Using magnetic susceptibility to assess soil degradation in the Eastern Rif, Morocco

Short Title: Magnetic susceptibility to assess soil degradation

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Abstract

The soil in the Rif, Morocco, is at serious risk because increasing anthropogenic pressures are gradually transforming large natural areas into farmland. The distribution of magnetic minerals within the soil profile can be used to assess soil development and degradation. The soils in the study area are severely eroded because a combination of highly erodible soils, intense rainstorms and scarce vegetation cover. For the sampling of representative soil profiles lithology, slope gradient and land use were considered. The ranges of magnetic susceptibility in the soil profiles distinguished between two primary soil groups. Magnetic susceptibility varied in the soil profile and along the soil toposequence, and the variations

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were related to the differences in the original magnetic composition and the influence of main erosion factors. Evidently, the lithology is the main factor contributing to the variation in magnetic susceptibility. The magnetic susceptibility values in soils on Tertiary marls ($\bar{x} = 13.5 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$) differed significantly from those on Quaternary terraces ($\bar{x} = 122.1 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$). Slope affected the distribution of magnetic susceptibility because of the continuous loss of topsoil in some parts of the slope and the deposition of eroded soil in others. The elimination of the natural vegetation cover and a shift to cultivated land for cereals has had a negative impact on soil development and, on similar slopes and substrates, magnetic susceptibility decreased significantly in cultivated soils. The soils on steep slopes that had natural vegetation cover retained better the magnetic minerals than did those on gentler slopes that were under cultivation. Grazing, clearing and, especially, tilling has weakened the soil and made it much more vulnerable to erosion. An analysis of the main factors causing erosion will help to promote the rational use of the land and to establish conservation strategies in such fragile agroecosystems.

Key words: Magnetic susceptibility; soil degradation; semiarid soils; agricultural land use; Rif; Morocco.

Introduction

Semiarid areas in the Rif, Morocco, are at risk of desertification because of severe soil erosion. The combination of highly erodible soils, abrupt topography, intense storm events, and the deforestation of rangelands for agricultural use is increasing the area of degraded soils, which is having a significant effect on development in the region (Faleh, 2004).

The use of soil magnetic signatures to assess soil degradation is based on differences in the specific behaviour of iron components, which have near full control over the magnetic order

in the soil. The distribution of magnetic minerals within the soil profile provides a means of assessing the status of soil development or degradation. In stable soils, magnetic susceptibility gradually increases between the deep soil layers to surface but, in degraded soils, this pattern is absent and magnetic susceptibility is lower.

Soil particles differ in their degree of magnetism because of differences in their iron components, which control the magnetic order within the soil (Maher, 1985). In Mediterranean soils, the concentration of iron oxides due to weathering has been demonstrated by several authors (Lamouroux and Ségalen, 1969; Paquet, 1970) and studies on these processes under semiarid climate have been carried out by Sadiki (1991, 2005). Iron originates from the primary minerals contained in the parent materials, thus, it becomes concentrated in the weathered material because of its low solubility under oxidizing conditions at the natural pH. Iron is less easily integrated than is Al within the clayey secondary phyllosilicates and, therefore, iron is generally in the form of iron oxides and hydroxides, such as hematite, limonite, goethite, lepidocrite, magnetite, and maghemite (Campy and Macaire, 1989).

Iron components in the soil are good markers of soil development. In stable, undisturbed soils, increases in magnetic susceptibility parallel increases in iron from the bedrock towards the surface (e.g. Mullins, 1977; Thompson and Oldfield, 1986) but, in disturbed soils, erosion and the loss of soil particles prevents the concentration of iron components. The detection of such minerals by means of measuring magnetic susceptibility and analyses of its vertical distribution in the soil provides information on the status of the soil.

Since the 1970s, magnetic susceptibility has been used in environmental studies (Thompson et al., 1975; Walling et al., 1979; Oldfield et al., 1979), many of which mainly focused on the identification of the sources of sediments. At the catchment scale, the bathymetry of water bodies is used to quantify the erosion rate as a measure of the specific degradation in the

entire area, but this method does not identify the sources of sediments or the degree of soil degradation. Soil magnetic data have been used to reconstruct Quaternary sedimentary sequences in SE Spain (Harvey et al., 2003).

Since Dearing et al. (1985) first reported using soil magnetism to study the distribution of soil erosion, several studies have demonstrated that soil magnetism profiling is a sound technique for estimating soil losses on cultivated lands (e.g. Gennadiev et al., 2002; Olson et al., 2002). The magnetic susceptibility of soils has the potential to provide information on the specific areas where soils are most degraded and, therefore, at the greatest risk of suffering erosion. In addition, to investigate soil erosion and sediment delivery in an agricultural catchment, Royall (2001) used magnetic measurements.

