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Relation between magnetic parameters and nematode abundance in agricultural soils of Portugal—a multidisciplinary study in the scope of environmental magnetism

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Abstract Soil is composed of different types of particles which are either natural or of anthropogenic origin. Anthropogenic particles are often related to the presence of heavy metals and thus provide information on soil quality. Magnetic parameters can detect the presence of such particles and may be used as a proxy for environmental pollution. This study explores the relationships between magnetic particles and the nematofauna of agricultural soils. Magnetic, pedological, microscopy and nematological analyses were conducted in soils collected from major regions of potato production in Portugal. The magnetic characterisation of soils identified regions with magnetic particles with possible anthropogenic origin. Microscopy analysis revealed the presence of spherical particles dominantly composed of Fe, O and C. A positive and significant relationship was found between saturation isothermal remanent magnetisation (SIRM) and mass-specific susceptibility (χ), confirming the importance the ferrimagnetic fraction to magnetic properties. The nematode communities were composed of nematodes belonging to four trophic groups (bacterial feeding, plant feeders, fungal feeders and omnivores/predators). The relationships between magnetic parameters and the nematodes showed that (1) S_{-25} has a linear correlation with number of nematodes per kilogram of soil and with plant feeders' trophic group and (2) SIRM correlates with the bacterial feeders trophic group. This study reveals that magnetic proxies may provide means for detecting regions with higher levels of pollution, possibly related to heavy metals. Due to the large background variability found in magnetic parameters, the sampling spacial mesh should to be further refined and the input of magnetic minerals needs to be locally calibrated.

Keywords Agricultural systems · Environment · Magnetic properties · Nematodes · Portugal · Soil biota

Introduction

Environmental magnetism is a relatively new research area (e.g. Thompson et al. 1980) involving the study of magnetic particles, of which the practical applications are being explored in several research fields, including

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agriculture (Fabian et al. 2012; Lageras and Sandgren 1994). Recent studies on magnetic soil properties found that ferromagnetic s.l. particles are related to soil pollution, namely the high content of toxic heavy metals. These particles alone are not toxic or directly harmful to humans. The use of magnetic parameters as a proxy for chemical methods is possible because, due to their large surface area, magnetic particles are good absorbers of several toxic metals (e.g. Hoffmann et al. 1999; Kapička et al. 2003; Petrovský et al. 2000). According to Reimann and Caritat (2005), heavy metals are preferentially adsorbed by iron oxides and hydroxides. When a correlation between metals and magnetic properties is established, magnetic parameters can be used to characterise heavy metal loading and to assess soil quality. Pollution by anthropogenic magnetic particles associated with heavy metals can be an important issue in urban and periurban agriculture.

Belowground, organisms are important role players for soil fertility and their presence may determine the appetence of a soil for agriculture. Monoculture agriculture or long-term exposures to soil polluted with heavy metals are regarded as types of chronic disturbances which can lead to gradual species extinction and eventually decreases resiliency of an ecosystem to disturbance or disruption (Neher 2010; Park et al. 2011). In addition, some groups of organisms, such as soil nematodes, are very responsive to plant cover, land use change and chronic disturbance and are regarded as biological indicators of soil health (Yeates et al. 1993). Nematode communities can be useful ecological bioindicators of various terrestrial ecosystems, including agroecosystems because of its ubiquity, diversity, direct contact with dissolved compounds in the soil water, ease of extraction and assignment into ecological groups (Neher et al. 2005). In this study, the magnetic properties of potato soils were compared and the existence of relationships between the magnetic parameters (low-field magnetic susceptibility (χ), frequency-dependent magnetic susceptibility ($_{\text{fd}}$), isothermal remanent magnetisation (IRM), ratios $S_{-300\text{mT}}$, $S_{-100\text{mT}}$, S_{-25}, HIRM, HARD %, SIRM/χ) and soil nematofauna was assessed. Although the χ has high natural variability, as documented by Reimann et al. (2014), the measurement of this parameter has been widely used as a proxy for contamination and thus to assess soil quality as a proxy for contamination and thus to assess soil quality. Mapping of the χ of topsoils has been considered as a proxy for anthropogenic pollution (Chaparro et al. 2006; Gomes et al. 2007; Kapička et al. 2008; Lourenço et al. 2012, 2014; Lu et al. 2008; Strzyszcz and Ferdyn 2005). The $_{\text{fd}}$ reflects the presence of stable remanence-carrying minerals and provides information on the mineralogy and grain size of the magnetic fraction. According to Dearing et al. (1996), this parameter can be used as a semi-quantitative measure of the concentration of pedogenic fine-grained magnetic particles. Samples where fine-grained particles and superparamagnetic (SP) grains are present have slightly lower values when measured at high frequency. The difference estimates the ultra-fine ferromagnetic minerals. IRM is the remanent magnetism resulting from short-term exposure to strong magnetising fields at constant temperature. The S ratios discriminate between ferrimagnetic and canted antiferromagnetic mineral types. When the $S_{-300}=1$, the magnetic mineralogy is composed only of magnetite-type minerals. The lower the S_{-300}, the higher is the content of high-coercivity minerals. HARD % is approximately proportional to the concentration of canted antiferromagnetic minerals (e.g. haematite and goethite) within the sample (e.g. Walden and Ballantyne 2002). The SIRM/χ ratio is commonly used to determine the grain size of magnetic particles (e.g. Lecoanet et al. 2003) when all samples have uniform mineralogy (saturation isothermal remanent magnetisation (SIRM)). Otherwise, this ratio will be influenced not only by the grain size but also by the proportion among magnetic phases such as paramagnetic minerals for weakly magnetic soils. When the magnetic mineralogy is homogeneous, the SIRM/χ ratio indicates changes in the grain size of the magnetic minerals or in the contribution of paramagnetic minerals (Moreno et al. 2003). The identification of possible differences, in nematode communities (abundance or structure) due to natural or anthropogenic magnetic particles correlated with the presence of heavy metals, may help to understand soil biodiversity and the impacts on agriculture. This is a pioneer study aimed to relate geological information with biological and agronomical data, combining the magnetic, pedological, scanning electron microscopy (SEM)/energy-dispersive spectroscopy (EDS) and nematological data. The main objectives were as follows: (1) to characterise a range of Portuguese agricultural soils under potato cultivation through pedological, microscopy and magnetic analyses; (2) to identify the nematofauna trophic groups; and (3) to correlate the magnetic parameters and the number of nematodes per kilogram of soil/region.

