UNIVERSIDADE FEDERAL DE LAVRAS

Lancaster University

PEDRO LUIZ TERRA LIMA

ASSESSING WATER EROSION IN DIFFERENT LAND USES BY MAGNETIC TRACERS

LAVRAS - MG

2016

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Thesis submitted for the degree of Doctor of Philosophy as a Dual PhD with Ciência do Solo Postgraduate Program, Universidade Federal de Lavras, Brazil and Lancaster Environment Centre, Lancaster University, United Kingdom.

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LAVRAS - MG
2015

Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Lima, Pedro Luiz Terra.
Assessing water erosion in different land uses by magnetic tracers / Pedro Luiz Terra Lima. – Lavras : UFLA, 2016.
170 p. : il.

Tese(doutorado)–Universidade Federal de Lavras, 2015.
Orientador(a): Marx Leandro Naves Silva.
Bibliografia.

1. Environmental magnetism. 2. Fingerprinting. 3. Sediments. 4. Tropical soils. 5. Water erosion. I. Universidade Federal de Lavras. II. Título.

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APROVED in 14 of December, 2015.

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2015

DECLARATION

I hereby declare that this work has been originally produced by myself for this thesis and it has not been submitted for the award of a higher degree to any other institution. Collaborations with other researchers, as well as publications or submissions for publication are properly acknowledged throughout the document.

Pedro Luiz Terra Lima, Lavras, December 2015.

Dedico esta tese a Deus.

I DEDICATE

ACKNOWLEDGEMENTS

I would like to take this opportunity to first and foremost thank God for being my strength and guide in the writing of this thesis.

I would like to express my eternal gratitude to my “supervisor team”: Marx Silva, John Quinton, Barbara Maher, Nilton Curi and Alona Armstrong. Thank you very much for your guidance, teachings and support!!

Besides my supervisors, I would like to thank my viva committee: Angela Brito, Phil Haygart, Wenceslau Teixeira, Humberto Rocha and Nick Ostle for their encouragement and insightful comments.

A deep respect and gratitude to ones that made this happen, the ones that gave me strengths, patience and bravery to finish this task: my parents Luiz and Mariana (we did it!), Júlia (cheers for UK great time) and João, my love Maísa (conseguimos minha rainha!), and all my family, specially Dona Licinha, José Maria and Andréia!!!

A special thanks for friends Betania Mansur, Carlinhos Ribeiro, Damy Pádua, Dirce Macedo, Téo de Abreu, Dulce Moraes, Jean Arantes, Maria Alice, Milton Arantes, Teotônio Soares, José Roberto Pezão and Negão from UFLA, as well as Vassil Karloukovski, Sam Harris and Gareth McShane from Lancaster University, for all their help, hard work and full availability when I most needed.

Also, my sincere thanks to people at UFLA: Gabriel Carvalho, Renzo Von Pinho, Luiz Gonzaga, Carlos Silva, Fátima Moreira, Geraldo Oliveira, João José, Luiz Bebeto, Michele Menezes, Moacir Dias, Mozart Ferreira, Valdemar Faquin, Vicente Gualberto, Yuri Zinn, Adalberto Ferreira, Cristina Ribeiro, Geila Carvalho, Gilson Fernandes, Humberto Fernandes, João Gualberto, Marcio Marques, Regina Lasmar, Roberto Mesquita, José Luis e Neném; at Lancaster University: Jos Barlow (thanks for the help and opportunity), Luke

Parry, Jackie Pates and Andy Harrod; and UFRGS’s Alberto Inda Júnior for all the support and help through all those years.

I thank my fellow labmates and friends in for the stimulating discussions and for all the fun we have had in the last four years: Mateus Naza, Pedro Jipa, Leandro Campos, Bernardo Nino, Tio Zumba, Tio Lucas, Fábio José, Barbara, Diego França, Dany Guim, Fabio Arnaldo, Adnane, Dani Boy, Tom, Endrew, Wharley, Fabinho Pereira, Rodrigo Diguinho, Thais Palumbo, Karine, Jéssica, Fani, Michael Thebaldi, Mateus Vô, Rafael Baiano, Marcelo Bin, Vinicius Zina, Cazuza, Matheus Caroço, Willian Jacaré, Rafa Gatto, Fagner Badalo, Glaúcio, Fábio Pociano, Gabriel Araujo, Murilo Machado, Lucas Abreu, Betão, Anderson Robsón, João, Regi Coelho, Igor Gods, Giovanna, Raphael Siqueira, Sérgio Henrique, Guilherme Dinali, Davi, Cristiano, Romulo Alexandrino, Romulo Duarte, Bruno Montoani, Cléber Rodas, Zélio, Silas, Élen Alvarenga, Lili, Ines, Diego Capado, Eliete, Fábio Bispo, Francisco Hélcio, Gabriel Caixeta, Henrique Maluf, Luana, Maíra, Samara and Wantuir.

A special thanks to the Lancaster “family” for the friendship and support: Toru and Lisi, Rob and Beth, Andrezão, Sifah, Jack, Vito, Ciça and Al, Arlete and Caio, Antonio Capponi, Filipe, Lucas Gent, Amy Valach, Wallace and Ananza, Mari, Ruanny, Arthur, Natalie, Dany, Hannah, Anne, Ceri, Artzai and Ainara; and the Brazilians/British, Bruno and Marcela, Alexandre, Alcides Perón, Bruno Cafeo, Iago, André Moraes, Natalia, Bruno Sanderberg, Carol, Júlia, Lucas, Lilia, Beto, Kamilo, Douglas and Juliano.

