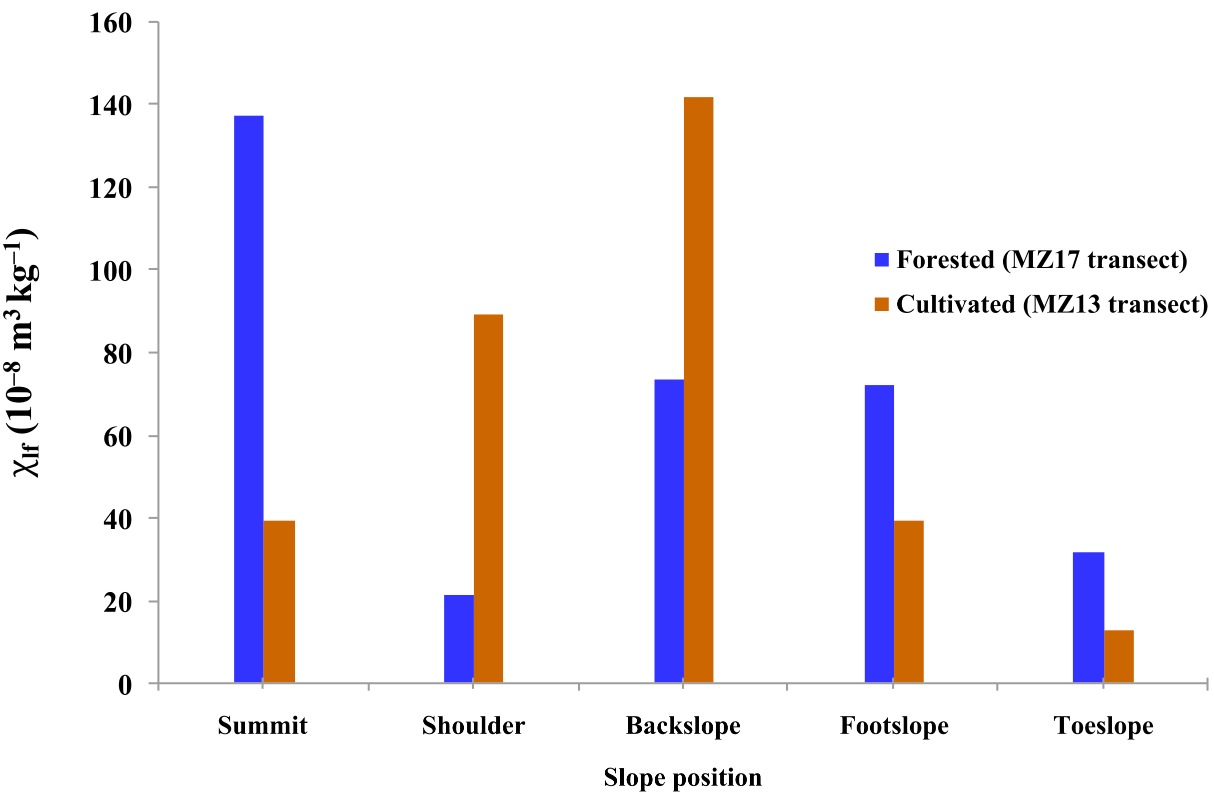

Figure 4. Variation of the mean of magnetic susceptibility at different slope positions in forested (MZ17) and cultivated lands (MZ13). (χlf: mass-specific low-frequency magnetic susceptibility).

are 39.2×10^{-8} m^{3}kg^{-1}, 89.4×10^{-8} m^{3}kg^{-1}, 142×10^{-8} m^{3}kg^{-1}, 39×10^{-8} m^{3}kg^{-1} and 12.6×10^{-8} m^{3}kg^{-1} respectively. These results indicate that the magnetic susceptibility of cultivated transect varied with slope position as follows: $\chi_{lf}(BS) > \chi_{lf}(SH) > \chi_{lf}(SU) > \chi_{lf}(FS) > \chi_{lf}(TS)$ (Figure 4). The mean of χ_{lf} in the summit position seems globally low resulting from possible high erosion in this position. Even if this position is known as the stable position, but in the selected transect after cultivation activities, a net erosion has been occurred [Ahmadi, 2011]. However, the means of magnetic susceptibility in the shoulder and backslope are higher compared to the magnetic susceptibility measured in the summit position in the cultivated transect. This could be due to the depositional processes in these positions and pedogenic processes caused by water received from the summit. It could be even due to the soil homogenization that can increases MS in such land after agricultural activities and such processes.

