



Assessment of areal water and tillage erosion using magnetic susceptibility: the approach and its application in Moroccan watershed

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Abstract

Soil erosion constitutes a serious threat for sustainable agriculture in many countries. Magnetic susceptibility of soil is a fast, cheap, and non-destructive technique that could be used to quantify soil erosion or soil redistribution on a long-term scale. This study attempts to analyze the variation of magnetic susceptibility in soil profiles having the same lithology and climatic conditions, but different land uses and slope gradients in a subcatchment in northern Morocco. Soil cores were collected on forested, cultivated, and pasture lands. Each core was associated to a field unit (also called a homogeneous unit) characterized by a set of four cited erosion factors. The samples were measured for mass-specific low-frequency magnetic susceptibility (χ_{lf}) and frequency-dependent magnetic susceptibility (χ_{fd}). The linear correlation of χ_{lf} and χ_{fd} indicates the homogeneity of magnetic population in soil. It supports the use of empirical models based on comparisons of χ_{lf} to predict the value of magnetic parameter after tillage homogenization and removal of soil material from the surface, and to estimate soil erosion or redeposition. The study built a methodology improving these empirical models and enabling a quantitative approach of the phenomenon. Two models, namely “tillage homogenization” (as improved in this study) and the proposed “simple correlation” result in globally similar estimates of erosion, while another model, the “simple proportional” model, underestimates it. The results give an estimate of long-term erosion (deposition) in sampled units and allow drawing of an areal soil redistribution map in the watershed.

Keywords Magnetic susceptibility · Magnetic mineralogy · Homogeneous unit · Tillage homogenization · Erosion models · Areal erosion

Highlights

- Magnetic susceptibility decreases in the order: forested area > pasture area > cultivated area.
- High correlation between χ_{lf} and χ_{fd} indicates homogeneity of magnetic population which means that the loss of fine magnetic particles is associated to χ_{lf} decrease.
- χ_{lf} is an important parameter to estimate erosion or deposition.
- Estimation of erosion using new approach synchronized to tillage model proposed by Royall.
- Comparison of the results of tillage model “TH,” simple correlation model, and simple proportional method proposed by Liang Liu.
- Establishment of a methodology and conditions to improve the use of magnetic susceptibility in the estimation of soil erosion or redeposition in watershed.

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Introduction

Soil erosion is a natural phenomenon that affects all land-forms. However, the high magnitude of land degradation in certain geographical regions poses a serious threat for sustainable agricultural activities (Moukhchane et al. 1998b; Bouhlassa et al. 2000; Hassouni and Bouhlassa 2005; Zhang et al. 2007; Fang et al. 2012; Liu et al. 2013). In agriculture, soil erosion is linked to the wearing away of a field’s topsoil by natural physical forces, including water and wind, or through agricultural practices such as tillage (Jordanova et al. 2014), this later is considered among the major sources of soil erosion and redistribution (Kapička et al. 2015). As this threat results in on-site soil degradation, it also leads to off-site problems related to downstream sedimentation as well as surface and groundwater pollution (Moukhchane et al. 1998a). The resulting on-site soil degradation, especially in cultivated and pasture lands, leads to reduced productivity. This is owing to a loss of organic matter,

plant nutrients, and soil depth (Abbaszadeh Afshar et al. 2010; Mehnatkesh et al. 2013). Magnetic methods can be successfully used in the soil erosion investigations; this method is based on the soil magnetic parameters measurement, such as magnetic susceptibility of soil (Aboutaher et al. 2005; Moukhchane et al. 2005; Menshov et al. 2018). It has also been used for obtaining paleoclimate information in loess-paleosol sequence (Liu et al. 1995; Han 1996). Jakšik et al. (2016) indicate that magnetic susceptibility presents a novel parameter for soil degradation assessment caused by water erosion. It is considered as a diagnostic criterion of erodibility degree (Nazarok et al. 2014). Clark (2015) used the universal soil loss equation (Wirschemier and Smith 1978) to evaluate soil erosion in the Moroccan Bouregreg basin. But this empirical model gives results that concern process that takes place over a few decades, whereas the magnetic susceptibility technique allows predicting erosion concern process that occurs over thousands of years.

Magnetic susceptibility, as a commonly measured magnetic parameter on soils (Naimi and Ayoubi 2013; Dankoub et al. 2012; Valaee et al. 2016), depends mainly on magnetic particle concentrations, their mineralogy, and grain size (Thompson and Oldfield 1986). It may also be affected by lithology (Karimi et al. 2017; Ayoubi et al. 2018a, b, c, Ayoubi and Karami 2019), soil drainage conditions (Hendrickx et al. 2005; Grimley et al. 2008; Asgari et al. 2018), geomorphological factors, and land uses (Sadiki et al. 2006, 2009). The magnetic minerals that are present in soils may either originate from parent rocks (lithogenic origin), neoformed or transformed during pedogenesis, or result from anthropogenic activities (Petrovsky et al. 2000). The variation of mass-specific low-frequency magnetic susceptibility (χ_{lf}) and frequency-dependent magnetic susceptibility (χ_{fd}) in soil profiles reflects the stability or instability of topsoil (Bouhlassa and Choua 2009; Faleh et al. 2003; Sadiki et al. 2006). Indeed, the enhancement of those parameters in topsoil is a mark of local pedogenesis or deposition of soil and thereafter constitutes a stability indication. The situation is reversed in the case of erosion or instability of soil surfaces. This specific enhancement, which is reported by many authors to occur in topsoils (Evans and Heller 2003; Le Borgne 1955; Mullins 1977; Sadiki et al. 2004; Menshov et al. 2018), could be used to identify differences between topsoil and subsoil. This could also be used as a tracer for long-term processes of soil erosion and deposition (Kapička et al. 2015; de Jong et al. 1988, 2000; Dearing et al. 1985, 1986). Those behaviors are described by many authors. In Illinois, USA, magnetic susceptibility decreases regularly with depth at all sites. To be precise, it is higher on forested land than on cultivated land for all slope positions except at the lower footslope (Hussain et al. 1998). In addition, Olson et al. (2002) found higher magnetic susceptibility values in forested soils than in cultivated lands for all landscape positions in a Moscow suburb in

Russia. Sadiki et al. (2009) also found similar results with the χ_{lf} values in the soil profiles of cultivated land, which were significantly lower than those of uncultivated land in the Eastern Rif, Morocco. Lower values of magnetic susceptibility are because of weaker pedogenesis and/or topsoil erosion (Ananthapadmanabha et al. 2013). The differentiated responses of this magnetic technique can be quantitatively used to evaluate the intensity of the erosion and deposition processes (Gennadiev et al. 2002). Kapička et al. (2014) report that difference between magnetic susceptibility in undisturbed soil profiles and after mixing due to tillage and erosion process is fundamental to estimate soil loss in the studied area. The magnetic susceptibility is also impacted by soil redistribution along a slope and exploited to quantify the phenomenon, as it is shown in many studies (Mokhtari Karchegani et al. 2011; Ayoubi et al. 2012; Rahimi et al. 2013; Jordanova et al. 2014). Magnetic enhancement is attributed to the stronger pedogenesis at higher elevation area (Wei et al. 2013).

Magnetic measurements are inexpensive, simple, rapid and non-destructive in comparison to radionuclide techniques. The technique is used for assessing soil redistribution along transects at different slope positions, in many landscapes and regions about the world as many previous studies have shown (Ayoubi et al. 2014, Liu et al. 2015, Yue et al. 2017). Yue et al. (2019) used soil magnetic susceptibility to quantify soil erosion and deposition on cultivated slope in northeast China and confirmed that the magnetic susceptibility measurement presents a promising approach in qualitative soil erosion research. As these studies were restricted to slope transects, our concern is the extension of the erosion estimate models developed on slope transects to large field or watershed. The watershed is divided into homogeneous units. Each unit is characterized by a set of four parameters, namely the lithology, slope inclination class, land use, and precipitation amount. Different units can be generated through the superposition of the digital map of the cited factors in a geographical information system (GIS). Since the erosion factor being the same in the homogeneous unit, its area is then assumed to be subject to the same processes and amount of soil erosion or deposition or at least to the same susceptibility to erosion-deposition processes. A homogeneous unit is selected as the representative of units having the same four attributes. The selected units represent the variable susceptibilities to erosion in the watershed. An estimation of soil losses or accumulated is performed on cores collected in the selected homogeneous units using the quantitative approaches developed on the framework given by Royall (2001) which proposes a simple tillage homogenization model (henceforth abbreviated, “T-H model”) to monitor change in surface soil magnetism with progressive erosion, while Liu et al. (2015) linearly relates the soil loss or gain to variation of the mean magnetic pedogenic enhancement of soil cores as compared with reference core. These models as improved and applied in this study result in a quantitative

punctual soil loss or accumulated which can be associated to the homogeneous unit. The gross and even the net erosion in the watershed is raised by algebraic summation of obtained results, knowing the unit areas.