Thanks to roommates and truly friends from Lancaster: Antonis, Leticia, Shuang and Bo, Petr and Victoria. It was great guys.

Thanks for everyone that somehow made this work possible!!

Finally, I also recognize my gratitude to CAPES (Coordination of Improvement of Higher Education Personnel – Process number 12082/13-9), FAPEMIG (Research Foundation of Minas Gerais State) and CNPq (National

Research and Development Council – Process number 143437/2011-9 and 167089/2014-5) for their financial support and scholarships.

“*The nation that destroys*
its soil, destroys itself.”

Franklin D. Roosevelt

ABSTRACT

This research was carried out to investigate water erosion in a tropical site (Lavras, Minas Gerais state, Brazil) accessing soil and water losses, measuring magnetic properties of different soil classes and particle sizes, as well as characterizing deposited sediments collected at bottom of downstream reservoirs. As described in article 1, rainfall erosivity and soil and water losses in standard plots were evaluated subject to different cultivation systems. Results observed lead to the conclusion that initial plant development must be intense and fast in order to protect the soil surface and prevent water erosion. Rather than using only traditional procedures for erosion evaluations, this research employed more sophisticated techniques such as magnetic environmental fingerprinting to better understand tropical soil erosion (Article 2). Magnetic properties varied according to soil classes and soil particle size. Results obtained revealed that tropical soils are mainly magnetically influenced by parent material, relief, internal profile drainage and landscape position. Their relationships were specifically linked to ferrimagnetic clay minerals. After detecting these differences, it investigated the magnetism of reservoirs sediments with purpose to associate it to different soil classes and possibly identify the sediment sources (Article 3). Pioneer in tropical soils, this research employed magnetic fingerprinting techniques to successfully find the origin of the deposited sediments, turning possible even to quantify the proportion that were originated from one or other soil class. The proposed procedure can be considered by researchers to better understand soil particle transport by erosion and find their origin.

Keywords: Environmental magnetism. Fingerprinting. Sediments. Tropical soils. Water erosion.

RESUMO

A presente pesquisa foi realizada com o intuito de investigar a erosão hídrica em uma área tropical (Lavras, Minas Gerias, Brasil) através de perdas de solo e água, mensurando propriedades magnéticas em diferentes classes de solos e partículas de solo, assim como pela caracterização de sedimentos depositados coletados no fundo de reservatórios. Como descrito no artigo 1, a erosividade da chuva e as perdas de solo e água em parcelas padrão foram avaliadas em diferentes sistemas de cultivo. Resultados observados permitiram concluir que o desenvolvimento inicial das plantas deve ser intenso e rápido com o intuito de proteger a superfície do solo e prevenir a erosão hídrica. Ao invés de utilizar apenas metodologias tradicionais para avaliações do processo erosivo, a presente pesquisa utilizou técnicas mais sofisticadas como 'fingerprinting' ambiental magnético para melhor entender erosão em solos tropicais (Artigo 2). As propriedades magnéticas variaram quanto às classes de solo e tamanhos das partículas do solo. Resultados obtidos revelaram que solos tropicais são predominantemente influenciados magneticamente pelo material de origem, relevo, perfil de drenagem interno e posição na paisagem. As relações foram especificadamente relacionadas com os argilominerais ferrimagnéticos. Após detectar tais diferenças, a investigação do magnetismo de sedimentos de reservatórios foi realizada com objetivo de associa-los com os diferentes solos e possivelmente identificar as fontes de sedimentos (Artigo 3). Pioneiramente em solos tropicais, a presente pesquisa aplicou técnicas de 'fingerprinting' magnético para com sucesso encontrar a origem dos sedimentos depositados, tornando possível até a quantificação percentual produzida por um ou mais classes de solos. O procedimento utilizado pode ser utilizado por demais pesquisadores com o intuito de melhor entender o transporte de partículas de solos por erosão e encontrar suas origens.

Palavras-chave: Erosão hídrica. 'Fingerprinting'. Magnetismo ambiental. Sedimentos. Solos tropicais.

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SUMMARY

FIRST PART – GENERAL INTRODUCTION

1. GENERAL INTRODUCTION

1.1 Tropical soils importance

By year 2050, the world will require 50% more food (PWC, 2015). In fact, one in nine people in the world does not have enough food and population increase will make this problem even worse (PWC, 2015). The major support for agriculture is the soil, which requires water from rain or from rivers, lakes and groundwater. Able to hold water, nutrients and microorganisms, this important resource should be preserved and protected against contaminants and destruction by natural events, such as rain and wind that can erode the soil.

Proper land use is the first step to preservation of such natural resource (soil) (Manzatto et al., 2002). Long-duration soil-forming in tropical soils added to natural weathering conditions, generated soils with elevated agricultural productivity with an elevated nutrient reserve and soil physical quality, due to soil structure and high organic matter content (Araujo et al., 2000; Ker, 2013). However, intense agricultural activities resulted into severe physical and chemical degradation, which lead to low fertility issues and erosion susceptibility (erodibility) increase. Among several negative effects, soil erosion promotes water pollution and siltation, crop yield depression, organic matter loss and reduction in water storage capacity (Cerdan et al., 2010; Pimentel et al., 1995).