Those process could explain the pattern of χ_{lf} in this part of the transect, but more probably the contribution of magnetic particles of soil deposited in the shoulder and backslope positions would be the pertinent process responsible in the χ_{lf} increase. The variation of χ_{fd}% values along the transect discussed below in paragraph 3.3.3 will support this finding. In the footslope and toeslope, the average values of χ_{lf} are low indicating the high and severe erosion that could be occurred in these slope positions. In the context of this study, Bouhsane and Bouhlassa [2018] have obtained in their study carried out in Ait Azzouz watershed characterized by a Mediterranean climate (located near to Mezguida watershed) that the mean magnetic susceptibility decreases according the following order: χ_{lf} cultivated land $< \chi_{lf}$ pastures land $< \chi_{lf}$ forested land; they confirmed that land use change constitutes the main factor influencing the physical stability of the soils and the geochemical and biochemical conditions of pedogenic ferrimagnetic and antiferromagnetic minerals evolution and development.

According to the above discussion, we summarize that higher values of magnetic susceptibility in the forested transect could be attributed generally either to the stronger pedogenic processes in the top layers, especially in the summit position, or to the soil deposition occurred in the backslope and footslope. However, lower values are linked to erosion produced especially in the shoulder and toeslope positions. Higher values of magnetic susceptibility in the cultivated transect in the middlslope are due to soil deposition, while the lower ones to erosion especially in the upperslopes and lowerslopes. The above discussion shows how the land use and the slope position affect the magnetic susceptibility of soils variation investigated in this study.

3.2.2 Lithogenic effect on soil magnetic susceptibility

Figures 5 and 6 show the variation of the mean of soil magnetic susceptibility with lithology in each profile in different land uses. Forested soils are typically developed on schistose sandstone, limestone, red argil, marl, and red conglomerate but with schist and sand as a dominant composition (Figure 5). Higher values of mean magnetic susceptibility are found especially in the soil profiles such as 17A (185.1×10^{-8} m^{3}kg^{-1}), 17B (89.5×10^{-8} m^{3}kg^{-1}), 17G (140.5×10^{-8} m^{3}kg^{-1}), 17H (125.1×10^{-8} m^{3}kg^{-1}), and 17M (124.1×10^{-8} m^{3}kg^{-1}). These profiles are developed on limestone, marl, schistose sandstone and sand respectively. In the cultivated transect, soils on schist and some profiles on sand have higher values of magnetic susceptibility. χ_{lf} on average is about 182.3×10^{-8} m^{3}kg^{-1} for 13C, 124.3×10^{-8} m^{3}kg^{-1} for 13J, 110.6×10^{-8} m^{3}kg^{-1} for 13K, and about of 89.3×10^{-8} m^{3}kg^{-1} for 13B (Figure 6).

These profiles are generally located in the shoulder and backslope positions representing the deposition sites of magnetic particles eroded from the upperslopes, hence the higher values of soil magnetic susceptibility recorded in these soil profiles. Magnetic susceptibility values for 13A, 13L, and 13M (developed on limestone and sand) located in the summit, footslope, and toeslope positions in the cultivated transect are 39.2×10^{-8} m^{3}kg^{-1}, 39×10^{-8} m^{3}kg^{-1}, and 12×10^{-8} m^{3}kg^{-1} respectively. These values are low compared to those of the other cores, it could be noticed that the presence of limestone and sand results in a dilution of magnetic response in these cores. Diamagnetic minerals including carbonate and gypsum dilute the concentration of ferromagnetic minerals in the soil [Boyko *et al.*, 2004]. As it is indicated in the precedent discussion, the summit and footslope positions in cultivated transect are easily affected by erosion processes, contributing to the transport of magnetic particles to the lower slopes; hence, the decrease of magnetic susceptibility in the cores sampled in the SU, FS positions. The substrates of soils in cultivated and forested transects are generally characterized by lower magnetic susceptibilities, due to their low content of magnetic minerals and the diamagnetic behavior of limestone and marl [Moukhchane *et al.*, 1998; Sadiki *et al.*, 2009]. According to the study performed by Sadiki *et al.* [2009] in the Msoun basin located in the Rif of Morocco, magnetic susceptibility recorded on marl was about 13×10^{-8} m^{3}kg^{-1}. In Bou Mellal subcachement located in the west of the Bouregreg basin, χ_{lf} was lower than 10^{-18} m^{3}kg^{-1} for soils developed on schist substrate and between 2.8×10^{-18} m^{3}kg^{-1}