To assess the feasibility of using magnetic susceptibility to track sediment movements on a semiarid hillslope, Parsons et al. (1993) introduced magnetic tracers in experimental plots under simulation rainfall in Arizona, and Hussain et al. (1998) used magnetic measurements to investigate erosion on hillslopes in Illinois. In semiarid Mediterranean regions, however, few studies have used the magnetic properties of minerals to quantify soil degradation and its relationship to changes in land use.

In the Rif region, the anthropogenic pressure to convert rangelands into cultivated fields is strong and, consequently, erosion has increased dramatically. Furthermore, the erosion has generated large amounts of sediments, which are impinging on the irrigation infrastructures in the region and therefore it is important to identify the surfaces that are suffering different degrees of erosion in the area. This study aims to assess the degradation of the soils in an area of the Msoun Basin, Eastern Rif, Morocco (Figure 1) by analysing the soil magnetic signatures along hillslope transects that are representative of the main lithologies, land uses, and slope topography of the region.

The primary objective of this study was to use magnetic susceptibility profiles to identify

features of soil degradation and to identify the sources of sediments that are contributing increasingly larger sediment loads to the drainage network of the Moulouya River, which outlets into the Mohamed V Reservoir. The reservoir is the largest in the region and drains a 50,000-km² (Lahlou, 1996). In 1967, when the reservoir was opened, the initial water capacity was 768 10⁶ m³. Subsequently, capacity has decreased drastically and, in 2002, water storage capacity was 323 10⁶ m³ (Mezghab, 2006). Thus, the average annual reduction in capacity was 11.5 10⁶ m³ (1.2% per yr). The basin of the Msoun River, which is the main tributary of the Moulouya River out of the Rif, is 2500 km² or 5% of the Moulouya River Basin, but it contributes 16% of the total sediment received by the Mohamed V Reservoir (Administration des Eaux et Forêts et de la Conservation des Sols, 1996).

Another objective was to assess the potential of magnetic susceptibility to identify the main factors that control the distribution of magnetic minerals in the soil, which, in association with other soil components such as organic matter, can be mobilized by erosion processes. The results were used to identify the areas where land-use changes have to be controlled in order to avoid desertification. Furthermore, the information gained will be used to promote conservation measures that will preserve the soil and water resources in this fragile region that is vulnerable to the effects of global climate change.

Materials and Methods

Study area

The Msoun Basin (2500 km²) is in the Eastern Rif (NE Morocco) (Figure 1). The elevation ranges between 2009 m a.s.l. at Azrou Akachar in the north and 360 m a.s.l. near the Moulouya River at Guercif. The structural divisions are the Meso-Rif, the Pre-Rif, and the Foreland, which includes the plains of the Guercif Basin and the Terni-Mezgout Mountains.

The landscape of the Rif Mountains at the north of the basin is abrupt and characterized by incised valleys where the elevation gradient is as much as 500 m. The Middle Msoun, where elevation ranges between 700 and 1330 m a.s.l., is underlain by marls of the Pre Rif, which form rounded hills. In addition, more consistent formations such as the Ouazzane nappe occupy the uppermost elevations. In the Middle Msoun, the river valley widens and a system of fluvial terraces occurs in this part of the basin. The lower section of the basin is a large plain that is composed of fluvial terraces and glacis that developed on the Neogen formations of the Southern Rif. In that part of the basin, the Msoun River is its widest and there are numerous meandering channels over an elevation that ranges between 360 and 700 m a.s.l.

In the Msoun Basin, the climate is semiarid to arid and the average annual rainfall ranges between 150 and 350 mm. The river system in the basin has a low discharge, but extreme flooding can occur after rainstorms that are often short, but very intense. In the upper part of the basin, the predominant natural vegetation is forest composed of oaks, Aleppo pine, and thuya, along with shrubs and grasses. The orchards and crops of cereals and legumes are well developed in the valleys. In the Middle Msoun, the natural vegetation is within the arid – semiarid bioclimatic zone. Matorral is the predominant vegetation cover but is degraded notably. The most common plant species are *Tetraclinis articulata* and *Lentiscus rotundifolia*. Reforestation with Eucalyptus occupies degraded areas. On the smooth slopes, there is steppe vegetation, mainly alfa grass (*Stipa tenacissima*) and *Artemisa sp.* On the flat valley floors, soils are cultivated for cereals, which have very low yields and are left fallow every second year. In the cereal fields, manure is commonly used as fertilizer. In addition, large areas are bare because of rocky or shallow soils. In the lower part of the basin, on the plains, there are mainly grasses and some irrigated areas where olive orchards and cereal crops are well established.