In order to ensure a high productive agricultural system needs at a low fertility and high soil erosion scenario, accomplishing soil conservation is fundamental. A conservation agriculture approach includes use of several practices aiming productive but sustainable agriculture, such as conservation tillage, diverse crop rotations, residue management, and cover crops (Abdolahhi and Munkholm, 2014; Resende et al., 2002).

1.2 Tropical soils and the environment

Tropical and subtropical soils are subject to bioclimatic agents causing intense rock decomposition, mainly due to elevated temperature and rainfall. Climate in the tropics is distinguished into two main regions, i.e., humid tropics and subtropics regions (approximately 2 billion hectares), characterized by elevated temperatures all year long and by no or short dry season (four to five months). On the other hand, there are some tropical soils at an extended dry season region (approximately 2.5 million hectares), with a short rainy season during the summer. Typical in some parts of tropical regions such as northeast of Brazil, lack of vegetation cover combined to elevated soil erodibility makes these tropical soils inappropriate to human agricultural activities (Lepsch, 2011).

Global demand for food and other agricultural products directly affects tropical countries and their soils. Tropical agriculture makes major contributions to global markets, e.g. half of orange juice in the world is produced in Brazil as well as one third of soybean and coffee. Meanwhile, one fifth of sugar and ethanol is also supplied by Brazilian agriculture (PWC, 2015). As a result, extensive agriculture activity expanded intensively in the last decades (Peres et al., 2013). In Brazil, deforestation rates are still increasing considerable in the *Cerrado* biome due to agribusiness expansion (Soares-Filho et al., 2014). Such intense agricultural activity can result into severe environmental problems, for instance enhancement of soil degradation (Lal, 2001; Jorge and Guerra, 2013). Another major issue of such intensive agriculture is transport of nutrients and other contaminants adsorbed to the suspended particles soils eroded and its sedimentation at lakes and reservoirs (Lepsch, 2011).

1.3 Sedimentation at lakes and reservoirs

Lakes and reservoirs serve several purposes, such as supply of water to irrigation, industries, humankind necessities, hydropower generation, flora and fauna preservation, among others (Garg and Jothiprakash, 2013; Von Sperling, 2014). Therefore, water quality and reservoirs storage capacity are vital to sustain an increasingly human equilibrated need (Garg and Jothiprakash, 2013). As mentioned above, soil erosion can reduce water storage capacity by deposition of eroded soil particles (sedimentation) transported to low lands, rivers and reservoirs (Troeh et al., 1980).

Sedimentation can result in several negative effects, e.g. reservoir's soil and water pollution. Nutrients enrichment at lakes and reservoirs (eutrophication), mainly nitrogen and phosphorous, results in disorganized increase of alga and plankton, consequently reducing oxygen levels in water degrading aquatic habitats (Lepsch, 2011; Walling, 2013).

Another main concern regarding sedimentation elevated rates is related to reservoir maintenance. Brazilian Electric Energy Agency (ANEEL) evaluated sedimentation in reservoirs used to generate electricity. In its report, Carvalho et al. (2000) predicts that national reservoirs are reduced 0.5% per year due to sedimentation, which allows predicting an average life of 200 years. Around Federal University of Lavras, the Funnel Lake built to generate electricity, extended through 38 thousand hectares, can accumulate 10.5 cm of sediments every year since 2004 when it was built (Santos, 1998), and there is a 1.05% capacity decrease per year due to sedimentation (Soares, 2015). The source of sediments is mainly agricultural and mining activities. In fact, concerns regarding reservoirs maintenance are worldwide, due to soil erosion and consequent siltation, consequently reducing water storage capacity (Yutsis et al., 2014; Hosseinjanzadeh et al., 2015). The World Bank expects that worldwide reservoirs life has been reduced from 100 to 22 years only (Mahmood, 1987).

For instance, sediment deposition in reservoirs has caused a 66% reservoir loss capacity in China (Wang and Hu, 2009). Elevated decrease (5-12% total storage capacity reduction) of a Mexican small-scale reservoir was also reported as a result from sediment siltation (Yutsis et al., 2014).

The main objective of sedimentation studies is to identify sediments sources. Sedimentation sources prediction are complex, due to processes that may vary with watershed sediment production, transportation rate and deposition mode (Hosseinjanzadeh et al., 2015). Several models have been proposed on reservoir sedimentation prediction, both at individual/small or at global/national scales (Yang and Lu, 2014).

1.4 Erosion processes

Soil erosion and the processes involved in such natural phenomenon are widely discussed in literature (Troeh et al., 1980; Pimentel et al., 1995; Lal, 2001; Pimentel, 2006; Pruski, 2009; Bertoni and Lombardi Neto, 2010; Lepsch, 2011; Jorge and Guerra 2013). Erosion processes include the detachment, transport and deposition of soil particles. Energy created to initiate such erosion processes are mainly physical (such as by wind and water), by gravity, by chemical reactions, and by anthropogenic perturbation (Lal, 2001).