The objectives of this study were to (i) assess the variation of magnetic susceptibility (χ_{lf}) and frequency dependent magnetic susceptibility ($\chi_{fd}\%$) in soil profiles collected on forested, cultivated, and pasture lands; (ii) develop consistent empirical approaches, improving the tillage homogenization model; (iii) determine a quantitative evaluation of erosion at the sampled sites, instead the percent estimates of soil redistribution obtained using Liang Liu et al.'s (2015) model; and finally (iv) bring out a methodological approach based on magnetic susceptibility. To quantify erosion in a field or watershed, an expected important output of this work would be the establishing of some fundamentals of another approach based on the extension of punctual erosion or deposition determination to the surface area using a geographical information system.

Materials and methods

Study area

The Ait Azzouz basin with an area of 195 km² is located at 32° 70′–33° N 5° 70′–5° 08′ W in the Moroccan Central Plateau. It

constitutes one of the most important watersheds in upstream of the Grou River (Fig. 1). The climate of the region is semi-arid with average yearly precipitations of 400 mm and an annual temperature varying between 11 °C as a minimum and 22 °C as a maximum. Cultivated and pasture lands occupy the major part of the basin while a small area is forested (Fig. 2). The slope classes are between 0% and 30% in the major part of the watershed, while the limited area has an inclination exceeding 40% (Fig. 3). According to the FAO classification (Fischer et al. 2008) (Soil Survey Staff 1999), the soil types in the Bouregreg basin are calcic kastanozems, chromic luvisols, eutric planosols, calcic cambisols, and vertisols (Clark 2015). The Ait Azzouz watershed is dominated specifically by chromic luvisol (Clark 2015). The schist constitutes the common and dominant watershed lithology with minor and distinct intrusion of quartzite, sandstone, limestone, and microgranite conglomerate in some areas. To the north and east is the Viseens conglomerates outcrop, and to the west we find the quartzite ridges.

Soil sampling

The watershed was subdivided into 28 homogeneous units (Fig. 4), using schist and flysch as predominant lithology, 0–5%, 5–15%, 15–30%, and > 30% as slope classes for different land uses. The watershed was assumed to be subjected

Fig. 1 Location of the study area

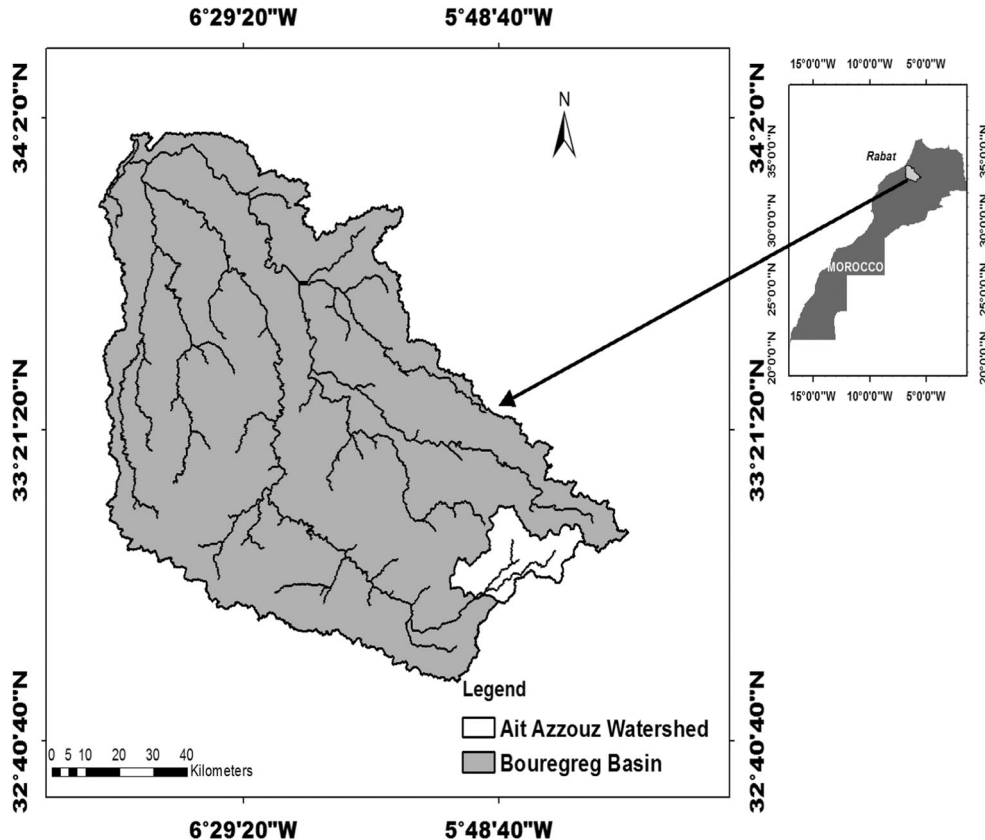
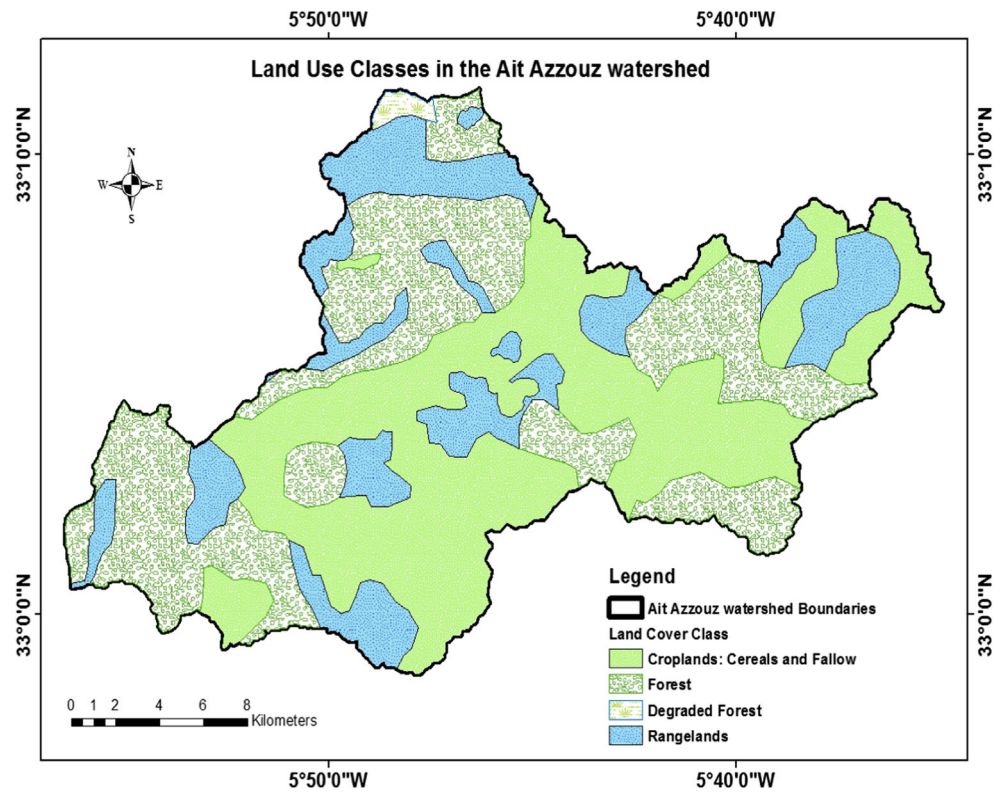


Fig. 2 Map of land use of Ait Azzouz watershed



globally to the same precipitation amounts and intensities. These units and their characteristics are presented in Table 1.