Soil sampling and analyses

In the study area representative transects were established to take account of some of the key factors that are involved in soil processes and the redistribution of soil particles. After a field survey identified the main physiographic units in the area and the most important factors causing soil degradation, six transects were established (Figure 1). The physiographic factors examined in this study were the parent materials, the slope gradient, and land use. The soil substrates selected were on marls and old alluvial deposits, fluvial terraces, the main parent materials from which representative soils of the area, Regosols and cromatic Cambisols, respectively, are developed (Figure 2). The slope gradients were between 10 ° and 25 °, which are common for the different land uses in the basin. Most of the land is natural forest, scrubland, grasses, cereal crops, and orchards. Five different land uses were represented in the transects. The sampling sites along the transects followed the direction of the slope and, in that way, the measures of MS in the profiles might provide information on the geodynamics of the slope.

To cover the main soil characteristics, slopes, and land uses in the study area, a soil sampling scheme was established in the transects. Sampling sites 10 m apart were established in each transect as a function of the length of the slope. Four transects (M1, M2, M3, CM4) were on marls (M1, M2 and M3) and calcareous marls (CM4) substrates that had different land uses and slopes. M1 (7 cores, C1 - C7) was on fallow land, M2 (7 cores, C8 – C14) was on cereal crops, M3 (7 cores, C15 – C21) was under alfa shrub cover, and CM4 (3 cores, C22 – C24) was on bare soils on a highly degraded slope of badlands. Another two transects (T5, T6) were on soils developed on a Quaternary formation that is a combination of glacis and old fluvial terraces. Transect 5, T5 (6 cores, C1 – C7), was on a fairly dense “matorral” that was reforested with Eucalyptus, and T6 (6 cores, C8 – C14) was on fields of cereal crops.

To determine the distribution of magnetic susceptibility within the soil profile, a 7-cm stainless steel corer was used to extract 30-cm deep soil samples, which were sectioned at 5-cm intervals. Thirty-six soil cores were collected from the hillslope transects.

The pattern of the depth distribution of magnetic susceptibility in undisturbed soils was established on relatively flat surfaces that were protected from erosion by natural vegetation cover. Those MS profiles were used as references for the natural development of the soils on each substrate. A forest of Thuya (*Tetraclinis articulata*) covered the soils on the terraces, and “Doum” grass (*Chamaerops humilis*) covered the soils on marls. Three soil cores were collected at stable sites, which served as references of undisturbed soil profiles in comparisons with the profiles at hillslope sites. In addition, a profile at a floodplain site on recent fluvial deposits and two others at sites where sediments accumulated at the bottom of a small reservoir were sampled and compared to the materials of the hillslopes within the study area.

Soil samples were dried at 40° C, disaggregated, and sieved (< 2 mm). Organic matter content was analysed (LOI) in topsoil samples (0 to 5-cm depth intervals) from each of the sampling points along the transects. For the analyses of the magnetic signatures of the soils, the 10-g profile subsamples were slightly compressed to avoid the movement of soil particles and placed into 10-ml containers. A Bartington susceptibilimeter with a MS2B probe was used to measure the magnetic susceptibility (MS) in 216 subsamples from the transects and 36 subsamples from the six reference and the control profiles. The Bartington susceptibilimeter can create an alternate magnetic field of 0.1μT at two frequencies (Dearing, 1994). The low (0.47 kHz) and high (4.7 kHz) frequencies of the Bartington susceptibilimeter provide measures of magnetic susceptibility at low (χ_{lf}) and high (χ_{hf}) frequencies, respectively.

Mass-specific susceptibility is defined as:

$$\chi = J / H$$

where H is the magnetic field applied to the subsample (Tesla), J is the magnetization per mass unit, and χ is the mass-specific susceptibility (m^3kg^{-1}).

Magnetic susceptibility at dependent frequency, χ_{fd} , is defined as follows:

$$\chi_{Fd} = \frac{(\chi_{lf} - \chi_{hf})}{\chi_{lf}} .100 \quad (1)$$

where χ_{lf} is the magnetic susceptibility at low frequency and χ_{hf} is the magnetic susceptibility at high frequency.

Magnetic susceptibility at dependent frequency provides information on the size of magnetic soil particles. At high frequency, the relaxation time of superparamagnetic grains is shorter than the measurement time then their contribution is not accounted. At low frequency, the measurement time detects the susceptibility of all grains including those that have a short relaxation time, such as the superparamagnetics, which are generally very fine. Thus, when the volume of grains in the soil is the same MS at low frequency is generally higher than it is at high frequency, and so in this study the measurements of MS at low frequency are represented in the soil profiles.

The effects of physiographic factors on the magnetic susceptibility of soils were assessed using the Least Square Method and an ANOVA to evaluate the significance of the main factors. To identify differences among class means, we used the General Linear Model Procedure of SAS.

Results and discussion

The physiographic characteristics of the transects and the other profiles sampled at the reference and control sites, and the basic statistics of magnetic susceptibility is presented in Table 1.