Consequently, erosion process will decrease soil structural stability and increase soil erodibility, enhancing soil particles transport by overland flow and interflow (Lal, 2001). The intensification of agricultural activities, mentioned above, generates severe soil and water erosion problems as a result from agricultural mechanization and excessive soil preparation insertion worldwide. Erosion directly affects ecosystems stability, causing for example irreversible land degradation, especially at tropical and subtropical countries where climate activity is more accentuated (Verstraeten et al., 2003).

Soil natural susceptibility to erosion processes is mainly a function of the interaction between climate, relief and soil type. It is a natural process that can be intensified by human activities. To understand soil susceptibility distribution in a tropical country like Brazil, Coelho et al (2002) stablished five erosion classes (table 1.1). Classes were distinguished each other by estimation of soil losses in experimental evaluations and interaction among several factors responsible for erosion susceptibility. Areas classified as very low and low comprise areas where are located very deep soils and lowland soils, both hydromorphic and non-hydromorphic; while medium, high and very high classes comprise soils more susceptible to erosive processes, such as sandy soils and shallow soils.

Table 1 Area extension and distribution of natural soil erosion susceptibility in Brazil's regions, adapted from Coelho et al. (2002)

Erosion Classes	Brazil's Regions										Brazil	
	North		Northeast		Center-west		Southeast		South			
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Very Low	306,533	8	38,389	3	82,518	5	7,493	1	5,690	1	440,623	5
Low	1,427,765	39	732,576	30	732,576	45	423,368	46	154,863	28	3,200,561	39
Medium	647,286	17	319,543	34	318,543	20	125,002	14	151,257	27	1,760,944	21
High	1,141,371	31	229,260	23	229,260	14	189,422	21	82,124	15	1,991,218	24
Very High	198,114	5	256,177	10	256,177	16	168,970	18	164,859	29	943,980	11

Brazil’s large area gives a great variation of edaphoclimatic environments, promoting a natural soil susceptibility variation from region to region (table 1.1). Traditional soil erosion plots research studies have been conducted all over the country during the past decades especially in the Southeast and South regions of Brazil. Several studies involving erosion at different crops, system managements for Brazilian tropical soils are listed in table 1.2.

Table 2 Summary of references on soil and water erosion losses, under natural and artificial rainfall, at Brazilian tropical soils studies

Brazil's region	State	Soil	Soil Erosion (Mg/ha/year)	Study scale/plot	Duration (years)	References
NO	RR	A	0.11 - 1.16	1 x 10 m	1	Barros et al. (2009)
NE	PB	L	0.1 - 61.7	Macroplots	8	Albuquerque et al. (2001)
CW	GO	L	16.86 -	3.5 x 22.1 m	5	Silva et al. (1997)
	MS	L	0.6 - 6.9	3.5 x 22 m	7	Hernani et al. (1999)
		L	0 - 0.505*	4.0 x 24.0, 14.0 x	1	Cândido et al. (2014)
	MT	L	0 - 10	3.5 x 22.1 m	1	Leite et al. (2009)
SE	ES	A / P	0.03 - 41.83	4.0 x 12 m	4	Martins et al. (2003)
		A / P	0.04 - 25.55	4.0 x 12.0, 12.0 x	7	Martins et al. (2010)
	MG	A	0 - 13.2*	2.0 x 2.0 m	< 1	Schaefer et al. (2002)
		A / L	10.44 - 12.72	3.5 x 21.7 m	3	Marques et al. (1997)
		C	3.4 - 151.2	36 m^2	1	Santos et al. (1998)
		C / L	14.90 -	3.0 x 9.0 m	5	Silva et al. (2005)
		C / L	5.6 - 776.0*	3.0 x 8.67 m	5	Aquino et al. (2013)
		L	0.01 - 1.77	4.0 x 24.0, 14.0 x	1	Brito et al. (2005)
		L	0.01 - 4.89	4.0 x 24.0, 14.0 x	2	Pires et al. (2006)
		L	1.27 - 2.89*	4.0 x 12.0 m	< 1	Castro et al. (2011)
		L	0.24 - 2.38*	4.0 x 12.0 m	< 1	Cardoso et al. (2012)
		L	0.18 - 7.67*	4.0 x 12.0 m	< 1	Dias et al. (2013)
		L	1.14 - 4.20*	4.0 x 22.1 m	< 1	Lima et al. (2014)
	SP	A	0.03 - 12.24	Multiple sizes	12	Prochnow et al. (2005)
		L	0 - 0.09*	0.5 x 1.0 m	< 1	Silva et al. (2012)
SO	RS	A	0.18 - 1.60*	3.5 x 11 m	< 1	Cassol et al. (1999)
		A	0.1 - 59.4	3.5 x 11 m	1	Levien, Cogo (2001)
		A	0.03 - 37.80	3.5 x 22 m	7	Amado et al. (2002)
		A	0.054 -	3.5 x 11 m	< 1	Gilles et al. (2009)
		A	0 - 4	3.5 x 11 m	2	Bagatini et al. (2011)
		A / C	1.1 - 6.2*	4.0 x 12.0 m	< 1	Oliveira et al. (2013)
		L	0.01 - 11.50	50.0 x 24.0 m	1.5	Cogo et al. (2003)
	SC	C	0.02 - 111.83	3.5 x 22.1 m	6	Schick et al. (2000)
		C	0.02 - 56.85	3.5 x 22.1 m	2	Guadagnin et al. (2005)
		C	0.036 -	3.5 x 11 m	< 1	Luciano et al. (2009)
		L	0.06 - 146.25	4.0 x 11 m	6	Beutler et al. (2003)
		N	0.02 - 22.51	3.5 x 11 m	1	Mello et al. (2003)
		N	0.02 - 25.70	3.5 x 11 m	2	Leite et al. (2004)

NO: North; NE: Northeast; CW: Center-West; SE: Southeast; SO: South; A: Argisol; C: Cambisol; L: Latosol; Ni: Nitosol; P: Plintosol. *Data with soil erosion rate in Mg/ha/period of study.