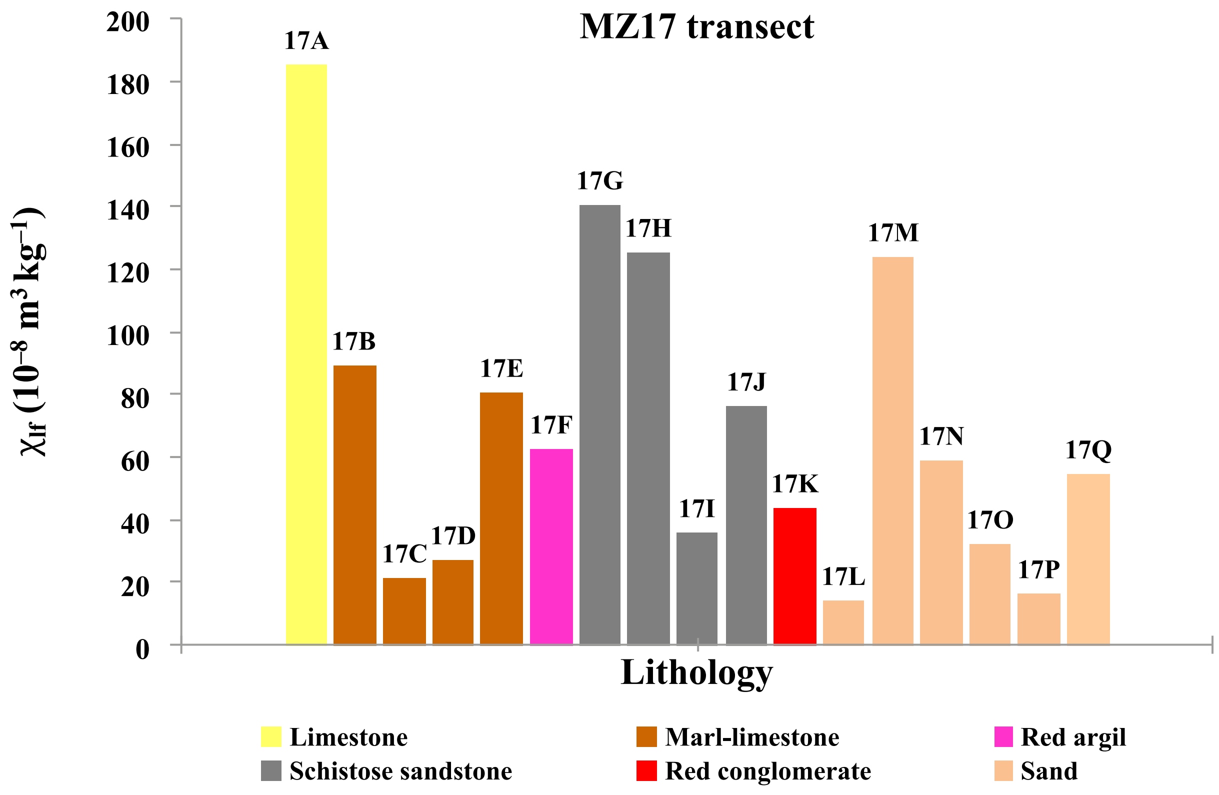

Figure 5. Variation of the mean of magnetic susceptibility with lithology in the MZ17 transect. (χlf: mass-specific low-frequency magnetic susceptibility).