While the sampling process should ideally cover all 28 units, due to logistical problems and access difficulties, in the

Fig. 3 Map of slope class of Ait Azzouz watershed

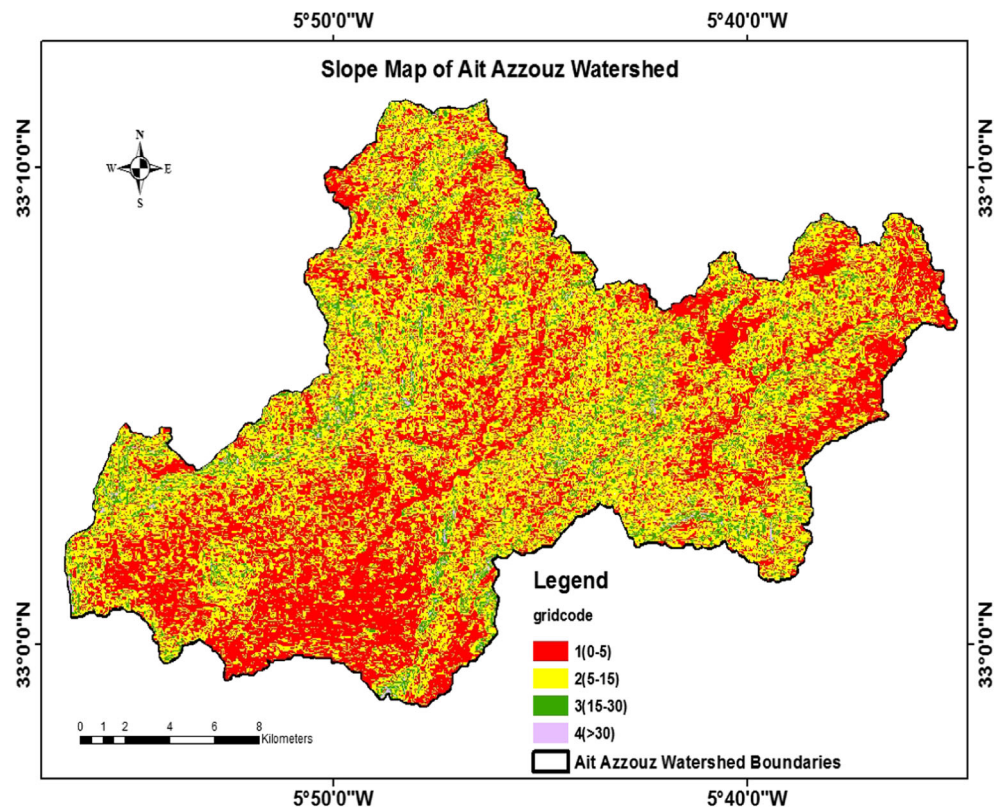
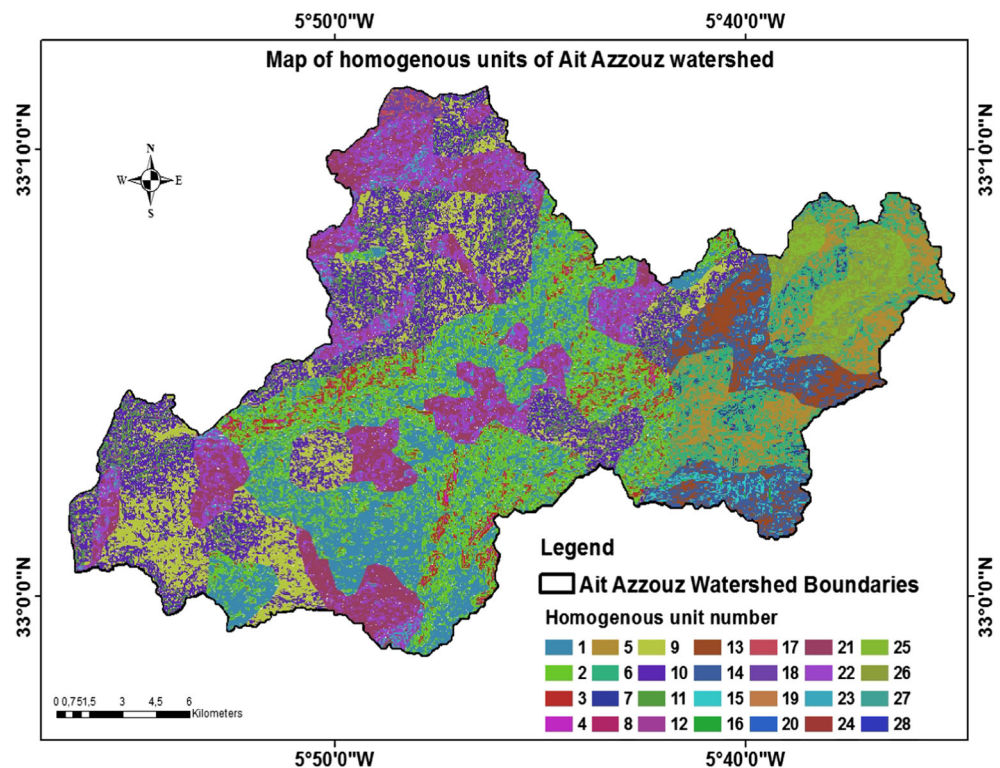


Fig. 4 Map of homogenous units of Ait Azzouz watershed



present study, it was restricted to representative units pertaining to the units characterized by comparable erosion factors or likely approximate erosion susceptibility.

Lands with different uses were sampled in the Ait Azzouz basin, whereby cultivated soils were denoted as AZC, pasture by AZP and forest or forested soil by AZF. The slope gradients ranged from 0% to 45% for different land uses. One sampling site in the dense forest (AZF14), two sampling sites in the residual forest (AZF1; AZF11), four sampling sites on the cultivated soils (AZC3, AZC9, AZC10, AZC12) and six sampling sites on the pastures soils (AZP2, AZP4, AZP5, AZP6, AZP8, AZP16) were considered interesting for the purpose of the study, selected and sampled as representative of the homogeneous units constituting the watershed, because more easily accessible than the others units. The homogeneous units in the watershed are reported in Table 1. The forested site AZF11 is located near AZC10, and AZF1 is close to AZP2, while AZF14 is surrounded by others cultivated and pasture lands. The characteristics of the sampled soils and associated homogeneous units are presented in Table 2. Samples location on a lithological map is shown in Fig. 5. At each sampling site, core samples of 35 cm length were collected using a hand auger which was 6 cm in diameter and 50 cm in length. The only exception was AZF14, in which the core samples extended to more than 1 m. To measure the magnetic susceptibility vertically, each core was divided from top to bottom into layers at 5 cm intervals. Next, a thin superficial layer of each soil core in direct contact with the metal corer was shaved off using a plastic knife to avoid the potential

effects of the iron coring devices (Dearing 1999). This process resulted in 62 samples collected from 13 sampling sites.

Laboratory analyses

The soil samples were oven dried at 40 °C for 8 h, with good air circulation and no hotspots, and then passed through a 1-mm plastic sieve. All samples were packed individually into cylindrical boxes of 10 cm³ and measured using a Bartington magnetic susceptibility meter (MS2) and dual frequency sensor (MS2B). The volume-specific magnetic susceptibility (κ) was measured at low (0.47 kHz; κ_{lf}) and high (4.7 kHz; κ_{hf}) frequencies. The mass-specific magnetic susceptibility (χ) at low (0.47 kHz; χ_{lf}) and high (4.7 kHz; χ_{hf}) frequencies were calculated respectively by dividing the κ_{lf} and κ_{hf} by the bulk density (ρ) of the sample. The χ value is proportional to the concentration of ferrimagnetic mineral (magnetite and maghemite). The frequency-dependent susceptibility χ_{fd} and the percent frequency-dependent magnetic susceptibility $\chi_{fd}\%$ are expressed as follows:

$$\chi_{fd} \text{ (m}^3\text{kg}^{-1}\text{)} = \chi_{lf} - \chi_{hf}$$

$$\chi_{fd}\% = \left(\frac{\chi_{lf} - \chi_{hf}}{\chi_{lf}} \right) * 100$$

where the χ_{lf} and χ_{hf} are the magnetic susceptibilities at low and high frequency respectively.