Materials and methods

Areas of study, field history, and soil sampling

The agricultural fields are located in six major regions of potato production in Portugal—Aveiro, Coimbra, Guarda, Faro, Lisboa and Porto (Fig. 1)—in both urban and rural areas, and GPS coordinates were recorded at each sampling site. No nematicide or supplementary irrigation was applied in any of the fields sampled. Maize or beans were used in rotation with potato, or a fallowing period followed the potato crop. The geological background and prevailing soil types of the sampling areas were classified according to the World Reference Base for Soils of International Union of Soil Sciences (FAO 2006) (Table 1). Soil samples were collected during May–June 2012, approximately 2 weeks before potato harvest. Each soil sample is consisted of 10–20 soil cores/ha taken around the root zone at 15–20-cm depth. The cores were then combined to form a composite soil sample per sampling site.

Magnetic parameters

In the laboratory, the soil samples (43) dried at 40 °C and passed through 2-mm sieves were used for magnetic and non-magnetic analyses. The samples were then handled with small plastic spoons, wrapped in diamagnetic plastic film (Dearing 1999) and packed into 10-ml polystyrene sample holders.

The magnetic parameter χ was measured with a Kappabridge KLY-4S (Agico, Brno), $_{\mathrm{fd}}$ with a Bartington MS2 (Bartington Ltd., UK) linked to MS2B dual frequency sensor (0.46 and 4.6 kHz) and the IRM on a minispin fluxgate magnetometer (Molspin Ltd) after magnetisation in a pulse magnetiser (Molspin Ltd).

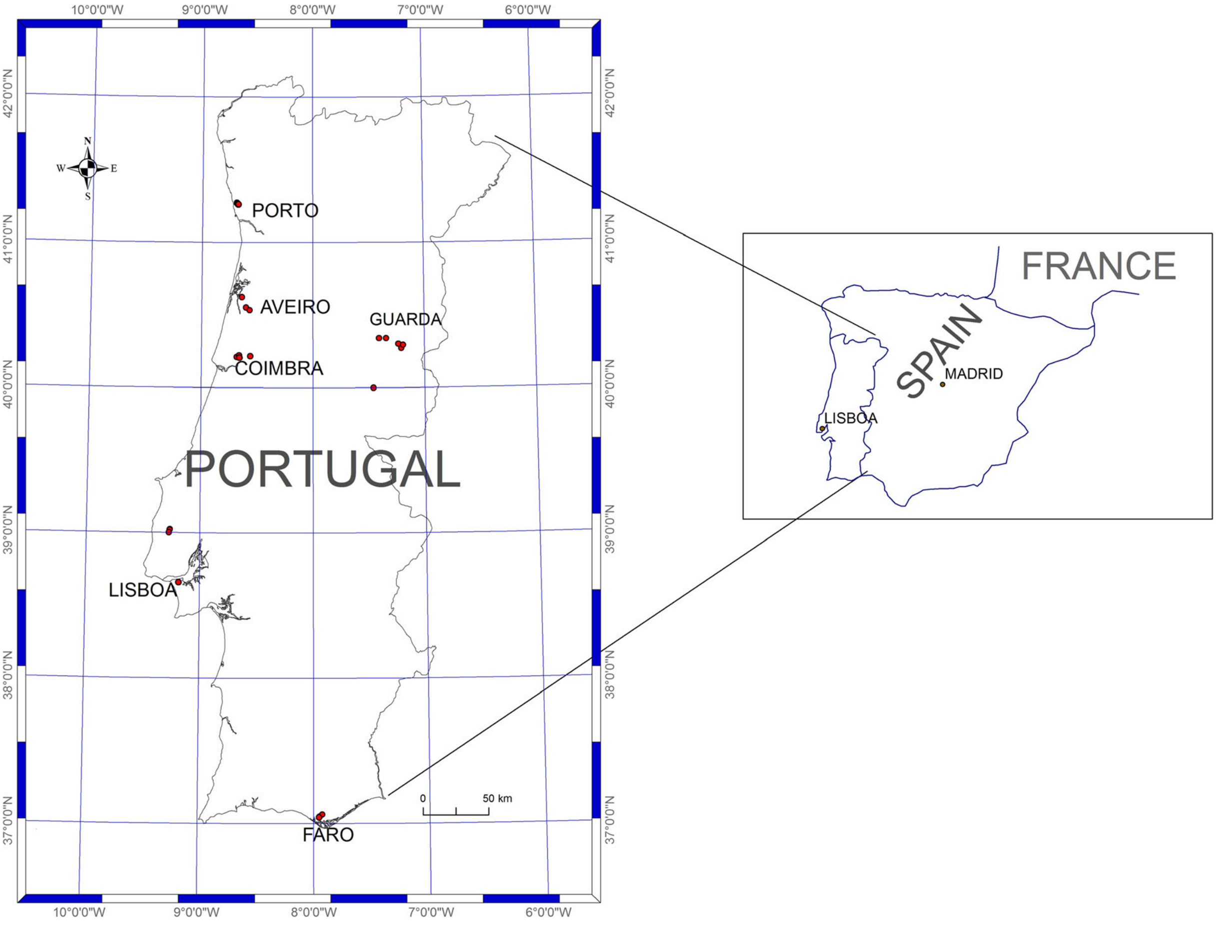


Fig. 1 Location of sampling regions

Table 1 Geological and pedological background of the studied regions

Region	Lithology	Soil type
Aveiro	Sedimentary rocks	Cambisolhumic
Coimbra	Sedimentary rocks	Cambisoleutric
Faro	Alluvial and sedimentary rocks	Fluvisolcalcaric
Guarda	Granites and metamorphic rocks	Cambisoldystric
Lisboa	Sedimentary rocks	Cambisolcalcaric
Porto	Granites and metamorphic rocks	Cambisolhumic

χ is the ratio between the magnetic field applied to a substance and the amount of magnetisation created, and it reflects the concentration of strongly magnetic Fe oxides, including those which have anthropogenic origin. This parameter is easy to measure and does not involve the destruction of the sample, which is therefore available for other analyses. The $_{fd}$, S_{-300mT}, S_{-100mT}, S_{-25mT}, HARD % and SIRM/χ were determined on the basis of the magnetic parameters. $_{fd}$ was calculated as difference percentage $_{fd}=100\times(_{lf}-_{hf})\ /\ _{lf}$. S ratios were determined using the formula $S_{-25}=IRM_{-25}\ /\ SIRM$, $S_{-100}=IRM_{-100}\ /\ SIRM$ and $S_{-300}=IRM_{-300}\ /\ SIRM$. The magnetisation acquired at 1 T was considered as the saturation (SIRM); IRM_{-25}, IRM_{-100} and IRM_{-300} are the values obtained in the 25, 100 and 300 mT back fields, respectively. The magnetic parameter HARD %=HIRM / SIRM×100, where $HIRM=(SIRM-IRM_{-300\ mT})\ /\ 2$, is based upon the amount of remanence remaining in a saturated sample after experiencing a backfield of 300 mT.