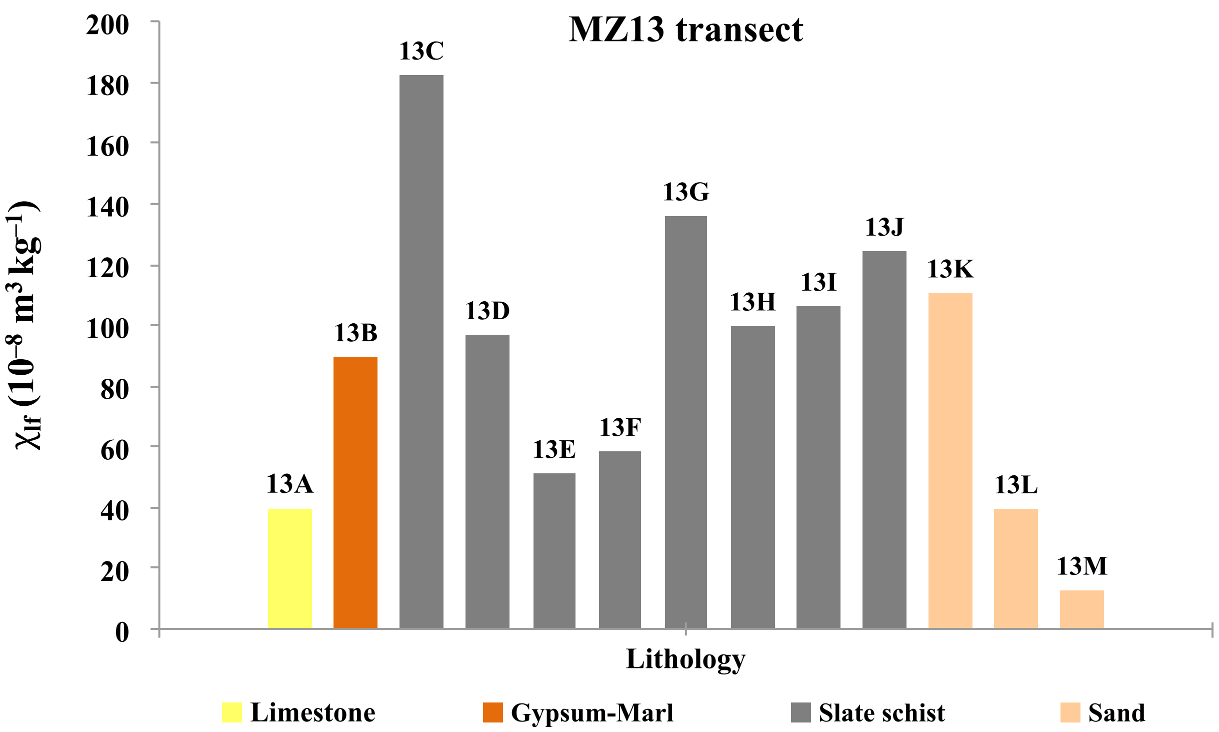

Figure 6. Variation of the mean of magnetic susceptibility with lithology in the MZ13 transect. (χlf: mass-specific low-frequency magnetic susceptibility).

and 4×10^{-18} kg^{-1} for soils developed on red argil [Bouhlassa and Choua, 2009]. Hanesch *et al.* [2007] reported that the carbonate content has a negligible influence on the magnetic susceptibility values. However, soils with volcanic parent materials have higher magnetic susceptibility values that exceed 400×10^{-8} m^{3}kg^{-1} [Wang *et al.*, 2000]; soils derived from basalt parent material have magnetic susceptibility attaining 1000×10^{-8} m^{3}kg^{-1} [Yu and Lu, 1991]. The values of magnetic susceptibility of soils obtained in this study are higher than the susceptibilities measured on weakly magnetic substrates. Bouhsane and Bouhlassa [2018] have obtained similar results in their study carried out in Moroccan watershed characterized by the same lithology of Mezguida watershed. They confirmed that the magnetic susceptibility enhancement was due to pedogenesis.

As the geologic substrates of soils in the MZ17 and MZ13 transects are totally dominated by schist, marl, sand, and limestone characterized generally by a weak magnetic signal and diamagnetic behavior, lithologic effect has insignificant contribution to magnetic susceptibility value of soils investigated in this study.

3.3 Determination of pedogenic influence on soil magnetic susceptibility

3.3.1 Detection of pedogenic influence by the χ_{lf} magnitude and its correlation with χ_{fd}

The variation of magnetic susceptibility (MS) is linked to many factors, such as the difference in lithology, pedogenesis, and anthropogenic contribution of magnetic material [Karimi *et al.*, 2017]. The magnetic minerals in soil could be inherited from the parent material, but also because of pedogenic or other autogenic local transformation [Gautam *et al.*, 2004; Sadiki *et al.*, 2009; Ayoubi *et al.*, 2014; Jordanova, 2017].The pollution fallout from industrial activities would be another source of magnetic particles, particularly in soil surface [Blundell *et al.*, 2009]. Magnetic susceptibility χ_{lf} was much enhanced attaining 600×10^{-8} m^{3}kg^{-1}, as El Baghdadi *et al.* [2011] have measured in a study carried out in urban soils of Beni Mellal city (Morocco). It exceeds 500×10^{-8} m^{3}kg^{-1} in polluted soils by industrial particles [Wang *et al.*, 2000]. Lu and Bai [2008] have also reported that magnetic susceptibility values of urban soils vary widely from 9×10^{-8} m^{3}kg^{-1} to 914×10^{-8} m^{3}kg^{-1}. However, the magnitude of magnetic susceptibilities χ_{lf} values obtained in the soils of the two transects MZ17 and MZ13 are lower compared to the susceptibilities recorded in the polluted soils by industrial activities. Gutam *et al.* [2004] classified soils into three classes as follows: normal ($\chi_{lf} < 10 \times 10^{-8}$ m^{3}kg^{-1}), moderately magnetic ($10 < \chi_{lf} < 100 \times 10^{-8}$ m^{3}kg^{-1}) and highly magnetic ($\chi_{lf} > 100 \times 10^{-8}$ m^{3}kg^{-1}). In accordance with this classification, most of soil samples in the transect MZ17 and MZ13 are normal and moderately magnetic, while polluted soils are mostly highly magnetic [Kanu *et al.*, 2013]. However, higher susceptibilities do not always imply pollution, because also soils on parent materials highly magnetic such as volcanic and basalt rocks have an enhanced magnetic susceptibility [Yu and Lu, 1991; Magiera *et al.*, 2006].