Table 1 Homogeneous units defined in the watershed

Homogenous unit number	Lithology	Slope class (%)	Land use	Soil type
1	Schist	0_5	Cultivated	Chromic luvisol
2	Schist	5_15	Cultivated	
3	Schist	15_30	Cultivated	
4	Schist	>30	Cultivated	
5	Flysch	0_5	Cultivated	
6	Flysch	5_15	Cultivated	
7	Flysch	15_30	Cultivated	
8	Flysch	>30	Cultivated	
9	Schist	0_5	Forest	
10	Schist	5_15	Forest	
11	Schist	15_30	Forest	
12	Schist	>30	Forest	
13	Flysch	0_5	Forest	
14	Flysch	5_15	Forest	
15	Flysch	15_30	Forest	
16	Flysch	>30	Forest	
17	Schist	0_5	Degraded forest	
18	Schist	5_15	Degraded forest	
19	Schist	15_30	Degraded forest	
20	Schist	>30	Degraded forest	
21	Schist	0_5	Pasture	
22	Schist	5_15	Pasture	
23	Schist	15_30	Pasture	
24	Schist	>30	Pasture	
25	Flysch	0_5	Pasture	
26	Flysch	5_15	Pasture	
27	Flysch	15_30	Pasture	
28	Flysch	>30	Pasture	

Data analysis

Descriptive statistical parameters, such as the mean, minimum, maximum, coefficient of variation (CV), standard deviation (SD), median, kurtosis, and skewness, were calculated (Wendroth et al. 1997). These parameters were generally used as indicators of the midpoint and degree of dispersion and skewness of the data. The CV was utilized to explain the variability in magnetic susceptibility and soil properties. The Jaque-Bera test was used to determine the normality of the data. All of these statistical parameters were obtained using XLSTAT (Addinsoft 2018).

Models of erosion estimates

T-H model Royall (2001) proposed a simple tillage homogenization model (T-H model), which permit to predict the mean values of magnetic parameters of the ploughing layers, after a sheet erosion of the surface soil layer. The model supposes homogenization of the uppermost 20 cm after tillage and simulates the variation of its mean magnetic value with the soil loss, on the core collected on stable and assumed non-eroded soil. When surface erosion event or soil stripping takes place, the mixing of the upper ploughed 20 cm of soil integrates deeper levels from the soil profile. This process is represented in general by the mathematical equations according to Royall (2001):

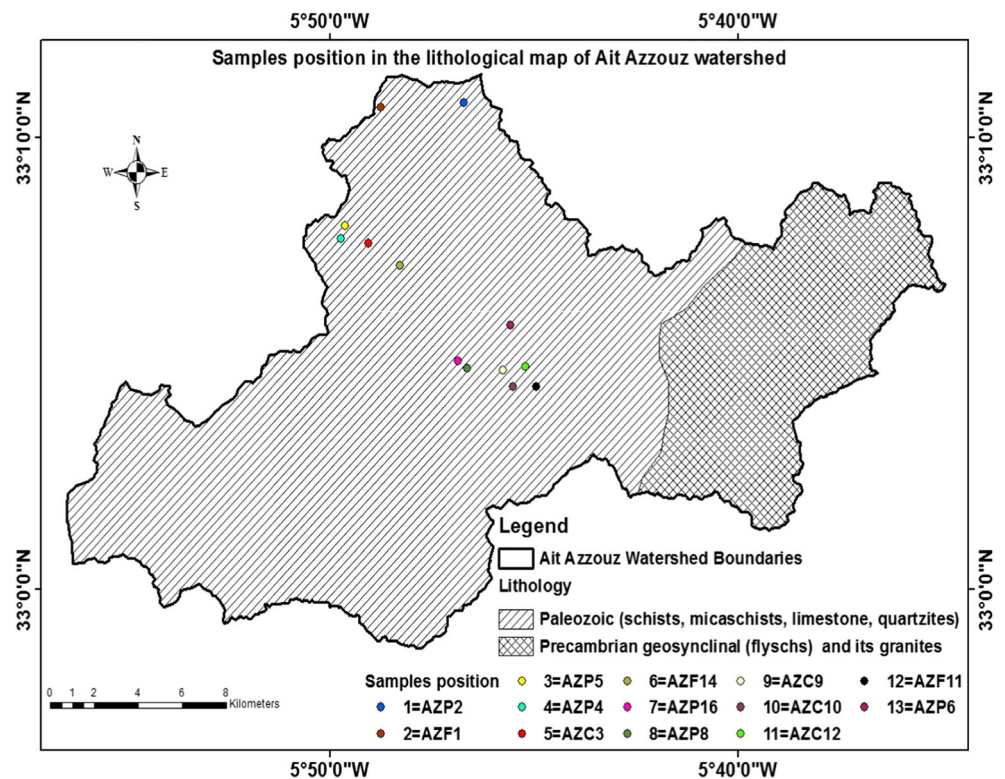
$X_0 = (\sum \chi_i) / N$, where χ_i is the magnetic parameter of the soil layer i and N is the number of the layers in plough depth or A_p horizon. X_0 is the average value of soil susceptibility without soil loss.

$$X_1 = ((N-1) (X_0) + (\chi_{N+1}))/N$$

Table 2 Characteristics of sampled lands and units associated

Sample	Position	Lithology	Vegetal cover	Slope %	Associate homogenous units	Total area (ha)
AZP2	33° 10' 46" N; 05° 46' 42" W	Schist	Pasture land	7	22; 26	3808.86
AZC3	33° 07' 41" N; 05° 49' 01" W	Schist	Cultivated land	0–5	1; 5	7055.01
AZP4	33° 07' 56" N; 05° 49' 41" W	Schist with quartzite	Pasture land	5–10	22; 26	3808.86
AZP5	33° 07' 56" N; 05° 49' 38" W	Sandy limestone	Pasture land	35	24; 28	22.04
AZP6	33° 05' 51" N; 05° 45' 33" W	Schist and limestone	Pasture land	15	23; 27	496.53
AZP8	33° 04' 56" N; 05° 45' 97" W	Schist	Pasture land	20–25	23; 27	496.53
AZC9	33° 04' 54" N; 05° 45' 46" W	Schist and limestone	Cultivated land	0	1; 5	7055.01
AZC10	33° 04' 31" N; 05° 45' 30" W	Schist and limestone	Cultivated land	0	1; 5	7055.01
AZF11	33° 04' 31" N; 05° 44' 54" W	Schist and limestone	Residual forest	45	9; 10; 13 14; 17; 18 19; 20	12,022.1
AZC12	33° 04' 59" N; 05° 45' 14" W	Schist and limestone	Cultivated land	10	2; 6; 3; 4; 7; 8	9005.31
AZF14	33° 07' 11" N; 05° 48' 19" W	Schist and quartzite	Dense forest	40	12; 16	92.17
AZF1	33° 10' 43" N; 05° 48' 44" W	Schist and limestone	Residual forest	22	11; 12; 15; 16	1501.32
AZP16	33° 05' 07" N; 05° 46' 52" W	Schist	Pasture land	5	21; 25	3552.62

Fig. 5 Samples position in the lithological map of Ait Azzouz watershed



X_1 is the expected magnetic susceptibility of A_p horizon after erosion loss of first layer. X_1 is a starting average value for the prior stage of erosion.

X_{N+1} is X value of the first soil layer below the plough depth.

The iteration of the process leads to magnetic susceptibility associated to surface soil losses. In our approach, we use a single increment of 5 cm in order to comply with the sampling interval of 5 cm along the soil profile.