Pedological and SEM/EDS analyses

Pedological parameters were determined at the Laboratory of Soils and Fertility at the High School of Agriculture, Coimbra, Portugal, and comprised the following variables: soil texture, organic matter (OM), pH, available phosphorus (P_2O_5) and available potassium (K_2O).

SEM/EDS analyses were carried out on representative samples from each region: Aveiro (2); Coimbra (3); Faro (1); Guarda (1); Lisboa (2) and Porto (3). Magnetic extracts obtained with a hand magnet were observed in an ultra-high-resolution field emission gun (FEG) SEM, NOVA 200 Nano SEM, FEI Company. Secondary electron images were performed in low vacuum mode at an acceleration voltage of 10 kV. Chemical analyses of samples were performed with the EDS technique, at 25 kV, using an EDAX Si (Li) detector with an ultra-thin window (SUTW) type. Qualitative and quantitative acquisition and analysis of X-ray spectra (B-U) were carried out using a ZAF correction matrix.

Nematode extraction and quantification

Nematodes were extracted from soil according to the Tray Method (Whitehead and Hemming 1965). Soil was sieved using a 4.5-mm sieve to remove root fragments, and 200 g were transferred evenly onto a Kleenex sheet on a plastic net, in a plastic tray with water. After 48 h, the nematode suspension was poured through a 20-μm pore size sieve. Nematodes were observed and plant-parasitic nematodes identified at family level. Each nematode was assigned to a trophic group (bacterial feeders, fungal feeders, plant parasites/feeders and predators/omnivores) according to Yeates et al. (1993). The total nematode abundance, relative abundance of each feeding type and number of families were assessed for each sample (Chelinho et al. 2011).

Data analysis

Basic descriptive statistics of the data, including the maximum, minimum, mean, standard deviation and coefficient of variation, were performed using SPSS 19.0 software. The Spearman correlation coefficient among the various parameters was used in order to minimise the influence of extreme values and used to interpret the relationships between soil properties and number of nematodes. The values were mass-normalised so that comparison can be made among the different variables. Maps were created with ArcGIS 10.2 software. The data was organised and analysed in order to rank samples and to tentatively identify possible relationships among them.

Results and discussion

The results for magnetic measurements of the soil samples and the average values for groups of samples, representing the regions of potato production in Portugal, are given in Tables 2 and 3. χ usually exhibited low values, ranging between 0.04 and $1.62\times 10^{-6}\ m^3\ kg^{-1}$ (Fig. 2). The samples collected in Porto presented the highest χ values (Fig. 3), ranging between

Table 2 Magnetic parameters of the potato field soil samples

Region	Sample	χ (10^{-6} m^3 kg^{-1})	IRM$_{1\ \mathrm{T}}$ (10^{-3} A m^2 kg^{-1})	IRM$_{-25\ \mathrm{mT}}$ (mA m^{-1})	IRM$_{-100\ \mathrm{mT}}$ (mA m^{-1})	IRM$_{-300\ \mathrm{mT}}$ (mA m^{-1})	S$_{-25}$	S$_{-100}$	S$_{-300}$	HARD %	SIRM/χ (kA m^{-1})
Aveiro	A33	0.04	0.16	7.65	20.14	36.61	0.17	0.45	0.82	8.90	4.03
	A34	0.14	0.72	6.44	98.56	143.66	0.04	0.57	0.84	8.14	5.13
	A35	0.54	2.53	93.76	530.46	624.57	0.14	0.82	0.96	1.80	4.67
	A36	0.17	0.65	4.21	116.18	150.19	0.02	0.68	0.87	6.37	3.89
	A37	0.37	0.97	42.86	124.01	153.82	0.26	0.75	0.93	3.45	2.63
	A38	0.05	0.18	2.93	26.87	45.42	0.06	0.53	0.89	5.30	3.85
Coimbra	C1	0.14	0.50	25.94	100.68	126.35	0.18	0.70	0.88	5.93	3.49
	C2	0.26	0.77	28.10	163.69	184.42	0.14	0.82	0.93	3.68	3.01
	C3	0.07	0.31	21.58	8.19	28.64	0.30	0.11	0.40	30.07	4.18
	C4	0.04	0.15	6.40	20.59	33.53	0.13	0.43	0.70	15.12	4.00
	C5	0.09	0.31	9.53	51.26	65.86	0.12	0.64	0.82	8.83	3.39
	C6	0.09	0.25	15.99	52.25	68.14	0.22	0.72	0.94	3.24	2.85
	C7	0.05	0.20	6.16	46.85	59.44	0.09	0.71	0.91	4.72	3.85
	C8	0.13	0.42	19.03	75.42	93.27	0.18	0.70	0.86	7.00	3.34
	C9	0.46	1.21	51.79	233.70	279.59	0.18	0.80	0.95	2.29	2.66
Faro	F25	0.16	0.68	17.18	126.18	156.36	0.10	0.71	0.88	6.05	4.25
	F26	0.14	2.06	316.34	482.58	529.16	0.58	0.88	0.97	1.62	14.32
	F27	0.17	0.58	46.77	109.70	160.16	0.27	0.64	0.94	3.02	3.33
	F28	0.16	0.65	41.58	128.83	166.37	0.22	0.68	0.88	5.81	4.00
	F29	0.05	0.38	40.33	95.60	114.21	0.33	0.79	0.94	2.90	7.84
Guarda	G10	0.20	0.44	26.51	106.99	127.66	0.19	0.79	0.94	3.16	2.17
	G11	0.34	3.67	320.24	571.13	868.10	0.36	0.64	0.98	1.15	10.91
	G12	0.93	2.83	146.38	470.27	533.26	0.26	0.83	0.95	2.73	3.05
	G13	0.17	0.46	18.89	95.15	117.39	0.16	0.86	1.06	2.85	2.63
	G14	0.23	0.76	20.47	133.97	168.40	0.12	0.75	0.95	2.66	3.34
	G15	0.37	0.83	82.92	210.19	236.54	0.33	0.84	0.95	2.66	2.21
Lisboa	L30	0.13	1.03	41.54	149.85	238.79	0.17	0.63	1.00	0.12	8.18
	L31	0.16	0.70	11.27	141.01	173.38	0.06	0.79	0.97	1.45	4.49
	L32	0.09	0.48	20.12	88.35	122.26	0.16	0.72	0.99	0.52	5.56
	L39	0.13	0.42	10.80	43.96	83.13	0.09	0.36	0.68	16.22	3.23
	L40	0.27	0.90	78.44	166.96	218.22	0.30	0.63	0.82	8.90	3.29
	L41	0.52	2.64	321.01	543.16	608.93	0.46	0.77	0.87	6.74	5.07
	L42	0.14	0.61	10.14	62.50	123.21	0.05	0.30	0.60	19.99	4.33
	L43	0.08	0.55	100.89	52.15	19.82	0.60	0.31	0.12	44.10	6.51
Porto	P16	0.92	2.22	206.11	471.47	537.87	0.37	0.84	0.96	1.91	2.42
	P17	0.57	1.07	47.36	226.57	239.27	0.18	0.87	0.92	3.86	1.88
	P18	0.93	2.30	230.86	431.14	471.89	0.47	0.88	0.97	1.70	2.48
	P19	1.62	3.23	265.94	631.18	709.59	0.36	0.85	0.96	2.05	2.00
	P20	1.14	2.64	275.31	586.84	627.63	0.43	0.91	0.98	1.19	2.32
	P21	1.47	3.05	242.23	522.69	580.09	0.41	0.89	0.99	0.72	2.07
	P22	0.57	1.05	58.86	178.99	202.21	0.27	0.83	0.94	3.06	1.84
	P23	1.34	3.58	205.37	748.88	782.62	0.25	0.92	0.96	1.81	2.67
	P24	1.51	3.18	359.08	678.35	783.38	0.46	0.90	1.04	2.15	2.11