The Brazilian Agriculture Research Agency (EMBRAPA) issued a report where Hernani et al. (2002) estimated soil losses, in Brazil, as 823 million tons annually. The authors quantified its economic impact to be equivalent to 3 billion US dollars, but if we consider the food that could be produced throughout soil´s life, the quantity would be much larger.

In order to reduce water erosion, technical assistance and agricultural extension governmental agencies introduced and spread soil and water conservation practices all over Brazil (Cassol, 2014). Conservation agriculture practices includes conservation tillage, crop rotations, residue management and cover crops (Abdollahi and Munkholm, 2014).

1.4.1 Soil erosion evaluation techniques

Large efforts have been carried to evaluate soil erosion and several methods have been proposed. The development of the Universal Soil Loss Equation (USLE), by Wischmeier and Smith (1978) was a landmark. Used in many countries, USLE equation was developed from standard sized plots. These plots were used to measure erosion from different tillage systems using 10,000 plots through the Eastern of United States. In the following decades, several models were developed to identify the detachment, transport and deposition of soil particles. Such erosion models differ each other in complexity and can be classified as empirical, statistical, conceptual or based in physical processes

(Merritt et al., 2003). The USLE integrates several parameters in order to obtain soil losses, as follows:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where: A refers to soil losses (Mg ha^{-1}), R is the rainfall erosivity index (MJ mm ha^{-1} h^{-1}), K is the soil erodibility (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the length slope factor, P is the conservation practice factor and C, soil cover factor that measures the combined effect of all the interrelated cover and management variables (Wischmeier and Smith, 1978). Traditional erosion plots for monitoring water erosion by USLE, although capable of collect important information on such natural process, do have limitations in terms of data representativeness, as well as spatial and temporal resolution, and elevated costs involved (Higgitt 1991; Armstrong et al., 2012; Guzmán et al., 2013; Deasy et al., 2014).

Other water erosion evaluation methods have unsuccessfully been proposed, such as by the use of a gauging station (Hudson, 1993). Application of fallout radionuclides for evaluation of erosion and sedimentation rates are developing, especially by its most widely used radionuclide, ^{137}Cs. However, such technique it can be only successfully used in the Northern Hemisphere, where it's concentration is still easily detectable (Golosov, 2014).

In order to try to get over these problems, fingerprinting offers exciting possibilities on measuring soil and water erosion.

1.4.2 New soil erosion evaluations techniques

The quest for alternative methods of soil loss measurements, complementing water erosion traditional methods, has led to the use of tracing approaches in order to evaluate and determine soil particle/sediments losses rates by erosion and to track soil redistribution trough the watershed (Guzmán et al., 2013).

There are two types of soil tracing methods (Armstrong et al., 2014). First one is by using existing soil properties, whereas studies using the natural properties of the soil includes radionuclides, ^{137}Cs, ^{210}Pb, ^{7}Be, magnetic properties and fingerprinting techniques which generally use a suite of measurements such as metals, base cations, organic constituents and natural magnetic. The second tracing method is by adding foreign material or labels to the natural soil, such as rare earth, artificial magnetic particles, fluorescent glass particles, steel nuts and radioactive elements. Summarized references of the erosion studies with tracers are presented in table 1.3, adapted from Guzmán et al. (2013).

Table 3 Summary of references on erosion studies with tracers, adapted from Guzmán et al. (2013)