The distinction of the major contributions of anthropogenic and pedogenic factors on χ_{lf} may be attempted using magnetic susceptibility measurements at various frequencies; the information collected from χ_{lf} magnitude and its correlation to χ_{fd} enable us to distinguish pedogenetic material from the parent material and anthropogenic one. Figure 7 shows a positive and statistically strong correlation between χ_{lf} and χ_{fd} in all the soils of cultivated and forested transects ($R^2 = 0.937$). This result reflects the high homogeneity in the magnetic mineralogy of the soils corresponding to grains size and their contents despite the land use change [Faleh *et al.*, 2003; Sadiki *et al.*, 2009; Mokhtari Karchegani *et al.*, 2011; Bouhlassa and Bouhsane, 2019; Ayoubi *et al.*, 2020]. Moreover, the high positive and significant χ_{lf} and χ_{fd} correlation confirmed that the increased χ_{lf} was due to pedogenic processes allowing the enhancement in super-paramagnetic particles (SP) [Hu *et al.*, 2007]. Besides this, Figure 7 present χ_{lf} against χ_{fd}, its allows us to determine the value of the magnetic susceptibility background χ_b associated to paramagnetic and coarse ferrimagnetic grains and the Fc% parameter. χ_b is about 0.8×10^{-8} m^{3}kg^{-1}, it remains low implying a weak contribution of paramagnetic and coarse ferrimagnetic grains to the magnetic susceptibility of soil (Figure 7). The high value in the average of Fc% (8.4%) close to χ_{fd}% determined in forested sites highlights the importance of fine particles in the increase of magnetic susceptibility. In accordance with Forster *et al.* [1994], such linear correlation obtained in Figure 7 shows that with increasing magnitude, the susceptibility is more controlled by the contribution of pedogenic magnetic fractions. Faleh *et al.* [2003] and Bouhsane and Bouhlassa [2018] have obtained similar results.

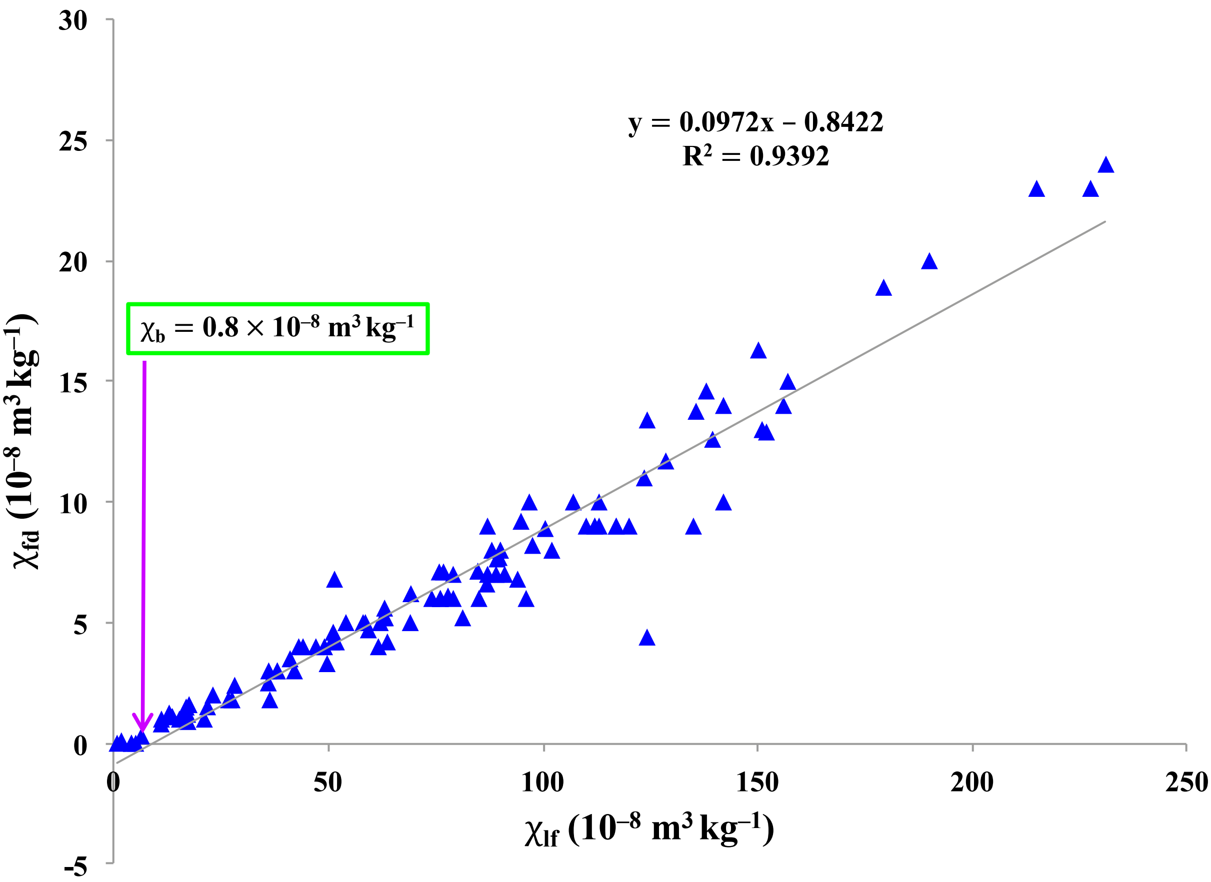

Figure 7. Interdependence between χlf and χfd for the two land uses. (χfd: Frequency-dependent magnetic susceptibility; χlf: mass-specific low-frequency magnetic susceptibility; χb: magnetic susceptibility background associated to paramagnetic and coarse ferrimagnetic 750 grains.