The values of magnetic susceptibility at dependent frequency were used to derive information about the characteristics of the magnetic soil particles in the studied soils. In all of the transects, there were positive and highly significant correlations between the interdependence of $\Delta\chi$ (the difference between χ_{lf} and χ_{hf}) and χ_{lf} (Figure 3), which indicated high homogeneity in the magnetic mineralogy of the soils corresponding with the mineral size and their contents in the soil profiles. In the soils of all transects, apart M2, there was one magnetic mineral assemblage. The transect M2 had two clearly differentiated groups that corresponded to two different mineral species in the soil. The presence of two magnetic mineral species suggests different sources derived from the mixing of weathering materials that came from parts of the slope that had differing lithologies and that accumulated in the colluvial formation at the footslope.

In the soils developed on the terraces, transects T5 and T6, the mean magnetic susceptibility at dependent frequency (χ_{fd}) was 8.8% and 9.3%, respectively (Table 1). In the soils on marls, transects M1, M2, M3, CM4, the mean χ_{fd} ranged between 5.3% and 10.1%. Therefore, in the soils of all the transects, the predominant magnetic minerals were superparamagnetics and the χ_{fd} values reflect their control of the magnetic signal (Dearing, 1994).

The magnetic susceptibility of the reference soils.

In all of the profiles of the undisturbed reference soils, MS increased gradually from the deep layers to the upper soil layers and was the highest at the soil surface. MS of the soil profiles on the terraces varied from $167 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ in deep layers to $256 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ at the soil surface, which indicated that the highest concentrations of magnetic minerals were in the upper soil layers (Figure 4). Relatively high concentrations of iron components at the surface of undisturbed profiles occur in a variety of soils, e.g., vertic meadow soils (Gennadiev et al., 2002). In the soils on marls, MS was distributed similarly, but was considerably lower and varied between $18 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ and $60 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$.

A decrease in MS with and increase in depth is a characteristic of stable soils that maintain the natural transformations that occur in undisturbed soils. On the other hand, the cultivation of soils mixes soil layers and, consequently, magnetic components. The irregular distribution of the magnetic components means that profiles differ from those in reference stable soils.

The MS in the reference soils on terraces and those on marls differed significantly. At the soil surface, MS was about five times higher in the soil on the terraces than it was on marls, and was as much as 10 times higher in the deep soil layers. The difference is due to the lower concentration of iron components in the marls substrate. In addition, the iron components in marls are within a carbonate matrix. Despite the low values in the carbonate materials, the depth profile distribution of MS might assist in the identification of the soil conditions at a particular site relative to the normal distribution of the magnetic particles in the soil.

The magnetic susceptibility in the soil profiles of the hillslope transects

As in the reference soils, in the soils on the hillslope transects, the mean magnetic susceptibility differed greatly between the soils on marls substrate ($13.5 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1} \pm 2.1$) and those on terraces ($122.1 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1} \pm 2.9$). The magnetic susceptibility in the soils developed on recent fluvial deposits ($12.5 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1} \pm 0.79$) was similar to those on the marls slopes of

the study area, which indicated that marls are the main source of the sediments, which are transported by the river system in the area. In the two control profiles of sediments collected at a small reservoir, the mean MS (12.8 and $16.0 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$) suggested that their sources also were the slope marls. Thus, it appears that Quaternary terraces have not contributed to the infilling of canals and other waters in the study area.

On the marls substrate of transect M1, the seven sample cores exhibited distinct MS profiles (Figure 5). The MS values of the three cores from the upper part of the transect (C1, C2, C3) were lower than were from the lower part of the transect (C4, C5, C6, C7). The range of MS within the upper 15 cm of the soil ranged from $3 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ to $10 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ in the cores from the upper section, and from $5 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ to $22 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ in those from the lower section. In the cores from the upper section, the MS profiles varied little with depth but, in those from the bottom section, the values of MS showed an exponential decay in the first 10–15 cm and a more homogeneous distribution in the deeper soil layers. Thus, MS at the soil surface in the bottom section of the transect was almost double that in the upper section, but the values in the deeper soil layers were similar among all of the cores. In that transect, the land was left fallow years ago and, coupled with the slope gradient, played an important role in the redistribution of magnetic components in the soil. At the top of the transect (C1, C2, C3), the slope (20°) was higher than it was at the bottom (15°). Thus, it appears that greater erosion at the top of the transect caused the loss of magnetic particles, which accumulated at the bottom of the transect and resulted in the increase of magnetic susceptibility at the soil surface. In addition, more intense soil processes at the bottom of the slope, which were in part due to water and the accumulation of nutrients from the upper part of the slope, contributed to the high MS in the uppermost 15 cm of the soil.