Table 3 Magnetic parameters (mean values) for the studied regions

Region	χ (10^{-6} m^3 kg^{-1})	IRM$_{1\ \mathrm{T}}$ (10^{-3} A m^2 kg^{-1})	HARD %	S_{-300}	S_{-100}
Aveiro (*n*=6)	0.20	0.87	5.66	0.89	0.58
Coimbra (*n*=9)	0.11	0.36	9.82	0.80	0.60
Faro (*n*=5)	0.14	0.87	3.88	0.94	0.80
Guarda (*n*=6)	0.37	1.49	2.53	0.95	0.78
Lisboa (*n*=8)	0.19	0.92	12.26	0.75	0.56
Porto (*n*=9)	1.12	2.46	2.05	0.96	0.87

0.57 and 1.62×10^{-6} m^3 kg^{-1}, mean=1.12. This is an industrial region with many roads including an airport and intense human occupation. These values are related not only to industrial and traffic pollution but also to the composition of the geological background (iron oxide-rich rocks).

The region of Guarda has a similar geological setting but the mean values for χ are much lower (ranging between 0.17 and 0.93×10^{-6} m^3 kg^{-1}, mean=0.37). This is a rural area where the pollution due to atmospherically deposited dust is relatively low, so the high χ may reflect the composition of the bedrock. Lithology may represent the primary effect on soil magnetic properties (Fialová et al. 2006).

The $_{\mathrm{fd}}$ as referred above is used as a proxy for the presence of fine viscous magnetic grains close to the superparamagnetic/stable single domain (SP/SSD) boundary (≈30 nm) (Dearing et al. 1996; Maher 1998). Very fine particles with short relaxation time are not detectable (Worm 1998; Shcherbakov and Fabian 2005). This parameter allows a distinction between anthropogenic magnetic particles and those which have a natural origin, which occurs often as SP grains in organic horizons as a result of pedogenic processes (Magiera and Strzyszcz 2000; Mullins 1977). We measured this parameter in a subset of samples. According to Dearing (1999), weak samples, with values of $_{\mathrm{lf}}$<10, cannot provide useful dual frequency data, and even samples with $_{\mathrm{lf}}$ values 10–25 are prone to large errors. Therefore, $_{\mathrm{fd}}$ was calculated only in samples with $_{\mathrm{lf}}$>25. In the selected samples, this parameter ranged between 4 and 10 %, confirming the dominance of multidomain (MD) and SSD grains.

Samples collected in Porto also exhibited higher values for IRM$_{1\ \mathrm{T}}$. For these samples, the S_{-300} ratio (>0.9) indicates a dominant ferrimagnetic component, with possible anthropogenic origin. The S_{-100} ratio with values <0.6 for the Aveiro and Lisboa samples indicates a major contribution from the pedogenic magnetic fraction while the parameter HARD % shows that the sam-

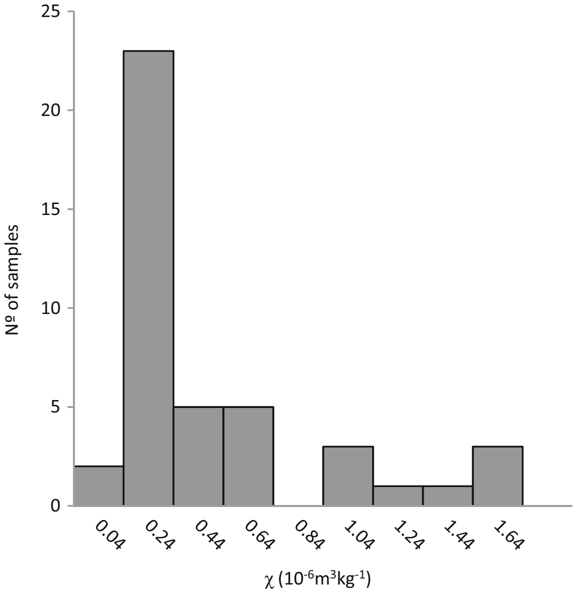


Fig. 2 Histogram of topsoil mass-specific susceptibility (χ)