Tracer type	References
Fallout radionuclides	[a]Benninger et al. (1998), Dai et al. (2011), Kronvang et al. (1997), Li et al. (2010), Porto et al. (2011), Walling et al. (2000), Zhang and Walling (2005); [b]Bacchi et al. (2000), di Stefano et al. (1999), Estrany et al. (2010), Lu and Higgitt (2000), Mabit et al. (2009), Mizugaki et al. (2008), Montgomery et al. (1997), Walling and He (1999), Walling et al. (1999), Wilson et al. (2008), Yang et al. (2006), Yin and Li (2008); [c]Belyaev et al. (2010), Fifield et al. (2010), Hassouni and Bouhlassa (2006), Higgitt et al. (2000), Li et al. (2009), Mabit et al. (2008), Olson et al. (2008), Quine et al. (1999a), Schuller et al. (2000), Wallbrink et al. (2002), Walling et al. (2009), Zhang et al. (1998); [d]Quine et al. (1999b), Syversen et al. (2001).
Rare earth elements	[a]Mahler et al. (1998); [b]Kimoto et al. (2006a), Polyakov et al. (2009); [c]Deasy and Quinton (2010), Matisoff et al. (2001), Stevens and Quinton (2008), Yang et al. (2008); [d]Kimoto et al. (2006b), Li et al. (2006), Michaelides et al. (2010), Polyakov and Nearing (2004), Pu-Ling et al. (2004), Zhang et al. (2003).
Soil magnetism and magnetic substances	[a]Dearing et al. (2001), Maher et al. (2009), Slattery et al. (2000), Walling et al. (1979), Yu and Oldfield (1993); [b]Hardy et al. (2000), Royall (2001); [d]Armstrong et al. (2010), Armstrong et al. (2012), Guzmán et al. (2010), Ventura et al. (2002).
Other tracers	[d]Bennett et al. (2010), Mentler et al. (2009), Plante et al. (1999), Sharma et al. (2009), Spencer et al. (2011), Yu et al. (2011).
Fingerprinting studies	[a]Barcellos et al. (1997), Collins and Walling (2002), Collins et al. (1998), Cunha et al. (2006), de Junet et al. (2009), Devereux et al. (2010), Fox and Papanicolaou (2008a, b), Juracek and Ziegler (2009), Kouhpeima et al. (2011), Martínez-Carreras et al. (2010a, b), Miller et al. (2005), Minella et al. (2008), Motha et al. (2003), Nosrati et al. (2011), Poulenard et al. (2009), Rhoton et al. (2008), Russell et al. (2001), Rustomji et al. (2008), Schoonover et al. (2007), Walling et al. (2008); [b]Fox and Papanicolaou (2007), Miguel et al. (2014), Poleto et al. (2009); [c]Bellanger et al. (2004).

[a] Studies made at large catchments (>100 ha); [b] Studies made at small catchments (<100 ha); [c] Studies made at hillslope scale; [d] Studies made at small plot or laboratory scale.

1.5 Environmental magnetism

Environmental magnetism is a valid option in monitoring soil erosion, specially due to different types of magnetic behaviour present in the soil particles. Diamagnetism happens only when an external (natural or artificial) magnetic field is applied. When such field is removed, the induced moment is lost and the electrons orbits process randomly to positions giving no net moment. Despite been an important magnetic behaviour, it is weak or even negative and can be easily disguised by other substances. The most common natural examples are the ones with no iron content, like Quartz (SiO_2) or calcium carbonate ($CaCO_3$), and also water and organic matter (Walden et al., 1999).

The paramagnetism magnetic behaviour is produced where a substance has some atoms with unpaired electrons and therefore a net magnetic exists. Interactions of atomic magnetic moments with each other are small, because of the distance between atoms. When there is not an applied field, the magnetic moment is zero, once there is a random orientation of such magnetic moments. Within an applied field, the magnetic moment tends to align in the same direction as the applied field. However, when the field is removed such alignment disappears and no net moment remains. The paragnetism is greater than the diamagnetic effect, but is still weak. Examples are silicate minerals which contain Fe^{2+}, Fe^{3+} or Mn^{2+}, like biotite ($K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$) and pyrite ($FeS_2$) (Walden et al., 1999).

The third and probably most significant behaviour is the ferromagnetic, generated by unpaired electrons in atoms with strong interaction (figure 1.1). Different forms of ferromagnetic behaviour result from the arrangement of atoms in the crystal lattice. Therefore, four conditions can be defined. Ferromagnetism, it may take place parallel coupling of all unpaired electrons resulting in the development of strong magnetization. In the iron oxides of those metals, because the coupling occurs via an intermediate oxygen atom, alternate layers of the crystal lattice become magnetized in opposite directions. If these alternate layers have equal numbers of unpaired electron sites, then the substance has no overall ferromagnetic behaviour (anti-ferromagnetic). However, if the atomic magnetic moments of these two layers are unequal, then there is a spontaneous magnetization, defined as ferrimagnetism. Canted anti-ferromagnetic is when at minerals, for several reasons, layers are in an otherwise anti-ferromagnetic arrangement, and may not be perfectly anti-parallel. In this case, a small residual spontaneous magnetization exists (Walden et al., 1999).

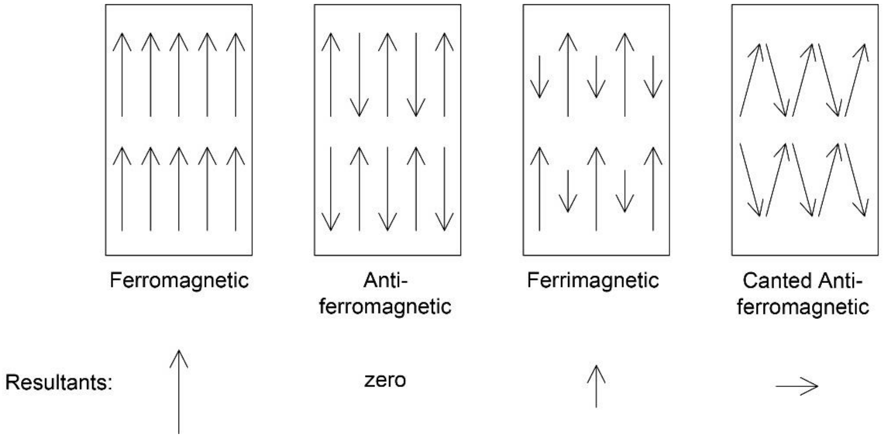

Figure 1 Schematic representation of the distribution of magnetization vectors in crystals and resultant magnetization, adapted from McElhinny (1973) and from Walden et al. (1999)

When an external field is applied and quantified as H, the magnetization intensity (M) induced by H can be measured and the derivation dM/dH can be quantified as magnetic susceptibility. A representation for a ferromagnetic material is presented in figure 1.2.