At transect M2, which was on land cultivated for cereals, the slope was slightly concave and the gradient decreased from 15° at the top to 10° at the bottom of the slope. MS was

greater in transect M2 than it was in transect M1 (Figure 5). The profile at the top of the transect (C8) indicated that MS at the soil surface was much higher than it was at deeper layers. The site was affected by road construction and, therefore, was not within the typical pattern of the profiles along the slope. The C9, C10, and C11 sites exhibited almost no variation in MS along the depth gradient, which indicated that the soil was mixed throughout the profile, as expected with the cultivation of cereals. In the three profiles at the bottom of the transect, MS was lower, especially at deeper soils layers, but increased at the soil surface. The increase was due to the transport by runoff of soil particles from the top of the transect, rather than to the processes involved in soil development because, at the top of the transect, sediments accumulated on the original soil. The thickness of the accumulated sediment decreased towards the bottom of the transect, where the original soil was found. At the lower part of the transect, MS was low and similar to that in transect M1, where the soils were very poor. At the top of the transect (C9, C10, C11), however, the profiles corresponded to accumulated sediments that overlay the original soil.

Along transect M3, the slope changed in shape and gradient, from 15° and convex at the upper part, then 25° in the middle, and decreased to 15° and concave at the bottom of the transect. The transect was among natural vegetation, mainly alfa grass, and the land was used for intensive grazing; consequently, the vegetation cover was degraded. The profiles at the top and bottom of the transect had high MS at the soil surface (Figure 5). The abrupt change in the slope gradient in the 10 m from site C21 to site C20, which changed from 15 ° to 25°, led to a decrease in mean MS from $14 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ to $7 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$. At the soil surface (first 5 cm), MS decreased sharply from $30 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ to $6 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$. Decreases in magnetic susceptibility with and increase in depth has been observed elsewhere (Hussain et al., 1998). The next four soil profiles showed a homogeneous distribution of MS and, paralleling the decrease in the slope gradient to 15°, MS increased. At the bottom of the transect, the depth

distribution of MS was similar to the pattern observed at the top and values were high within the first 10 cm of the soil. At the top of the transect, which is a water divide, there is no supply of soil particles and, therefore, the abundance of magnetic components within the first 15 cm should be due to the processes involved in the natural development of the soil. In addition, the site is protected from a dense cover of alfa. The magnetic components that were depleted at the soil surface in the following profiles, especially at the site that had the steepest slope, were transported down the slope and accumulated at the bottom of the transect. The lower part of transect M3 led into transect M2, (Figure 2), and the accumulation of soil particles and, therefore, of magnetic components, continued in the lower part of the hillslope.

Transect CM4 was in badlands on Miocene calcareous marls that correspond to the first phase of alteration post nappe. The soils were very poor and the 20° slope surfaces were virtually barren. In the three profiles, MS were the lowest of all profiles and comparable to those found in the deeper layers of the soils in other transects that were on marls substrates (Figure 5), which was coincident with the highest erosion rates estimated by fallout ^{137}Cs in badlands of the study area (Sadiki et al., 2007). The Regosols that underlaid transect CM4 were poorer and less developed than were the other soils on marls that had a granular structure. The MS in the profiles of transect CM4 were the lowest and only in the deeper layers was it similar to the other profiles of soils on marls. Thus, MS increased as the degree of soil development increased and it appears that MS can trace soil development. In addition, by identifying soil loss or deposition along the slope, MS profiles provide information on the geodynamics of the surface.

In the field, the homogeneous composition of marls makes it difficult to distinguish between the marls weathered in situ and the accumulated material composed of weathered marls. The analysis of the MS distribution can identify whether there is loss or accumulation of soil particles. The gradient and shape of the slope in the transects greatly influences the transport

338 of material down the slope and its accumulation, preferably, at the bottom of the slope, but
339 also to places where there are changes in slope, e.g., slope inflexion. This can be observed in
340 the steepest transects, especially in M3, which had the lowest MS among the profiles that had
341 high slopes. At the top of the transect, however, where the original soil remained, MS was
342 higher and similar to that at the bottom slope, where the soil accumulated. Along transect M1,
343 the pattern was similar.

344 At the upper part of transect M2, which was downslope of transect M3 (Figure 2), the
345 profiles corresponded to accumulated materials and not to the original soil underneath. The
346 accumulation of soil particles from the better preserved soils under alfa cover from upslope
347 caused the relatively high values of MS, but they occurred at the part of the transect where the
348 thickness of accumulated material reached its maximum in comparison with the less than 10
349 cm thickness of deposited material found at the lower part of transect M2. There, the MS of
350 the deepest soil layers corresponded to the original soil, but the increase at the upper layers
351 indicated the deposition of soil particles.