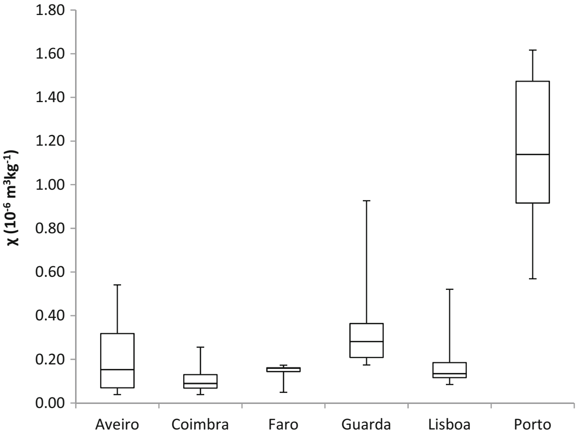


Fig. 3 Boxplot of mass-specific susceptibility (χ) values found in studied regions

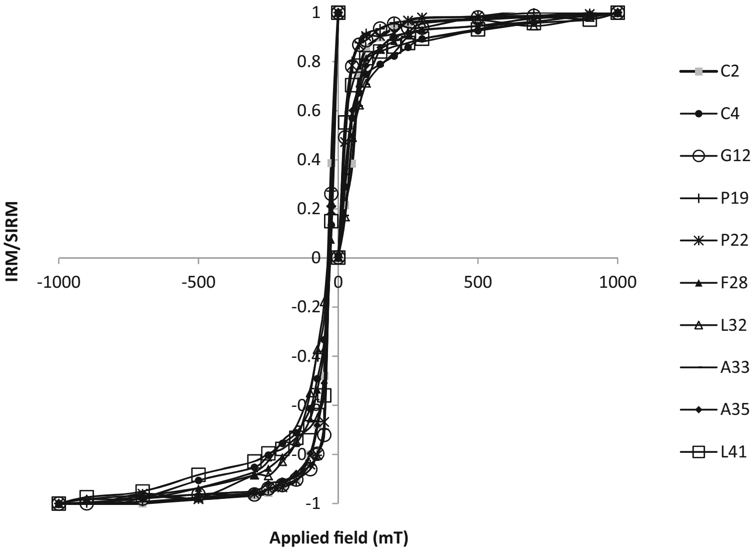


Fig. 4 Isothermal remanence magnetisation (IRM) acquisition curves for representative samples (Aveiro (A33, A35), Coimbra (C2, C4), Faro (F28), Guarda (G12), Lisboa (L32, L41) and Porto (P19, P22))

ples collected in Lisboa contain more antiferromagnetic material (hematite/goethite), which is possibly related to the composition of the bedrock (sandstones). The IRM acquisition curves for representative samples revealed that, for the majority of samples, saturation is reached at a magnetic field of 300 mT, indicating the dominant presence of ferrimagnetic minerals for these samples (Fig. 4). Only two samples, one from Coimbra (C4) and another from Lisboa (L41) do not saturate even at the maximum field of 1 T, suggesting the presence of an additional magnetic phase with high coercivity such as hematite or goethite (Thompson and Oldfield 1986).

The value of the SIRM/χ ratio is commonly used to determine the grain size of magnetic particles over several microns in diameter (Lecoanet et al. 2003). Thompson and Oldfield (1986) reported that SIRM/χ values close to 10 kA m^{-1} should be characteristic of a magnetite grain size of approximately 5 μm while Sandgren and Thompson (1990) considered that a value of 6.4 kA m^{-1} corresponds to a magnetite grain size of 8 μm. The mean values obtained for the regions of Aveiro, Coimbra, Guarda, Lisboa and Porto are lower than the value proposed by these authors, thus representing particle sizes >8 μm (Fig. 5).

On the other hand, the value obtained for Faro (6.7 kA m^{-1}) indicates a mean grain size for ferrimagnetic particles of 8 μm. According to Moreno et al. (2003), this interpretation is valid if the mineralogy is uniform. Otherwise, the SIRM/χ ratio is influenced not only by the grain size but also by the proportion among magnetic phases such as paramagnetic minerals in weakly magnetic soils. As the magnetic mineralogy pointed out by the S_{-300} was homogeneous, it can be assumed that the changes in the SIRM/χ are due to changes in the grain size.

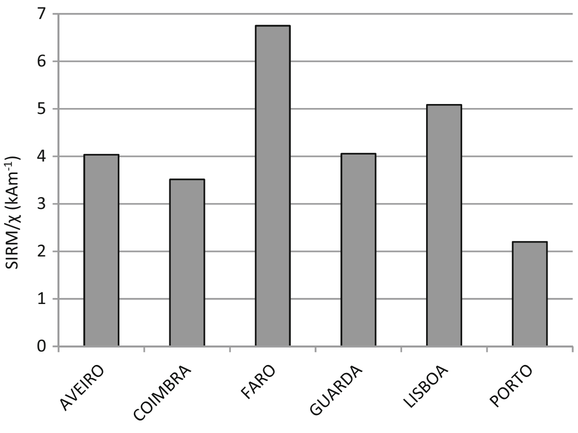


Fig. 5 SIRM/χ ratios of studied regions

Table 4 Pedological parameters for the studied regions

Region	Field texture	Organic matter (%)[a]	pH (H_2O)[a]
Aveiro	Light	2.7±0.8	5.5±0.7
Coimbra	Medium	1.7±1.0	4.9±0.6
Faro	Light	2.1±0.7	7.0±0.2
Guarda	Medium	2.4±1.1	5.0±0.9
Lisboa	Medium	1.0±0.7	7.4±0.1
Porto	Medium	3.0±0.5	4.2±0.4

Table 5 Potato soil nematode communities, expressed as relative abundance of families, allocated in four trophic groups and total abundance (sum of the organisms/replicate)