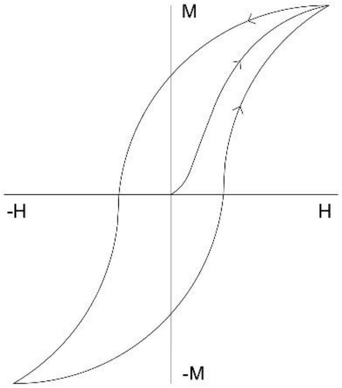

Figure 2 Schematic representation for a ferromagnetic material showing a relation between strength of an external applied field (H) and intensity of magnetization (M), adapted from Walden et al. (1999) and from Maher et al. (2009)

Dearing (1994) measured magnetic susceptibility at different iron oxides (table 1.4) when submitted to an external magnetic field (Thompson and Oldfield, 1986). Therefore, differences on magnetic properties of ferromagnetic materials, for example by magnetite and antiferromagnetic minerals such as haematite can be measured and used to identify the structure of iron oxides in sediments (Walden et al., 1999).

Table 4 Minerals/materials classified by magnetic behaviour, chemical form, Fe content and low frequency magnetic susceptibility, adapted from Dearing (1994) and from Costa and Bigham (2009)

Magnetic Behaviour	Mineral/Material	Chemical Form	Fe ($g\ kg^{-1}$)	Low Frequency Magnetic Susceptibility ($10^{-8}\ m^3\ kg^{-1}$)
Ferromagnetic	Iron	Fe	1,000	27,600,000
Ferrimagnetic	Magnetite (0.012 - 0.069 µm)	Fe_3O_4	720	44,000 - 111,600
	Magnetite (1 - 250 µm)	Fe_3O_4	720	39,000 - 71,600
	Maghemite	γ-Fe_2O_3	700	28,600 - 50,000
	Titanomagnetite	Fe_2TiO_4	Variable	16,900 - 29,000
Antiferromagnetic	Haematite	α-Fe_2O_3	700	27 - 169
	Goethite	α-FeOOH	630	35 - 125
Paramagnetic	Ilmenite	$FeTiO_3$	370	170 - 200
	Lepidocrocite	γ-FeOOH	630	50 - 75
Diamagnetic	Quartz	SiO_2	0	-0.1
	Kaolinite	$Al_2Si_2O_5(OH)_4$	0	-0.01

1.5.1 Research on magnetism in tropical soils

The interactions between tropical weathering conditions, long-duration soil-forming intervals and a range of different parent materials have often produced in Brazilian soils, both high soil Fe oxide concentrations and a range of different Fe oxide minerals, which makes Brazilian soils as excellent environment to study magnetic properties. This variability in soil magnetism helps researchers to interpret different soil environments and formation processes. In relation to Brazilian and others tropical and subtropical soils worldwide, several studies on magnetic properties have been carried out recently aiming to better understand soils formation. The main studies involving environmental magnetism properties at Brazilian and global tropical soils are listed in table 1.5.

Table 5 Summary of references on environmental magnetism at Brazilian and other tropical soils studies

Soil research site	References
Brazil	Anami and Costa (2013), Araujo et al. (2014), Costa et al. (1999), Fontes et al. (2000), Matias et al. (2013), Matias et al. (2015), Moukarika et al. (1991), Oliveira et al. (2015), Paduani et al. (2009), Resende et al. (1986), Santos et al. (2011), Silva et al. (2010), Siqueira et al. (2010), Souza Júnior et al. (2010).
Other Global Tropical sites	Ananthapadmanabha et al. (2014), Balsam et al. (2004), Chen et al. (2005), Eyre and Shaw (1994), Fischer et al. (2008), Han et al. (1996), Lu (2000), Lu et al. (2008), Lu et al. (2012), Owliaie et al. (2006), Torrent et al. (2007), Van Dam et al. (2008), Zhang et al. (2007).

1.6 Objectives and structure of the thesis

The aims of this thesis is to magnetically characterize possible sediments sources - three Brazilian soils at different slopes and landscape positions; to understand contemporary erosion rates of a potential sediments source; and to explore magnetic correlations between deposited sediments in a reservoir and its possible sources (soils), to determine the origin of these sediments.

In order to accomplish such task, three experiments were carried out. The first one measured the soil losses at Brazilian plots and how they can be affected by different cultivation systems. At the second experiment, soil samples were analysed at three different soil classes in Brazil, identifying the magnetic susceptibility at sand, silt and clay particles. The results were compared and associated to soil formation factors. At third experiment, sediments samples collected at bottom of downstream lakes were also analysed for magnetic susceptibility and fuzzy clustering techniques allowed to link them to their origin. The experiments resulted in three articles. While the first one will be targeted to submission at “Ciencia e Agrotecnologia”, the other two will be submitted to Geoderma.