3.3.2 Determination of pedogenic influence on χlf using topsoil-subsoil difference and median absolute deviation (MAD) methods

In addition to the comparison of magnetic susceptibility magnitude of soil samples of Mezguida watershed to those of polluted soils, two methods have been applied in this study to determine the pedogenic effect on the magnetic susceptibility: topsoil-subsoil difference and median absolute deviation (MAD) methods [Hanech *et al.*, 2007]. Following the results obtained using the topsoil-subsoil difference (Table 3), the magnetic susceptibility differences of the major soils from forested and cultivated transects are mostly below 20×10^{-8} m^{3}kg^{-1} which indicates that the longitudinal variation of χ_{lf} in topsoil is due to pedogenic transformation. Only three samples 17I, 17J, and 17N in forested transect and one sample in cultivated transect 13A show magnetic susceptibility differences exceeding 20×10^{-8} m^{3}kg^{-1}, which could be attributed to an anthropogenic impact. But this enhancement is observed specifically in soil cores developed on limestone, schist, and sandstone as parent materials. This type of bedrocks contributes to magnetic dilution in subsoil, and therefore magnifies the difference between magnetic susceptibility of the subsoil and topsoil. The difference of topsoil-subsoil magnetic susceptibilities would be due to pedogenic processes instead of an anthropogenic contribution.

The application of the median absolute deviation in the studied soils shows that the values of magnetic susceptibility are practically all in the field limited by $\chi_{Mediane} \pm 2$MAD (Table 4). According to the Median absolute deviation (MAD) method, the results obtained by this method exclude the anthropogenic pollution influence as it is expected because there isn't any industrial activity in the study area and around it is in more than 100 km circumference. The MAD method supports the pedogenic processes as a source of topsoil magnetic susceptibility enhancement.

Land use	Core	$\chi_{lf\ (top)}$ [10^{-8} m^{3}kg^{-1}]	$\chi_{lf\ (sub)}$ [10^{-8} m^{3}kg^{-1}]	$\chi_{lf\ (top)} - \chi_{lf\ (sub)}$ [10^{-8} m^{3}kg^{-1}]
Forested transect MZ17	17A	96.74	231.15	−134.41
	17B	89.22	84.73	4.49
	17C	21.74	61.56	−39.82
	17D	27.45	27.45	0
	17E	77.79	76.74	1.05
	17F	58.53	75.75	−17.22
	17G	100.46	139.46	−39
	17H	97.49	152.02	−54.53
	17I	63.66	10.95	52.71
	17J	94.02	50.71	43.31
	17K	36.26	63.01	−26.75
	17L	17.17	6.34	10.83
	17M	124.19	124.19	0
	17N	62.88	12.8	50.08
	17O	35.91	28.07	7.84
	17P	17.44	13.54	0.68
	17Q	49.62	59.23	−9.61
Cultivated transect MZ13	13A	39.25	11	28.25
	13B	89.33	107	−17.66
	13C	182.33	190	−7.66
	13D	96.66	91	5.66
	13E	51	42	9
	13F	58	54	4
	13G	135.75	157	−21.25
	13H	99.5	117	17.5
	13I	106	112	−6
	13J	124.33	142	−17.66
	13K	110.66	102	8.66
	13L	39	36	3
	13M	12.66	4	8.66

Table 3. Magnetic susceptibilities differences between topsoil and subsoil in forested and cultivated lands.

Land use	Core	χlf (Median) [10^{-8} m^{3}kg^{-1}]	MAD [10^{-8} m^{3}kg^{-1}]	2MAD [10^{-8} m^{3}kg^{-1}]	Min [10^{-8} m^{3}kg^{-1}]	Max [10^{-8} m^{3}kg^{-1}]	χlf (mean) [10^{-8} m^{3}kg^{-1}]
Forested Transect (MZ17)	17A	227.57	3.58	7.16	220.41	234.73	185.15
	17B	89.22	0	0	89.22	89.22	89.58
	17C	11.7	10.54	21.08	1.16	22.24	21.4
	17D	27.45	0	0	27.45	27.45	27.45
	17E	77.79	1.05	2.1	75.69	79.89	80.46
	17F	60.86	5.71	11.43	49.34	72.29	62.31
	17G	138.73	7.27	14.54	124.19	153.27	140.5
	17H	124.22	4.34	6.68	115.54	132.9	125.16
	17I	33.96	20.19	40.39	−6.42	74.35	35.63
	17J	79.42	12.44	24.88	54.54	104.3	75.89
	17K	40.98	10.06	20.12	20.86	61.1	43.58
	17L	15.19	1.92	3.84	11.35	19.03	13.86
	17M	124.19	0	0	124.19	124.19	124.19
	17N	70.95	9.17	18.34	−18.34	89.29	58.98
	17O	31.99	3.92	7.84	24.15	39.83	31.83
	17P	16.76	0.68	1.36	15.4	18.12	15.91
	17Q	54.42	4.8	9.61	44.81	64.03	54.42
Cultivated Transect (MZ13)	13A	35	18	36	−1	71	39.25
	13B	89	1.5	3	92	86	89.33
	13C	190	48	96	94	286	182.33
	13D	91	2	4	87	95	96.66
	13E	46.5	3.5	7	39.5	53.5	51
	13F	58	4	8	−8	66	58
	13G	153.5	3	6	147.5	159.5	135.75
	13I	101	17.5	35	66	136	99.5
	13J	112	0.5	1	111	113	106
	13K	135	7	14	121	149	124.33
	13L	38	2	4	34	42	39
	13M	4.5	25	50	3.5	5.5	12.66