Simple proportional model or Liang Liu et al. (2015) approach

Much soil erosion is occurring in cultivated regions, while significant vegetation protects forested land against erosion. Therefore, forested soil could be reasonably considered non-perturbed or stable and could serve as a reference behavior. A deviation from this reference profile would be interpreted as a consequence of erosion or deposition and used to estimate the relative erosion or deposition in the study area. Liu et al. (2015) estimate the loss or gain of soil, comparing the mean χ_{lf} of soil cores (from the surface to geologic substratum) to the mean χ_{lf} of the non-perturbed equivalent column of soil. The authors correlate the erosion intensity to ratio defined as below:

Ratio of erosion R

$$R = \frac{[\text{mean } \chi_{lf} (\text{sample}) - \text{mean } \chi_{lf} (\text{reference})]}{\text{mean } \chi_{lf} (\text{reference})}$$

A positive value is associated with deposition while a negative value indicates erosion. However, it is important to note

that the comparison must be made between soil profiles from the surface to the parent material or sampling cores extending from the soil surface to the geologic substratum.

New simple correlation model Another approach analogous to tillage model proposed by Royall (2001) could be attempted. When surface erosion event occurs, the underlying soil layer becomes soil surface, and then the topsoil χ_{lf} varies as erosion progresses. This trend could be illustrated by successive striping of surface soil layers on the reference soil core AZF14 collected from a supposedly stable and non-eroded site. Topsoil χ_{lf} varies with the depth of eroded layers. As the depths of the ploughing layers in the study area were limited to 20 cm, we examined the variation of the mean χ_{lf} related to the successive 20 cm layers along the reference soil core. This process yields a reliable variation of mean χ_{lf} due to erosion. The mean magnetic value (X_0) of the 20 cm uppermost layer corresponds to no erosion, while the mean magnetic value X_1 of the layer from 20 to 40 cm depth is associated with the soil erosion column $d = 20$ cm. Thus, at a value X_i relative to the soil layer located at $20 \cdot i$ cm depth, the column of eroded soil would be $(i - 1) \cdot 20$ cm. Subsequent linearization of the graphic representation of erosion (d in cm) versus X_i values leads to an equation that can be applied when predicting the soil loss correlated to the measured magnetic parameter on cultivated or pasture lands. More details on the implementation are given in the forthcoming paragraph on the application and results of the method.

Results and discussion

General characteristics of topsoil magnetic properties

Table 3 presents the statistical characteristics of soil magnetic susceptibilities (χ_{lf} ; χ_{fd} %) in the cultivated, pasture, and forested soils at 0 to 30 cm depths. According to the Jaque-Bera tests employed in this work, all the data followed a normal distribution, as confirmed by the skewness values that varied between -1 and $+1$. The standard deviation (SD) of the χ_{lf} value pertaining to the forest land was higher, as was the coefficient of variation (CV) than those of cultivated and pastures lands. These results imply that χ_{lf} values are linked to land use. Approximately, the χ_{lf} values are roughly proportional to the content of ferrimagnetic minerals, which contribute to the total magnetic signal of the sample. This content is closely related to soil transformation processes and pedo-environmental conditions (Thompson and Oldfield 1986). This result would also reflect and trace the variations in the soil environment and physical degradation of soil associated with erosion (Ayoubi et al. 2012; de Jong et al. 1988; Dearing et al. 1985, 1986; Gennadiev et al. 2002; Mokhtari Karchegani et al. 2011; Rahimi et al. 2013).

The value of low-frequency mass specific-magnetic susceptibility ranges from 8.4×10^{-8} to $88.6 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, with a mean of $42.7 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ for the cultivated land data. The pasture land's low-frequency magnetic susceptibility value ranges from 14.3×10^{-8} to $133.3 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, with a mean of $57.3 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, while the forested land's value ranges from 12.4×10^{-8} to $252.8 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, with an average round to $107 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The mean magnetic susceptibility decreases as follows: forested area > pasture area > cultivated area. This result shows the increase of magnetic susceptibility of soil with the degree of soil stability. Magnetic susceptibility increases in stable soils and remains low in degraded soils. Differences in geology (lithogenic/geogenic), soil formation processes (pedogenesis), and anthropogenic contribution of magnetic material causes the magnetic susceptibility to decrease or increase, as previous studies have shown (Dearing et al. 1996; Boyko et al. 2004; Jordanova 2017; Ayoubi et al. 2014, 2018a, b, c). Lithology is the main cause

for the magnetic susceptibility variation among the soil profiles; it is higher on the highly magnetic substrate such as quaternary terraces but remains low on tertiary marls characterized by low magnetic signal (Sadiki et al. 2009). Magnetic susceptibility of soil is higher in the topsoil of polluted areas in comparison to those in the agricultural area. El Baghdadi et al. (2011) found very high values of magnetic susceptibility in their study carried out in the Beni Mellal city of Morocco: it attained about $600 \times 10^{-5} \text{ m}^3 \text{ kg}^{-1}$; their results show the large contribution of anthropogenic ferrimagnetic minerals to the magnetic signal of the soil surface and indicate that the anthropogenic minerals have a high magnetic signal than the pedogenic and lithogenic minerals. As the soil's geologic substratum is the same, with predominant schistose character, and the catchment may be considered far from industrial pollution, the differences in the values of magnetic susceptibility likely result from differences in soil redistribution under different vegetation covers. The values of magnetic susceptibility are very close in cultivated and pasture land (Table 3). This indicates that the total amounts of ferrimagnetic minerals are nearly equivalent in the two types of land use, and proves that long-term farming and pasture may cause the redistribution of magnetic materials along the slope via soil erosion by water and tillage.

χ_{fd} % is used to determine the presence of a superparamagnetic (SP) mineral fractions in the soil, which were formed inorganically (Forster et al. 1994; Liu et al. 2015; Zeng et al. 2018). The pedogenic processes are the factors controlling the concentration of SP grains. According to a semi-quantitative index defined by Dearing (1999), environmental magnetic samples can be classified into four classes: samples with χ_{fd} % < 2% and SP concentration < 10% (i.e., very few SP grains); samples with χ_{fd} % between 2% and 10% indicate the coexistence of both SP and coarser non-SP grains; samples with χ_{fd} % between 10% and 14%, and SP concentration > 75% (i.e., nearly all grains are SP); and samples with χ_{fd} > 14%, which represent rare values, erroneous measurements or contamination. According to many previous studies, polluted soils are characterized by the dominance of lower values of χ_{fd} % less than 3% (Wang et al. 2000). Ferrimagnetic minerals generated in the pedogenic processes

Table 3 Descriptive statistics for χ_{lf} ($10^{-8} \text{ m}^3 \text{ kg}^{-1}$) and χ_{fd} (%) in cultivated, pastures, and forested land

Land use in AZ	Variable	Depth (cm)	N	Min	Mean	S.D.	C.V.	Max	Median	Skewness	Kurtosis	Normality test
Cultivated	χ_{lf}	0–25	19	8.4	42.7	30.07	0.7	88.6	32.97	0.33	-1.55	N
	χ_{fd}	0–25	19	0.8	3.6	1.9	0.52	6.8	3.27	0.15	-1.27	N
Pasture	χ_{lf}	0–25	29	14.3	57.3	40.6	0.71	133.3	37.52	0.77	-1.02	N
	χ_{fd}	0–25	29	1.4	4.9	1.76	0.36	8	4.79	0.33	-0.53	N
Forested	χ_{lf}	0–25	14	12.4	107	79.35	0.74	252.8	133.6	0.03	-1.06	N
	χ_{fd}	0–25	14	0.6	4.5	2.61	0.58	8.9	5.15	-0.29	-0.97	N

χ_{lf} in $10^{-8} \text{ m}^3 \text{ kg}^{-1}$, χ_{fd} in %. S.D. means standard deviation, C.V. means coefficient of variation

are mainly in the superparamagnetic (SP) ($< 0.02 \mu\text{m}$) to stable single domain (SSD) ($0.02\text{--}0.04 \mu\text{m}$) grain sizes, while anthropogenic magnetic particles are generally dominated by multiple domains (MD) and SSD grain sizes (Ranganai et al. 2015; Hu et al. 2007; Jiang et al. 2010).

The values of $\chi_{\text{fd}}\%$ varied from 0.82 to 6.8% with a mean of 3.62% for the cultivated land, from 1.44 to 8.08% with a mean value of 4.87% for the pasture land, and from 0.62 to 8.9% with a mean value of 4.5% for the forested land (Table 3). The mean of $\chi_{\text{fd}}\%$ values in the three land use is close and in the same range. This confirms the redistribution of the magnetic grains of the same mineralogy and size. $\chi_{\text{fd}}\%$ value ranges between 0.62 and 8.9% in all the studied soil, implying the mixture of MD grains, superparamagnetic and stable single domain grains (SP-SSD), but these later are the predominant as it is shown in Fig. 6. As the anthropogenic magnetic minerals are characterized by the presence of coarser magnetic grain size, and from our results of $\chi_{\text{fd}}\%$, the anthropogenic contribution of magnetic susceptibility enhancement is excluded and confirms the pedogenesis contribution.