352 Along transect T5, on the cromic Cambisols developed on Quaternary terraces, the depth
353 distribution of MS was very similar in four of the six profiles (range of means = $129 \cdot 10^{-8}$
354 m^3kg^{-1} - $194 \cdot 10^{-8} \text{m}^3\text{kg}^{-1}$). Apart from two sites, MS profiles showed depth distributions that
355 were very similar to that at the reference site, although average values were slightly higher in
356 the latter (Figure 6). In transect T5, the soil remained untilled under a cover of natural
357 vegetation (matorral). Despite some degradation, the MS profiles indicated that the highest
358 values were at the soil surface and decreased with increasing depth. Those features indicate
359 relatively unaltered soils where natural soil development processes and chemical
360 transformations are preserved. At the top of the transect, the higher MS and the shape of the
361 profiles suggested the presence of better developed soils than those found in the lower part,
362 where MS profiles indicated some degradation in the upper soil layers.

In transect T6, which was on land cultivated for cereals, the profiles indicated lower MS (range of means = $64 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ - $119 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ (Figure 6). The depth distribution of MS was variable and did not exhibit a consistent specific pattern in the distribution of magnetic minerals. Tilling mixed the soil components, which increases the vulnerability of the soil to erosion and, ultimately, leads to the loss of some magnetic minerals.

On terraces, the natural vegetation cover offers good protection against soil erosion and affords the iron components a stable environment, which promotes the genesis of magnetic minerals, which was evident in some of the soil profiles in transect T5. However, a decrease in vegetation cover because of the partial deforestation in T5 causes a loss of 25% of magnetic minerals relative to the reference soil. In the 1960s, the land occupied by T6 was deforested for cultivation and the total deforestation led to the loss of as much as 50% of the magnetic minerals in the soils in just 40 years.

The MS of the soils on marls and terraces is similar to the values observed in a nearby area of the Rif (Faleh et al., 2005). Differences in the MS profiles along a transect can be a valuable tool in identifying the pattern of soil movement and relating it to hillslope processes. A magnetic tracer and measurements of magnetic susceptibility have identified areas of net detachment and deposition in experimental field plots (Ventura et al., 2001, 2002).

It appears that the magnetic susceptibility of soil can reflect the conservation status of the soil, and can indicate degradation and development. In addition, the factors that influence the MS of soils are the same as those operating on soil processes and, in this way, MS can be a useful indicator of soil stability.

Factors affecting variation in soil magnetic susceptibility

Lithology was the main cause of the wide variation in magnetic susceptibility among the soil profiles, from $13.5 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ in soils on marls to $122.1 \cdot 10^{-8} \text{ m}^3\text{kg}^{-1}$ on terraces, because of the composition of parent materials. The marls substrates had low iron mineral content, which was diluted within a carbonate matrix. On the other hand, the terrace substrate was composed of a variety of materials including magnetic minerals, some carbonate, and sandy materials. Consequently, the cromatic Cambisols, which are the soils that developed on the terraces, have high concentrations of iron components. Although the composition of parent materials determines the quantity of magnetic minerals, its effect on the development of soil is limited. In spite of the substrate, the weathering of parent materials that have low levels of primary magnetic minerals will result in soils that have low levels of magnetic minerals, even if iron is concentrated by selective solubility of other components. That said, MS profiles might indicate whether the soil is degraded or stable by comparing their MS to that in stable reference profiles on the same substrate.

Along the transects, the effects of land use appeared to be a key factor influencing the distribution of MS in the soil profiles. There were large differences in the average MS of the different land uses (Table 2). The soils that were cultivated for cereals or left fallow had significantly lower values than did those that were covered by natural vegetation (scrubland and alfa grass), with the lowest MS in the bare soils. Hussain et al. (1998) found that MS was higher in uncultivated soils than in cultivated soils. In the Canadian Prairies, de Jong et al. (1998) used soil magnetism in combination with fallout ^{137}Cs to document soil erosion. In a . In a previous research in this study area, Sadiki et al. (2007) used ^{137}Cs to quantify erosion rates. The highest losses were found in badlands ($46 \text{ t ha}^{-1} \text{ yr}^{-1}$) and in cultivated soils on marls substrate. Because, the soils developed on marls were the steepest and more erodible than were the soils developed on terraces, the soil loss measured in cultivated soils on marls substrate ($34 \text{ t ha}^{-1} \text{ yr}^{-1}$) was almost twice as high as that on terraces ($19 \text{ t ha}^{-1} \text{ yr}^{-1}$). The

erosion rates measured in cultivated soils was twice that found in uncultivated soils, where average losses were 15 and 10 t ha⁻¹ yr⁻¹ on the marls and terraces substrates, respectively.