Table 4. Results of the median absolute deviation method for all the samples in the study area.

3.3.3 Determination of pedogenic effect on magnetic susceptibility using Dearing's model [1999a]

Frequency-dependent magnetic susceptibility percentage (χ_{fd}%) reflects the relative significance of the SP/SSD fraction in the total magnetic signal, it is sensitive to the total quantity of pedogenic magnetic grains [Dearing, 1999a; Liu *et al.*, 2004; Liu *et al.*, 2015; Grison *et al.*, 2017; Liu *et al.*, 2018]. Pedogenic processes are the factor controlling the SP grains concentration. If the latter is high, the pedogenic processes are strong [Dearing, 1999; Liu *et al.*, 2015; Yu *et al.*, 2017]. Lu *et al.* [2007] reported that unpolluted soils are usually characterized by the presence of an important super-paramagnetic fraction produced during pedogenesis. Wang *et al.* [2000] confirmed that polluted soils are characterized by the dominance of lower χ_{fd}% values that are generally less than 3%. Hay *et al.* [1997] used a criteria based on $\chi_{fd}\% < 3\%$ to define the polluted topsoils. Kanu *et al.* [2013] obtained lower mean value of frequency-dependent magnetic susceptibility percentage ($\chi_{fd}\% = 2.6\%$) in the urban area, suggesting that pedogenic SP grains did not contribute to the total magnetic susceptibility variation in the studied area. This χ_{fd}% value is lower comparing to those obtained in the soils of MZ17 and MZ13 transects. In many studies, it is reported that the main magnetic components in urban topsoil originated from an anthropogenic source are in multidomain (MD) form [Lu and Bai, 2006, 2008; Hu *et al.*, 2007; Qi *et al.*, 2010]. However, ferrimagnetic minerals generated during pedogenic processes are characterized mainly by super-paramagnetic (SP) (< 0.02 μm) and stable single domain (SSD) (0.02-0.04 μm) grain sizes [Rangani *et al.*, 2015]. In addition, previous studies confirm that the industrially polluted soils display a negative correlation between χ_{lf} and χ_{fd}% indicating that the main susceptibility variations are due to magnetic enhancement as a result of industrial pollution [Karimi *et al.*, 2017]. However, this correlation is positive in unpolluted soils [Wang *et al.*, 2000; Lu and Bai, 2005]. Figure 8 presents the correlation between χ_{lf} and χ_{fd}% in each slope position in the MZ13 and MZ17 transects selected in cultivated and forested lands respectively. It shows that χ_{lf} values are positively correlated with χ_{fd}%. According to the theoretical model of