Variation of the mean of χ_{lf} and $\chi_{\text{fd}}\%$ profiles in topsoil from different land uses

Figure 7 shows the variation in the χ_{lf} and $\chi_{\text{fd}}\%$ means according to depth in topsoils with different land uses; an increasing pattern of χ_{lf} is noted in the upper layers of topsoil, notably from 0 to 10 cm deep.

In forested areas, $\chi_{\text{fd}}\%$ increases with a smooth slope from 20 to 15 cm in depth and decreases slightly until reaching the soil surface. The magnetic minerals remain largely dominated by SP grains, as $\chi_{\text{fd}}\%$ varies along the soil depth between 3.8 and 5.05% in average. When $\chi_{\text{fd}}\%$ increases from 20 to 15 cm in depth, χ_{lf} shows a substantial variation, increasing from 76.4 to $106.3 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ in average. This large variation could reflect the formation of pedogenetic secondary

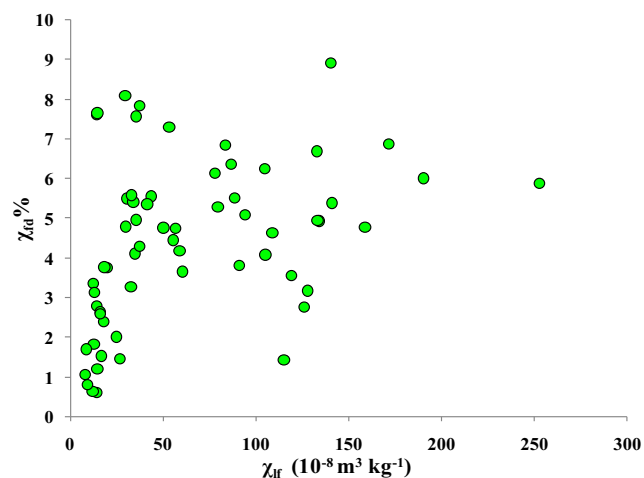


Fig. 6 Biplot $\chi_{\text{lf}}\text{--}\chi_{\text{fd}}\%$ showing the magnetic grains size of all the samples

ferrimagnetic minerals. Between 15 cm in depth to the surface, χ_{lf} decreases slightly.

Globally, $\chi_{\text{fd}}\%$ decreases towards the surface in forested soils (Fig. 7a and d), while χ_{lf} shows a maximum at 10 cm. This would indicate that changes in χ_{lf} are not governed by the SP content but the dominance of larger magnetic grain sizes. The slight decrease of $\chi_{\text{fd}}\%$ from 15 to 0 cm in depth is accompanied by a slight decrease in χ_{lf} .

Variations of χ_{lf} and $\chi_{\text{fd}}\%$ present similar or parallel patterns and reflect the impact of the pedo-environmental factors on those magnetic parameters. A decrease of χ_{lf} would be generally due to the effect of anthropogenic activity or erosion.

On the cultivated land, from 20 to 10 cm in depth, χ_{lf} and $\chi_{\text{fd}}\%$ have the same increasing pattern, but between 10 and 0 cm depth, χ_{lf} is almost stable or very slightly increasing while $\chi_{\text{fd}}\%$ decreases (Fig. 7b and e). This divergent variation in the surface layer (0 to 10 cm depth) could result from erosion of fine soil particles and clay minerals.

On pasture land, it is noted that the difference in patterns of χ_{lf} and $\chi_{\text{fd}}\%$ appears between 5 and 0 cm in depth: $\chi_{\text{fd}}\%$ decreases while χ_{lf} increases slightly (Fig. 7c and f). It would be explained by the loss of the superparamagnetic grains or fine soil particles. The fact that the established divergent behavior on top soil layers (0 to 5 or 10 cm) between χ_{lf} and $\chi_{\text{fd}}\%$ are associated with the loss of fine particles, may constitute a sustainable background for using of magnetic susceptibility as a tracer to monitor, or even estimate soil erosion or deposition.

Globally significant differences can be noted between forested, pasture, and cultivated lands (Liu et al. 2015; Yue et al. 2017; Bouhlassa and Choua 2009; Sadiki et al. 2009). The change in land use affects the distributions of ferrimagnetic minerals and superparamagnetic grains in soil profiles. Therefore, among other possible factors, χ_{lf} profiles reflect the impact of human activity on soil and could be used to establish a quantitative approach of the erosion and/or deposition processes.

Characterization and origins of magnetic minerals

Magnetic minerals in soil can be generated by four mechanisms: (i) from parent materials (Grimley and Vepraskas 2000); (ii) pedogenesis; (iii) wet and dry fallout from industrial activities (Blundell et al. 2009); (iv) and their dissolution (iron-reducing bacteria) in poorly drained organic-rich soils. Magnetic susceptibility values at various frequencies were used to obtain information on the magnetic characteristics of soil particles.

There was a positive and statistically strong correlation between χ_{fd} and χ_{lf} in all studied soils, with a correlation coefficient of $R^2 = 88\%$ (Fig. 8), reflecting the homogeneity in their magnetic mineralogy. The high correlation between the two parameters implies that the magnetic signal is basically controlled by fine-grained pedogenetic constituent (χ_{fd}). Faleh et al. (2003) obtained a close result of the interdependence between