Slope affected variations in MS (Table 3). The highest MS was in soils on gentle slopes. In the profiles on the marls substrate, generally, MS decreased as slope increased. In the situation where sediments are deposited downslope, as in transect M2, there is a mixing of magnetic minerals, some of which come from the chemical transformations of soils in situ, and others of an allocton origin that are contained in the deposited materials. If the thickness of the deposit does not exceed the total depth of sampling, it is possible to find increases in MS that indicate the location of the upper layers in the original soil.

Mineral magnetic signatures are influenced by a variety of soil properties, particularly, organic matter (Thompson and Oldfield, 1986). On average, the organic matter content is slightly higher in the soils on marls transects than elsewhere (Table 4). As expected, on marls and terraces substrates, the transects that had perennial vegetation cover (M3 and T5) had higher organic matter content (apart from transect M2, where the high OM content was due to the organic manure applied in this cereal field).

To evaluate hypotheses to explain patterns of soil magnetism, Dearing et al. (1996) studied magnetic susceptibility in soils across England by combining data for soil type, geochemistry and concentrations of magnetotactic bacteria. In topsoil samples, the strength of the relationships between organic matter and MS differed between the marls ($r = 0.782$) and terrace transects ($r = 0.533$). Organic matter explained about 60% of the variation in MS in the marls transects, but only 30% in the terrace transects. In Canada, de Jong et al. (2000) showed that magnetic susceptibility in soils varied with the slope position and soil properties such as texture, organic and inorganic C, and Fe components.

In our study, the patterns of MS and organic matter content in the topsoil (0-5 cm depth) differed along the transects (Figure 7). In some transects, high OM content was associated with low values of SM, such as at the top of transects M1 and T6, and in the middle of transects M3, CM4, and T5. At the top of transect M2, however, SM was high but OM content was low. Processes of soil redistribution associated with the topography of the slope or the mixing of the soil by cultivation and roadworks might explain those differences. In the transects on the marls, generally, MS was higher at the end of the transect, which indicated that soil particles accumulated at the footslope in these steeper transects; but, similar strong increases in organic matter content did not occur.

This study demonstrated that magnetic susceptibility profiles might provide a cost efficient, rapid means of assessing soil degradation. In the study area, the increasing anthropogenic impact that is rapidly transforming natural lands into cultivated lands poses a serious risk to the conservation of soils in regions of the Rif Mountains. Cultivation is a main cause of soil erosion, which is aggravated if cultivation occurs on steep lands. Natural vegetation protects the soil surface from erosion and the soil is best preserved when the vegetation cover is not degraded. This was also observed in other Mediterranean semiarid environments (Quine et al., 1994).

To preserve the soils in fragile environments, cultivation should be restricted to gentle slopes and soil conservation measures such as terracing together with stripes of natural vegetation should be implemented. Furthermore, the preservation of the natural vegetation cover has to be encouraged and grazing has to be managed to avoid degradation.

Conclusions

The magnetic susceptibility of soils can be used as an indicator of the conservation status of soils and provide valuable information about soil degradation and stability, as well as the

geodynamics of the surface formations. For soils on steep slopes, if erosion occurs because of loss of vegetation cover or tillage, the magnetic minerals will be exported along with other soil particles; consequently, their concentrations will decrease and the development towards minerals that have high MS will be constrained. For the soils that remain protected by natural vegetation, the distribution of MS in the profiles that had the highest values at the soil surface indicated that soil processes generating iron components were active. Cultivation tends to eliminate that pattern and the mixing of soil layers contributes to a more homogeneous distribution of iron components in the soil profile. Runoff and the transport of soil particles that are deposited in some parts of the hillslopes results in values of magnetic susceptibility that differ from those in the original soil from where the materials originate, which might be used as a quick and efficient method to identify the areas where erosion or accumulation occurs. That is relevant to areas such as the Rif Mountains of Morocco, where rapid transformation of the land is modifying the slopes. Other undesirable effects include the high sediment loads that are exported through the drainage system and contribute to the siltation of reservoirs in the region. In addition, MS might serve to identify the areas that require urgent intervention and control of the supply of sediments to canals and other water bodies, thereby increasing the functional lifespan of reservoirs.

MS has the potential to document soil degradation because it is a rapid, cost-efficient method, but further research is needed before the magnetic techniques can be adapted for the quantification of soil redistribution. The identification of degraded soils is essential for promoting strategies for better land use in the Rif, where it is necessary to preserve the soil and water resources because intense anthropogenic pressures are compromising the sustainability of agroecosystems as soils lose their fertile horizons.

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571

572 FIGURE CAPTIONS
573

574 Figure 1. Location and geology of the study area in the Eastern Rif, Morocco. Numbers
575 indicate the transects.

576 Figure 2. Landscape and physiography of the transects and reference soil on terraces (T) in
577 the Eastern Rif, Morocco.

578 Figure 3. Interdependence between $(\chi_{lf} - \chi_{hf})$ and χ_{lf} in the transects in the Eastern Rif,
579 Morocco.