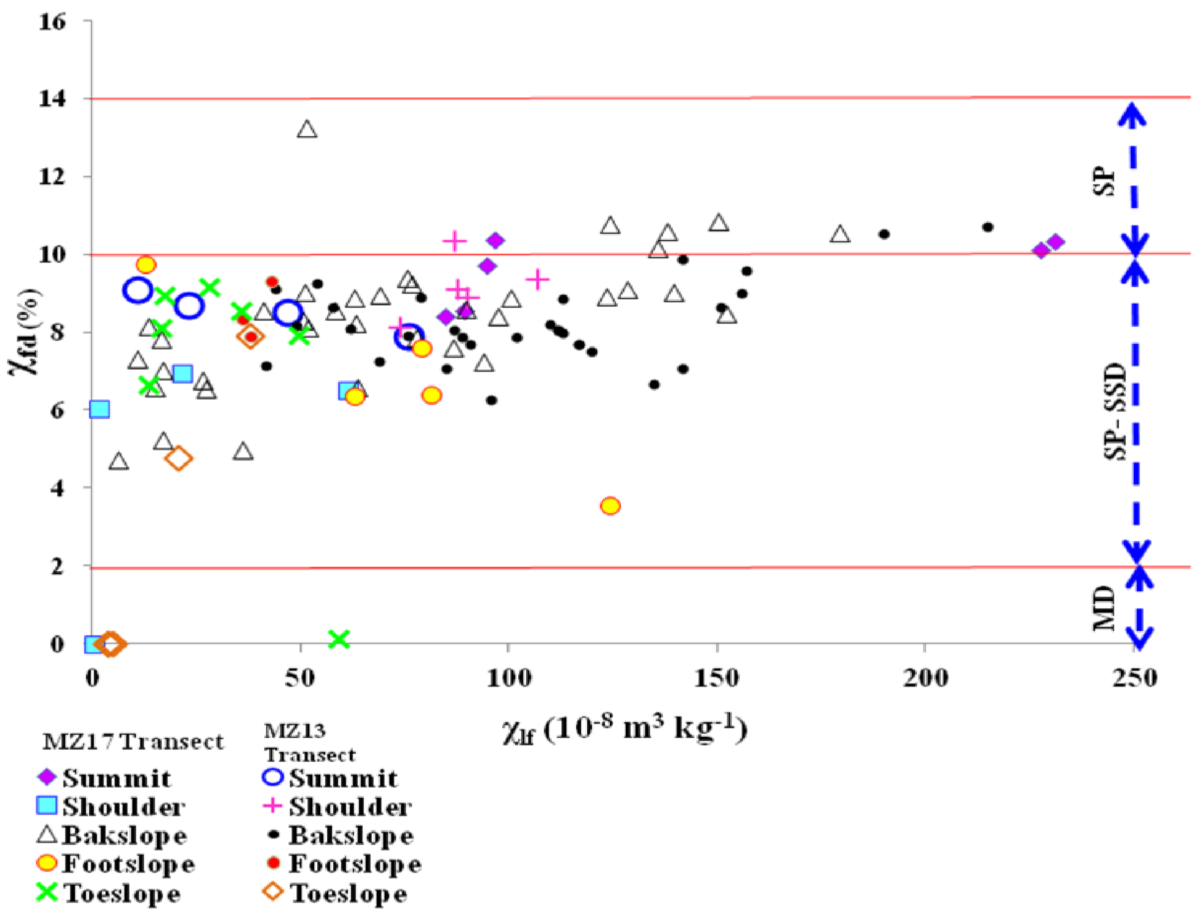

Figure 8. Biplot of χlf–χfd% showing the grain sizes type in the MZ17 and MZ13 transects. (χfd%: Frequency-dependent magnetic susceptibility percentage; χlf: mass-specific low-frequency magnetic susceptibility; SP: Superparamagnetic; MD: Multidomain; SSD: Stable single domain).

Dearing [1999], Figure 8 confirms the dominance of super-paramagnetic (SP) and stable single domain (SSD) grain sizes originated from pedogenesis; this is observed in almost all slope positions in the two land uses. Dearing model [1999] confirms also that χ_{fd}% values are lower to those of polluted soils.

Figure 8 shows that the most of χ_{fd}% values in forested transect are ranged from 4% to 13% and from 6% to 10% in cultivated transect. In the forested transect, the values of χ_{fd}% in the summit are all above 8%; these higher values indicate the high pedogenesis process resulting in high super-paramagnetic grains produced in this stable position. The most of χ_{fd}% values in MZ17 in the backlsope, footslope, and toeslope exceed 6% indicating the strong SP grains accumulation during soil deposition occurred in such slope positions. Lower χ_{fd}% values in the shoulder are explained by an erosion process including a selected loss of fine particles i.e. SP and SSD grains. In cultivated transect, χ_{fd}% values in the summit are higher even if this position constitutes an erosion site. This higher values would result from an erosion process with the transport of coarse ferromagnetic and paramagnetic particles and the concentration on site of SP and SSD fine magnetic particles. In the shoulder, backslope, and footslope positions, χ_{fd}% values are above 6% as these positions constitute a deposition sites. The cultivation activities affect strongly the soil redistribution process on cultivated slopes. The more redistribution has occurred, the more SP and SSD grains are transported by erosion processes from the upperslopes to the lowerslopes [Yu *et al.*, 2017]. Higher χ_{fd}% values in lowerslopes in the cultivated transect are linked to deposition of magnetic particles transported from the upperslopes and their accumulation in the lowerslopes, but it could be also result from transport by erosion of coarse and paramagnetic particles. However, the lower ones are due to erosion and redistribution of soil along the transect. This contributes to losses of SP and SSD grains amount in the upperslopes and their deposition in the lowerslopes.

4. Conclusions

Our results confirmed the impact of erosion factors including land use change and slope position on the variability in magnetic susceptibility of the studied soils. However, the contribution of lithologic effect to magnetic susceptibility enhancement was insignificant. The present study confirmed that pedogenic origin was the most crucial factor that had a considerable contribution in the χ_{lf} enhancement of the studied soils, this is unlike several last studies that consider that anthropogenic or lithogenic factors are the main cause for the χ_{lf} enhancement. The study established and validated a simple method to determine pedogenic influence on the soil magnetic susceptibility enhancement.

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