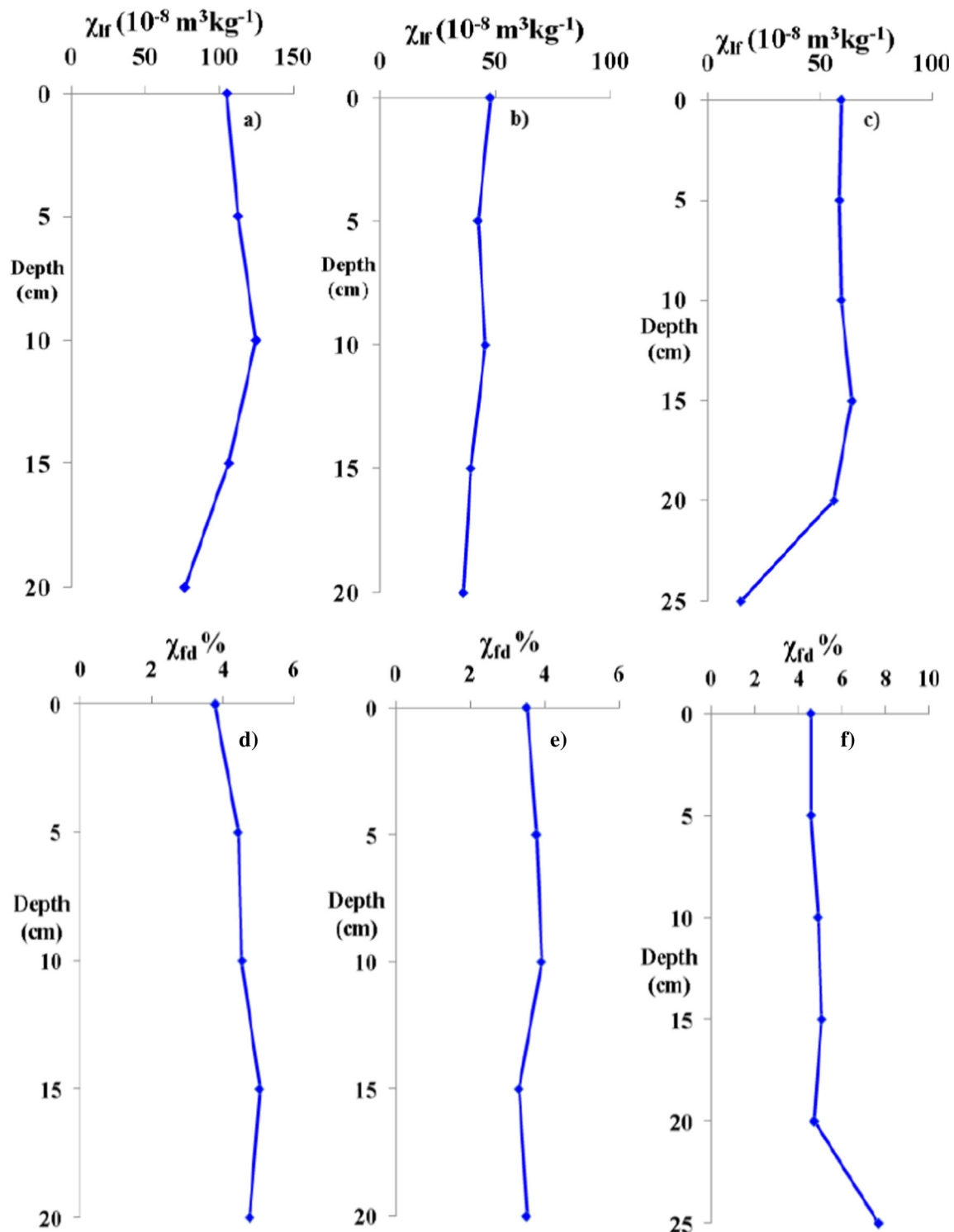


Fig. 7 Variation of the mean of magnetic parameters in 25 cm topsoil with depth. (a) χ_{lf} in the forested land; (d) χ_{fd} in the forested land; (b) χ_{lf} in the cultivated land; (e) χ_{fd} in the cultivated land; (c) χ_{lf} in the pasture land; (f) χ_{fd} in the pasture land

χ_{lf} and χ_{fd} of soils on marl substrate in their study carried out in the Abdelali watershed pre-Rif of Morocco, and confirm the predominance of superparamagnetic particles. Sadiki et al. (2009) also found analogous result. Previous studies reported that the polluted soils industrially display a negative correlation

between χ_{lf} and χ_{fd} ; however, this correlation is positive in unpolluted soils (Wang et al. 2000).

χ_{fd} was also highly dependent on χ_{lf} or, put another way, superparamagnetic particles had a high impact on χ_{lf} values. The decrease in χ_{lf} could be explained by a loss of fine

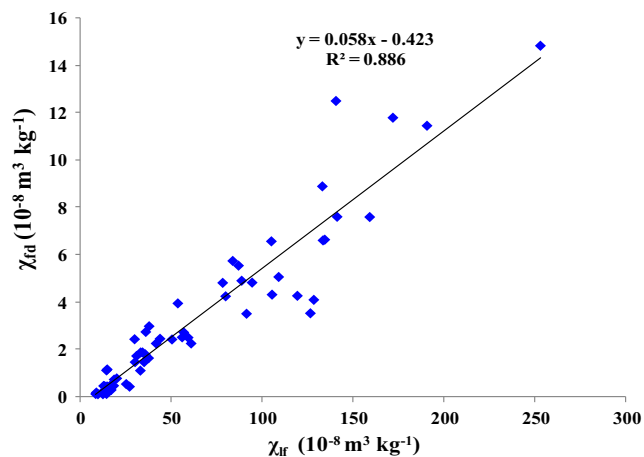


Fig. 8 Linear regressions between χ_{fd} and χ_{lf} for all the studied soils

magnetic grains through water and tillage erosion. A comparison of χ_{lf} recorded in cultivated land or pastures with stable reference soil would shed light on the qualitative and even quantitative physical instability of soil (i.e., by erosion or re-deposition).

The χ_{fd} versus χ_{lf} graph denoting values recorded in the watershed can also be used to obtain the low magnetic susceptibility background (χ_b) from the intercept on the axis where χ_{fd} is zero. The magnetic susceptibility background was $7.3 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. This value, which is associated with coarse ferrimagnetic particles and paramagnetic grains, is very low compared with the mean χ_{lf} value obtained for each land use; this result shows a weak contribution of coarse ferromagnetic grains to the magnetic susceptibility of soil.

Estimation of erosion in the Ait Azzouz catchment

Application of improved T-H model The application of the T-H model to the forested site that was assumed stable and non-perturbed in the last few decades, or even centuries, enables us

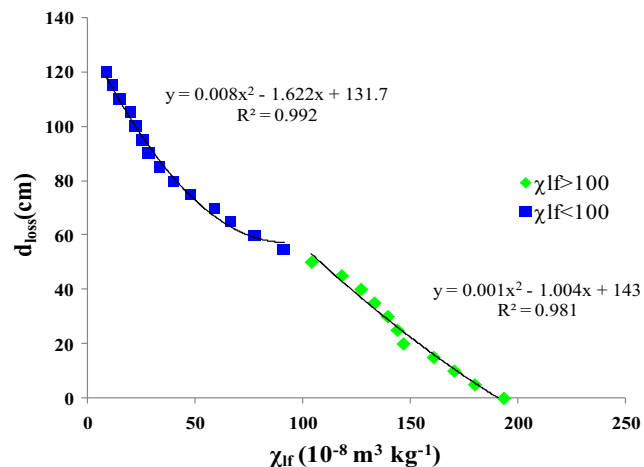


Fig. 9 The polynomial relations correlating the soil loss (in cm) to measured χ_{lf} in reference soil after tillage homogenization (T-H model)

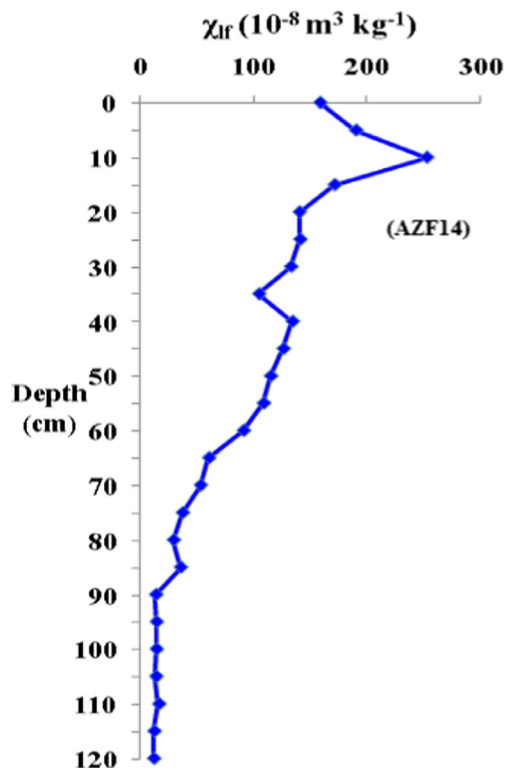


Fig. 10 Depth distribution of magnetic susceptibility χ_{lf} in reference core AZF14

to establish an approximate evaluation of the effect of surface erosion (especially the sheet erosion) on the susceptibility of plough depth soil surface. The model allows us to obtain a predictive curve of erosion depth and measured mass-specific magnetic susceptibility. Figure 9 reproduces the dependence of χ_{lf} on soil loss depth for soils related to (or having the same substratum and climatic conditions) the reference site. This is where core AZF14 extended to more than 120 cm depth, in

Table 4 Soil loss in different soil profiles after homogenization using T-H model (in cm)

Sample	Erosion by T-H model d_{loss} (cm)
AZP5	− 89.06
AZP2	− 91.51
AZP4	− 99.04
AZC12	− 99.48
AZF11	− 110.21
AZC10	− 113.44
AZF1	− 30.61
AZP6	− 52.15
AZP8	− 39.89
AZC3	− 52.04
AZC9	− 66.26
AZP16	− 80.12

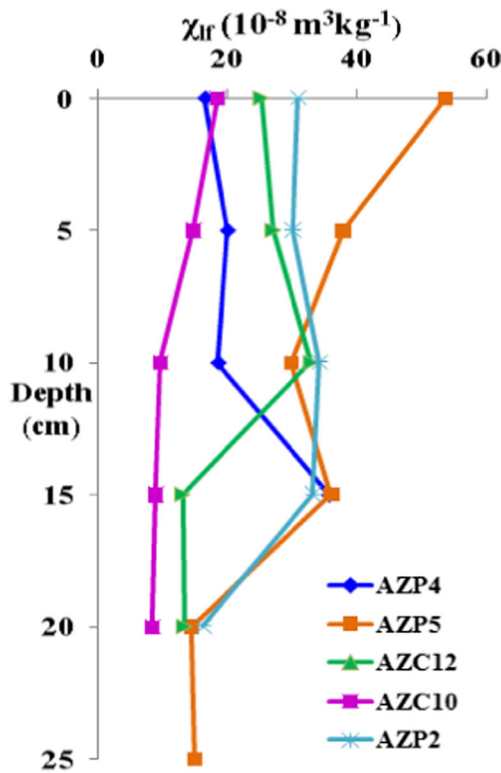


Fig. 11 Magnetic susceptibility (χ_{lf}) profiles of cores reaching lithologic substratum

order to reach parent material, is collected (Fig. 10). Figure 9 reports the polynomial relation correlating the soil loss (in cm) to measured χ_{lf} . This function gives a prediction of the continuous decrease of the values as erosion proceeds. The deduced estimates of soil surface depths eroded in different sampling sites were reported in Table 4.