Trophic group Family	Relative abundance (%)						
	Aveiro (*n*=6)	Coimbra (*n*=9)	Faro (*n*=5)	Guarda (*n*=5)	Lisboa (*n*=8)	Porto (*n*=9)	Total
Bacterial feeders	67.83±19.46	78.47±14.87	76.16±14.08	71.1±19.12	71.13±15.89	57.35±8.14	70.97±14.58
Rhabditidae							
Fungal feeders	2.57±1.68	2.93±0.86	3.30±2.46	11.46±5.79	4.69±1.25	1.81±0.65	3.86±2.10
Aphelenchoididae							
Plant feeders	21.74±10.02	15.49±6.10	17.88±7.33	12.89±6.06	19.61±5.98	37.53±12.05	21.19±8.09
Belonolaimidae	8.70±6.04	2.26±1.25	2.86±1.22	1.95±0.96	6.63±2.90	4.41±1.55	4.22±2.10
Criconematidae	0.00±0.00	0.00±0.00	0.50±0.33	0.77±0.77	0.00±0.00	0.00±0.00	0.28±0.21
Heteroderidae	7.27±2.28	3.36±0.74	12.08±3.61	4.41±1.00	11.21±2.33	3.55±0.36	8.55±2.29
Hoplolaimidae	0.12±0.12	2.61±1.30	0.57±0.58	0.34±0.25	0.00±0.00	1.92±1.02	0.79±0.54
Meloidogynidae	0.04±0.04	0.75±0.56	1.42±1.30	1.42±2.14	0.20±0.16	0.92±0.68	0.95±0.91
Pratylenchidae	5.61±1.45	6.52±2.25	0.45±0.30	4.00±0.94	1.57±0.58	26.73±8.44	6.39±2.03
Predators/omnivores	7.86±0.93	3.11±0.59	2.67±0.53	5.33±1.20	4.57±1.19	3.31±0.19	3.98±0.67
Dorylaimidae	7.32±1.30	1.97±0.82	2.61±0.76	4.12±1.42	4.38±1.64	3.08±0.20	3.63±0.91
Mononchidae	0.55±0.31	1.14±0.29	0.06±0.06	1.20±0.76	0.19±0.14	0.23±0.16	0.36±0.20
Total abundance	4599.26±337.37	2579.79±165.25	14100.93±1075.37	3207.90±254.84	4144.84±260.79	5635.59±294.23	34268.30±397.98

Values express mean±standard error

The SIRMs/χ values were very low compared to the literature (e.g. Chaparro et al. 2011; Hay et al. 1997; Lourenço et al. 2014; Moreno et al. 2003). For the whole set of samples, this ratio varies between 1.84 and 14.32 kA m^{-1} (Table 2), and in accordance with Peters and Dekkers (2003), these values belong to the range of (titano) magnetite.

The majority of the soils presented a medium texture (Table 4), with more than 80 % of fine soil (fraction <2 mm). Concerning the organic matter

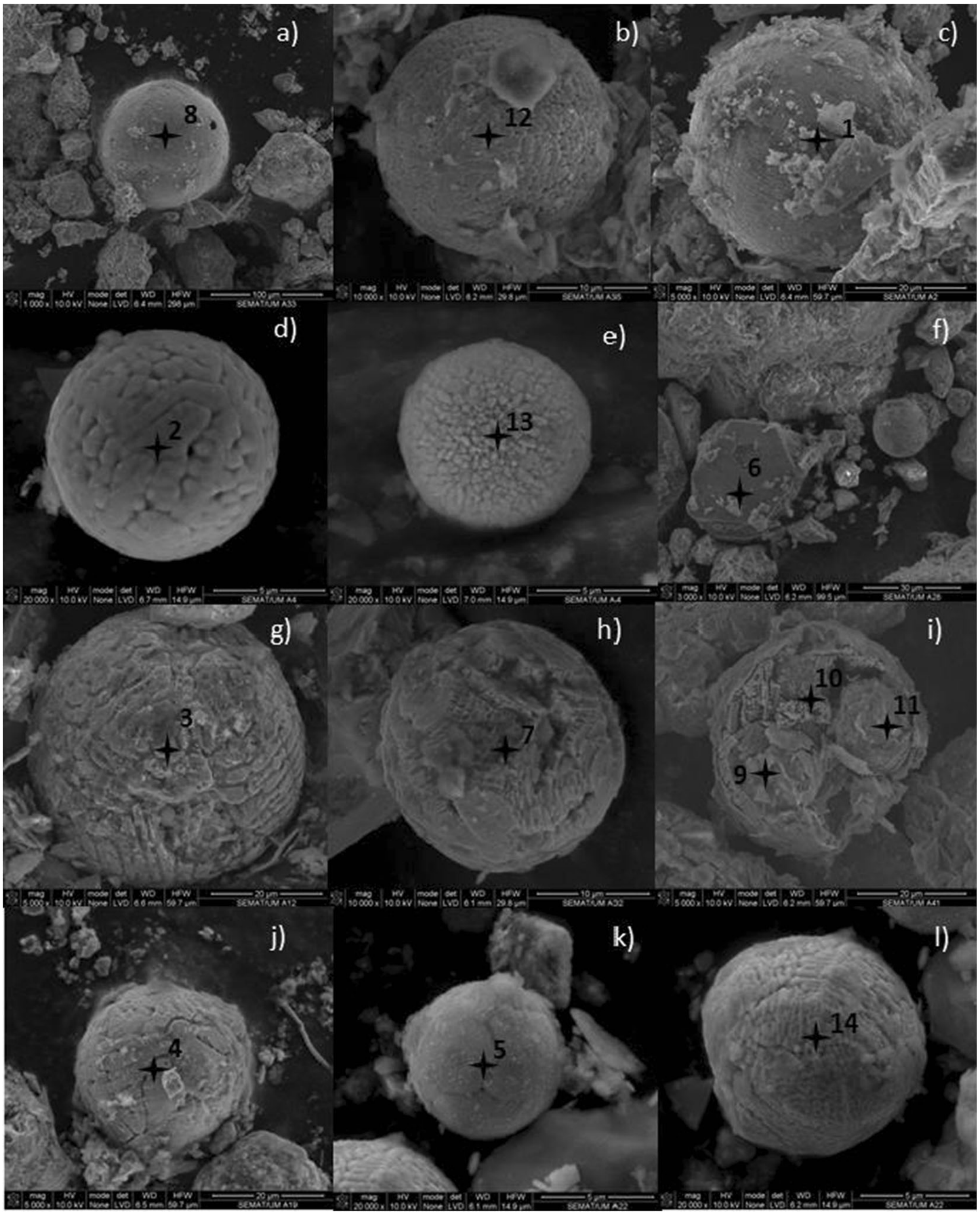


Fig. 6 Photomicrographs of magnetic particles from representative samples: **a**, **b** Aveiro; **c**–**e** Coimbra; **f** Faro; **g** Guarda; **h**, **i** Lisboa; **j**–**l** Porto. The *numbers in the pictures* indicate the locations analysed by EDS (Table 6)

contents, all the soils showed medium to low or very low content of organic matter which can be explained by the intensive agricultural practices such as ploughing.