580 Figure 4. Depth distribution of magnetic susceptibility in stable soils on Quaternary terraces
581 and on Tertiary Marls in the Eastern Rif, Morocco.

582 Figure 5. Depth distribution of magnetic susceptibility and variation in the soil profiles along
583 transects on marls in the Eastern Rif, Morocco.

584 Figure 6. Depth distribution of magnetic susceptibility and variation in the soil profiles along
585 transects on terraces in the Eastern Rif, Morocco.

586 Figure 7. Magnetic susceptibility and organic matter content in the topsoils (0 – 5 cm) along
587 the transects in the Eastern Rif, Morocco.

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Table 1. Physiographic characteristics of the transects, reference and control sites and basic statistics of values of magnetic susceptibility (χ_{lf} & χ_{fd} $10^{-8} \text{ m}^3 \text{ kg}^{-1}$)

Transect	lithology	Land use	Slope shape	Slope Gradient °	$\chi_{lf} \text{ my}^1$	se	$\chi_{lf} \text{ min}^2$	$\chi_{lf} \text{ max}^3$	$\chi_{fd} \text{ my}^4$
M1	marls	fallow	concave	15 - 20	7.4	2.66	2.7	22.3	10.1
M2	marls	cereals	concave	10 -15	23.9	2.72	4.1	45.2	6.5
M3	marls	alfa	convexe- concave	15 – 25	12.7	2.72	5.6	31.4	6.0
CM4	calcareous marls	bare	straight	20	6.1	4.06	4.1	10.6	5,3
Reference	marls	grasses (doun)		level	41.2	9.36	26.3	47.8	8.43
Reference	marls	pine forest		level	34.1	5.39	26.0	60.2	10,53
T5	terraces	matorral	straight	10	151.8	2.87	105.3	215.8	8.8
T6	terraces	cereals	straight	10	92.4	2.87	42.4	127.6	9.2
Reference	terraces	thuya forest		level	204.1	33.2	167.3	255.9	9,3
Floodplain	alluvial	water course		level	12.1	0.79	10.9	12.9	5.0
Floodplain	alluvial	dam		level	16.0	1,11	14.8	17.6	13.72
Floodplain	alluvial	dam		level	12.8	2.48	9.5	14.7	4.16

¹ $\chi_{lf} \text{ my}$:mean MS low frequency

² $\chi_{lf} \text{ min}$: minimum MS low frequency

³ $\chi_{lf} \text{ max}$: maximum MS low frequency

⁴ $\chi_{fd} \text{ my}$: frequency dependant MS

Table 2. Summary statistics for the soil magnetic susceptibility in function of land use.

Magnetic susceptibility 10 ⁻⁸ m ³ kg ⁻¹				
	n	average		se
<hr/>				
<u>land use</u>				
matorral	42	151.84	b	4.49
alfa	36	12.72	a	4.26
cereals	76	56.33	c	3.09
fallow	42	7.41	a	4.16
bare soil	18	6.05	a	6.35

different letters means significant differences ($p \leq 0.05$)

Table 3. Summary statistics for the soil magnetic susceptibility in function of slope.

Magnetic susceptibility $10^{-8} \text{ m}^3 \text{ kg}^{-1}$			
	n	average	se
<hr/>			
<u>slope°</u>			
< 10	72	107.72 a	3.74
10-20	115	15.34 b	3.52
> 20	35	8.4 b	5.77
<hr/>			

different letters means significant differences ($p \leq 0.05$)

Table 3. Summary statistics for the soil magnetic susceptibility in function of slope.

Magnetic susceptibility $10^{-8} \text{ m}^3 \text{ kg}^{-1}$			
	n	average	se
<hr/>			
<u>slope°</u>			
< 10	72	107.72 a	3.74
10-20	115	15.34 b	3.52
> 20	35	8.4 b	5.77
<hr/>			

different letters means significant differences ($p \leq 0.05$)

Table 4. Basic statistics of organic matter contents (%) in the topsoil samples (0-5 cm) of the studied transects.

Substrat	Transect	n	mean	min	max	sd
Marls	M1	7	3.18	2.65	3.85	0.46
	M2	7	9.44	7.38	11.37	1.66
	M3	7	4.98	3.73	7.43	1.26
	CM4	3	3.51	3.09	4.16	0.58
Terraces	T5	6	3.89	2.60	5.09	0.95
	T6	6	2.66	2.20	3.08	0.33

Figure 1

Figure 2

Marls

Transect M1

Transect M2

Transect M3

Transect CM4

Terraces

Transect T5

Transect T6

Figure 3

Figure 4

M1

M2

Figure 5

M3

CM4

Figure 5

Figure 6

Marls

Terraces

Figure 7