Estimation of soil erosion by simple proportional model As the method required the soil cores reaching the geologic substratum, its application will be restricted in our case to sampled soil profiles reaching the parent material with χ_{lf} of about 14 to $16 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. That would be the case of the profiles AZC10, AZC12, AZP2, AZP4, and AZP5 (Fig. 11). The erosion estimate is based on the comparison of mean χ_{lf} of the soil column from surface to substratum to the mean value of the parameter for the reference core. The mean χ_{lf} (reference) defined on the core AZF14 is $87.52 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The ratio of erosion is expressed in percent or in soil column in cm which would be loosed by reference core that is 125 cm long. Table 5 shows that soil erosion that occurred in those cultivated and pastures lands are confirmed by the Royall model, giving the average thickness of surface soil layer stripped by sheet and rill erosion in sampling sites. Table 5 indicates clearly that the high erosion of about 113.4 cm of soil deduced from the Royall approach is associated to the most important ratio ($\sim 86.3\%$) or about 107.93 cm in the Liang Liu model but not to an expected value closer to 100%. Although the results obtained by these approaches are slightly different, the two methods seem to be likely useful to estimate the relative intensities and variations of soil redistribution in the watershed. The simple proportional method proposed by Liang Liu probably underestimates the soil redistribution in the watershed.

Erosion estimate using the new simple correlation model

The reference core profiles AZF14 is decomposed in 20 cm layers. The couples of mean χ_{lf} and depth determined for successive layers for the reference core are reported in the graphic shown in Fig. 12. The strong linear correlation attested by $R^2 = 0.94$ support the direct and linear relation between erosion and

Table 5 Comparison of soil erosion estimates obtained by the improved T-H model, simple correlation model, and Liang Liu or simple proportional model. The rate of erosion (t/ha) is obtained assuming soil density of 1.4 t/m^3

Sample	Associate unit in watershed	Area of associate units (ha)	Erosion rate or soil loss (t/ha) by T-H model	Mean χ_{lf} ($10^{-8} \text{ m}^3 \text{ kg}^{-1}$)	Erosion by simple correlation model (cm)	Erosion by T-H model (cm)	Ratio in % of erosion (<0) by Liang Liu or simple proportional model	Erosion by simple proportional model (cm)
AZP5	24; 28	22.04	- 12,468.4	31.035	- 70	- 89.06	- 64.54	- 80.67
AZP2	22; 26	3808.86	- 12,811.4	28.89	- 82.16	- 91.51	- 66.99	- 83.74
AZP4	22; 26	3808.86	- 13,865.6	22.67	- 85.56	- 99.04	- 74.1	- 92.62
AZC12	2; 6; 3; 4; 7; 8	9005.31	- 13,927.2	22.32	- 85.75	- 99.48	- 74.5	- 93.12
AZF11	9; 10; 13; 14; 17; 18; 19; 20	12,022.1	- 15,429.4	14.25	- 100	- 110.21	- 83.71	- 104.64
AZC10	1; 5	7055.01	- 15,881.6	11.96	- 91.40	- 113.44	- 86.33	- 107.9
AZF1	11; 12; 15; 16	1501.32	- 4285.4	128.34	- 25	- 30.61	-	-
AZP6	23; 27	496.53	- 7301	100.56	- 45	- 52.15	-	-
AZP8	23; 27	496.53	- 5584.6	116.12	- 34.53	- 39.89	-	-
AZC3	1; 5	7055.01	- 7285.6	83.47	- 52.36	- 52.04	-	-
AZC9	1; 5	7055.01	- 9276.4	55.58	- 67.59	- 66.26	-	-
AZP16	21; 25	3552.62	- 11,216.8	39.49	- 76.37	- 80.12	-	-

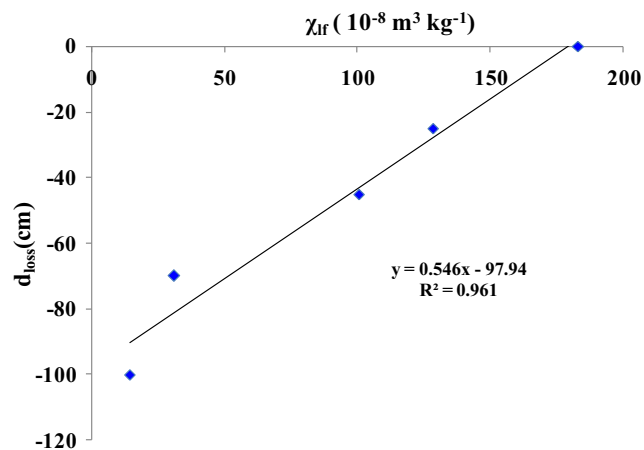


Fig. 12 Linear correlations between mean of magnetic susceptibility and soil loss (d_{loss}) in the reference core

mean χ_{lf} . The obtained graph and linear relation enables us to associate mean χ_{lf} of each soil sample and especially the ploughing layer in the watershed to an erosion estimate.

Globally, the model compares or correlates the mean sample χ_{lf} to one recorded on non-perturbed soil. The position of the sample in the graph representing mean χ_{lf} at each 20 cm versus depth for the non-perturbed soil (Fig. 12) results in erosion estimates given in Table 5.

The three methods are comparable. They lead to the same erosion variation patterns: χ_{lf} decreases while erosion increases. The values of erosion estimates by T-H model and simple correlation model are closer. Their differences are within the uncertainty limit of about ± 10 cm. The difference increases as the mean of χ_{lf} decreases. In contrast, the Liang Liu model results in lower erosion values. It seems that the Liang Liu method underestimates slightly the erosion process, as the method ignore the contribution of the soil layers below the ploughing zone after tillage to new measured χ_{lf} . That could find its justification in the limited depth of the cores and then a subsequent more important contribution of the pedogenic part in mean χ_{lf} . The application of the method needs cores reaching the soil substratum. The method we propose (the simple correlation model) overcomes this fact; it requires, as the Royall method, a stable non-perturbed pedogenetic profile on more than 20 cm depth and subsequently a reference soil core (about 1 m) reaching the substratum or parent material.

Conclusion

The study performed on a watershed having globally the same lithology and subject to the same climatic conditions enables us to state the following:

- The mean of magnetic susceptibility decreased in the order: forested area > pasture area > cultivated area;
- χ_{lf} and χ_{fd} are highly correlated. This provides clear evidence of the homogeneity of the magnetic population and indicates that the loss of fine magnetic particles is associated with a decrease in χ_{lf} ;
- As well as parent material, drainage conditions, anthropogenic impacts, χ_{lf} reflects erosion, or redeposition processes and may be used to estimate these processes;
- The erosion or redeposition estimates may be assessed by empirical approaches or models, such as “tillage homogenization and simple correlation” models, as improved and applied in this study;
- Since all sampled soils were subject to erosion, the soil losses calculated by these methods are convergent and comparable, and provide an estimate of the phenomenon during the last century.

Furthermore, this study establishes a methodology and specifies conditions that improve the use of magnetic susceptibility in the estimation of erosion or redeposition in the watershed. It effectively also devise a novel conceptual approach for the areal soil erosion-deposition in the watershed, based on its decomposition in units characterized by sets of erosion factors.

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