Moreover, a continuous production of crops such as potatoes usually results in a rapid decline of soil organic matter due the low amount of crop residue that is returned to soil. Soil pH varied between very acid and slightly alkaline, being the lowest values detected in samples from Guarda and Porto, which may reflect the subjacent geological rock formation composition (eruptive and metamorphic rocks). The soil pH from Faro and Lisboa soils, originated from sedimentary rocks, ranged from neutral to slightly alkaline. In relation to the available phosphorous and potassium (data not shown), the majority of the samples had high concentrations, reflecting an intensive use of fertilisers. The nematode communities of potato soils were composed by nematodes belonging to the four trophic groups, with a clear dominance in abundance of the bacterial-feeding nematodes (70.97 %) followed by plant feeders (21.19 %) (Table 5).

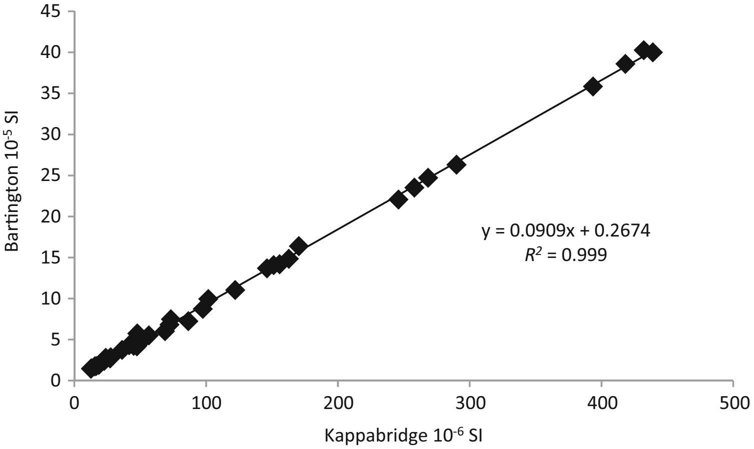
The numbers of fungal feeders and predators/omnivores were detected in low numbers. The diversity of plant feeders was the greatest among the trophic groups, and its abundance was greater in samples from Porto. Plant feeders may affect plant growth and have negative impacts on agricultural crops. Since bacterial feeders, known to influence soil mineralisation, are usually abundant in cultivated soils while predators and omnivores often disappear with cultivation (Fu et al. 2005; Wardle et al. 1995), the results obtained may therefore be typical of those found in agricultural soils. Natural areas are known to support lower nematode diversity, when compared with cropped fields (Neher et al. 2005; Sánchez-Moreno et al. 2006). In this study, a maximum of ten nematode families were found in soils from Faro and Guarda, and in the other regions, nematodes were grouped in eight to nine families. The family Criconematidae was not found in samples from Aveiro, Coimbra, Lisboa and Porto, and Hoplolaimidae was not found in samples from Lisboa. Tillage and vegetation are among the most important factors for shaping nematode assemblages in agricultural soils (Neher 2010; Neher et al. 2005). However, these can be little imputed to explain differences in the nematode composition found since all the studied soils were sampled from potato fields cropped using similar cultural practices.

The morphology of magnetic particles provided information on the origin of particles and helped to ascertain the main pollution sources in the study regions. The combination of SEM and EDS analyses supplied additional information about the morphology, size and chemical composition of the magnetic particles. Particles with spherical morphology observed in all representative samples (Fig. 6) are typical of emissions that involve the burning of fossil fuels (Flanders 1994)

Table 6 EDS analyses of the spherical particles (element content in weight %)

Region	Sample	Locationnumber	C	O	Al	Si	Ca	Fe	Mg	K	Mn	Ti	P	Zn	V	Cr
Aveiro	A33	8	10.84	35.35	10.07	16.47	0.41	16.08	2.79	5.76	0.25	1.98	0.42			
	A35	12	8.26	31.64	4.04	5.99		49.08		0.32	0.66					
Coimbra	C2	1	11.03	19.83	0.76	1.50	0.35	66.53								
	C4	2	12.70	29.63		0.44		57.23								
	C4	13	16.49	33.14	2.49	0.79	0.61	41.03	2.07					3.38	2.22	7.08
Faro	F28	6	6.81	24.14	2.27	3.31		49.04			1.02	13.41				
Guarda	G12	3	12.16	26.19	4.37	3.86		52.48	0.61	0.33						
Lisboa	L32	7	8.88	34.49	2.58	4.16	1.18	47.70	0.65	0.36						
	L41	9	4.82	48.35	12.20	17.88		12.30	1.41	1.94		0.69				
	L41	10	2.97	36.31	5.69	6.25	0.30	45.07	1.50	0.64		0.60	0.66			
	L41	11	5.41	27.35	9.74	18.66	0.95	31.95	1.00	2.98		1.26	0.73			
Porto	P19	4	14.26	31.27	1.61	1.25		51.13			0.49					
	P22	5	14.69	35.25	0.87	1.01	0.22	47.96								
	P22	14	14.47	30.78	1.31	1.26	0.26	42.15			0.47					

Fig. 7 Bi-plot for Bartington versus Kappabridge susceptibility measurements. *R* is the Spearman correlation coefficient



and have been reported in several studies (e.g. Gomes et al. 2008; Kim et al. 2009; Lourenço et al. 2014; Maher 2011; Wang et al. 2014; Yan et al. 2011; Yang et al. 2011). A variability in the surface morphology was detected from smooth faces (Fig. 6a), "brain-like" (Fig. 6d), hexagonal pattern (Fig. 6f, k), shallow dissolution structures (Fig. 6g, c) to deeper crevasses (Fig. 6j). These particles have sizes from≈5 to≈ 110 μm, and the bigger usually falls very close to their source. In fact, the bigger particles were found in samples from Porto that were collected near the airport. The chemical composition of the particles is presented in Table 6. EDS analyses identified that the spherical particles were dominantly composed of Fe, O and C, and additional minor elements including Al, Si, Ca, Mg, K, Mn, Ti, P, Zn, V and Cr.

The content of C in all particles possibly originated from fossil fuel combustion indicating their anthropogenic origin (Kim et al. 2007). Contents of elements like Al, Ca, Mg and Si were probably related to the composition of burning fossil fuels (Kim et al. 2009). The elements Cr and Ti may result from abrasion products from vehicles (Hoffmann et al. 1999; Wang and Qin 2006; Zhang et al. 2012).

Relationship among the available parameters

Magnetic parameters

In order to deal with possible differences in χ measurements made with different instruments, Bartington and Kappabridge, the results obtained on both devices were compared (Fig. 7). The linear correlation coefficient R^2 is 0.999, indicating a high degree of agreement between these two instruments.

The coefficient correlation found between SIRM and χ (Fig. 8, R^2=0.892) showed a very good correlation,

Fig. 8 Bi-plot for IRM versus χ

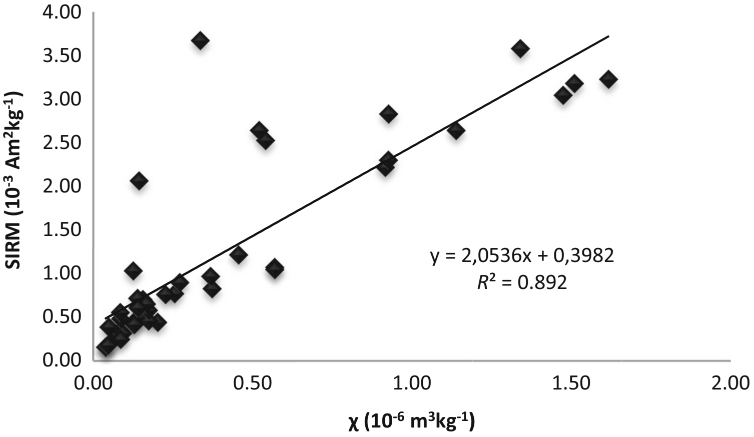


Table 7 Correlation coefficients between magnetic parameters and nematodes (n=43)

	IRM$_{1\ T}$	HIRM	S$_{-300}$	S$_{-25}$	S$_{-100}$	SIRM/χ	HARD %	χ	PLF	FGF	BTF	PD/ OM	Nematodes
IRM$_{1\ T}$	1.000	−0.613**	0.613**	0.520**	0.672**	0.974**	0.477**	0.892**	0.257	0.199	0.305*	0.001	0.234
HARD %		1.000	−1.000**	−0.332*	−0.700**	−0.590**	0.276	−0.523**	−0.198	−0.192	−0.273	−0.040	−0.258
S$_{-300}$			1.000	0.332*	0.700**	0.590**	−0.276	0.523**	0.198	0.192	0.273	0.040	0.258
S$_{-25}$				1.000	0.461**	0.507**	0.346*	0.472**	0.316*	0.181	0.291	0.127	0.305*
S$_{-100}$					1.000	0.745**	0.167	0.773**	0.252	0.031	0.061	−0.013	0.156
SIRM/χ						1.000	0.533**	0.961**	0.286	0.110	0.230	−0.004	0.195
HIRM							1.000	0.565**	0.140	−0.106	0.055	−0.141	−0.032
χ								1.000	0.275	0.011	0.148	−0.029	0.156
PLF									1.000	0.393**	0.209	0.130	0.726**
FGF										1.000	0.429**	0.007	0.814**
BTF											1.000	−0.027	0.377*
PD/OM												1.000	0.185
Nematodes													1.000

PLF plant feeders, *FGF* fungal feeders, *BTF* bacterial feeders, *PD/OM* predators/omnivores

*Correlation is significant at the 0.05 level (two-tailed); **correlation is significant at the 0.01 level (two-tailed)

confirming that the magnetic properties are mainly due to ferrimagnetic fraction (Oldfield 1991).

χ and organic matter

Despite all soils having low OM content, the correlation between χ and OM (R=0.416) was statistically significant (ρ=0.01) and reflects one of the main binding mechanisms for magnetic material in the soil. Usually, the OM content is positively correlated to magnetic susceptibility (Hanesch and Scholger 2005). According to Chaparro et al. (2002), OM is an ideal substrate for heterotrophic microorganisms which creates reducing conditions that facilitate the removal of iron in solution. However, the authigenic formation of iron oxides from Fe is also a major contributor to χ and could provide other mechanism of χ increase unrelated to pollution (e.g. Dekkers 1997).

Magnetic and nematological analyses

Table 7 lists the Spearman correlation coefficient between the magnetic parameters, trophic group and number of nematodes per kilogram. The correlation matrix indicates that IRM$_{1\ T}$ have a linear correlation (significant at the 0.05 level) with the bacterial feeders trophic group. The S$_{-25}$ ratio correlates with the plant feeders' trophic group and the total number of nematodes per kilogram. Relationships with some groups did not yield significant results, possibly because of the small number of available samples (Hanesch and Scholger 2005).

Conclusions

The magnetic characterisation of the studied soils showed that the samples collected in Porto region presented the highest χ and IRM$_{1\ T}$ values, as well as an S$_{-300}$ ratio greater than 0.9, indicating a dominant ferrimagnetic component, with possible anthropogenic origin. SEM and EDS analyses revealed the presence of particles with spherical morphology, typical of emissions that involve the burning of fossil fuels. These particles were dominantly composed of Fe, O and C and were also found in samples from Aveiro, Coimbra, Faro, Guarda and Lisboa. The SIRM/χ ratio showed that the mean grain size for ferrimagnetic particles in all regions was greater than 8 μm. A positive and significant relationship was found between SIRM and χ, confirming the importance the ferrimagnetic fraction to magnetic properties. The positive correlation between χ and OM elucidated about one of the main binding mechanisms for magnetic material in the soil. Since nematode plant feeders were more abundant in samples from Porto where the magnetic parameters suggested a high degree of pollution, this region may be a potential candidate for subsequent geochemical analyses and the impacts for agriculture should further investigated. However, due to the large background variability found in natural magnetic parameters, the anthropogenic input of magnetic minerals needs to be locally calibrated and the spacial mesh further refined. Also, a larger number of samples should be analysed and the relationships with other soil biota be assessed. Although the content of heavy metals in soils was not measured, the results revealed that magnetic proxies may provide means for detecting regions with higher levels of pollution, possibly related to higher content of heavy metals. Therefore, the magnetic parameters, namely the magnetic susceptibility, may be used to characterise heavy metal loading and to assess soil quality but in order to obtain more reliable results, it should be combined with knowledge about possible local sources, and after local calibration; in this way, magnetic susceptibility can be used as a tracer to map the extent of other parameters, e.g. heavy metal pollution. Potato is a cheap, widely consumed and ubiquitous crop that can be potentially vulnerable to metal accumulation since tubers are in direct contact with soil (Stasinos et al. 2014); thus, it is crucial to ensure the quality of soils in this crop.

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Compliance with ethical standards This article does not contain any studies with human participants or animals performed by any of the authors.

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