2 GENERAL DISCUSSION

2.1 Concluding remarks

This research described the sediments derived from water erosion processes. It characterized the origin of sediments, e.g., three soil classes (Cambisol, Red-Yellow Latosol and Red Latosol) through magnetic analysis. The magnetic parameters evaluated were distinct among soil classes and particle sizes. This research also quantified the erosion at a Red-Yellow latosol as well as water losses. The procedures involved traditional techniques in which the runoff is collected and its sediment content analysed. Finally, sediments from the bottom of downstream reservoirs were characterized through magnetic analysis. Values obtained were compared to those obtained for each soil class, allowing to obtain the fingerprint which describes from where the sediments came from.

2.2 Synopsis of key findings

Erosion measurements described in article 1 revealed exciting findings. For example, during crop seasons from 2011 to 2014, the erosivity ranged from 4.050 to 8.384 MJ mm ha^{-1} h^{-1} $month^{-1}$. Soil losses by water erosion varied from 1.12 to 9.61 Mg ha^{-1} $period^{-1}$. The highest soil loss among the different cultivation system evaluated were found for bare soil followed by maize, jack beans and finally maize intercropped with jack beans. It is clear that the presence of crop plants decreased soil losses, once bare soil produced two to four times more soil losses than the cultivated systems. After crop establishment and development, soil losses tends to reduce as aerial vegetation parts decreased the erosion effects by intercepting rainfall and protecting soil surface against direct impact of raindrops. In order to prove such cultivation systems sustainability, tolerance limit values were calculated as 10.90 Mg ha^{-1} $year^{-1}$. It is safe to assume that the cultivation systems were adequate since soil losses were lower than tolerance limits while for bare soil the losses were higher than the referred limits.

Intercropping system presented better soil coverage than single crops treatments, with maximum soil cover index of approximately 94%. For all treatments, the maximum soil cover index was achieved at 70 days after seedling. This result suggests that initial plant development must be intense and fast.

Different from soil losses, water losses were directly related to erosivity but less influenced by soil cover management. Elevated rainfall erosivity values resulted in high water runoff losses, despite the soil coverage by crop plants.

With the possibility to employ modern techniques to study soil erosion, magnetic properties were evaluated at all three soil classes and their different particle sizes. Details presented at article 2 confirm a magnetic variation among soil classes, mainly associated to the Fe oxides assemblage within a soil. Magnetic measurements clearly reflected the different parent material characteristics. For Red Latosol, elevated weathering of gabbro (parent material) and high drainage conditions resulted in high Fe oxide content, while granite gneiss generated soils with low Fe oxides levels as the case for Cambisol and Red-Yellow Latosol.

Due to low frequency magnetic susceptibility and low ‘saturated’ IRM/χ_{LF} ratio values, minerals with paramagnetic behaviour (biotite) were predominant at Cambisol. Erosion process promoted such mineral accumulation at the lower landscape position sites.

At clay particle size fraction of Red-Yellow Latosol high percentage of frequency difference and easy demagnetization of ‘saturated’ IRM curves evidenced magnetic behaviour that demonstrated in situ formation of maghemite.

At Red Latosol, all measured magnetic parameters indicated a predominance of ‘soft’ mineral maghemite over ‘hard’ mineral (like hematite), justifying strong magnetic susceptibility.

Unsurprisingly, parent material emerged as the factor with the highest influence among all soil factors on environmental magnetism. Relief and drainage also played major roles on soil formation and soils with high drainage conditions such as Latosol presented very high levels of magnetism. For Cambisol, the sites located at the lowest part of the landscape presented a magnetic enhancement due to erosion accumulation. Elevated rainfall at Lavras region did favored Fe oxide formation/transformation. Weathering index suggested that the older soils (Latosol) exhibit higher magnetism levels than the younger ones (Cambisol).

Considering the differences detected at soil classes magnetic analysis can be successfully used as a fingerprinting technique to identify the sources of sediments found at downstream positions such as at the bottom of reservoirs. Therefore, at article 3, the fingerprinting was explored by comparisons of magnetic properties with aid of fuzzy clustering tools. The properties investigated were χ_{ARM}/IRM_{100mT} ratio in relation to χ_{LF}. Both soil samples, possible sediment sources, displayed a narrow range of χ_{ARM}/IRM_{100mT} ratio.

Low χ_{ARM} values were attributed to hematite presence in soils. The reduced levels of Oxygen as at the bottom of reservoirs, favours Fe oxide reduction. Therefore the difference is mainly stated at χ_{LF} values, ranging from 2.43 to 31.91 x 10^{-7} m^3 Kg^{-1} at the Red-Yellow Latosol, and from 58.99 to 601 x 10^{-7} m^3 Kg^{-1} at Red Latosol.

Results of fuzzy clustering analysis presented differentiation between sources allowing a dominant cluster affiliation of the reservoir sediments. At reservoir A approximately 93% of the sediments presented higher cluster affiliation to Red-Yellow Latosol, already expected since the draining area of reservoir A was delimited near the Red-Yellow Latosol transect. Particles from both soils contributed to sediment load of reservoir B as demonstrated by the fuzzy cluster analysis in which almost 41% presented higher cluster affiliation to Red Latosol and 59% to Red-Yellow Latosol.

2.3 General conclusions

The main cause of soil degradation in tropical and subtropical environments is water erosion and activities that contribute to increase soil loss. Other negative effects of this phenomenon include the change in water quality and siltation of streams and reservoirs. Finding the origin of the sediments sources can ensure high agricultural productivity and preservation of natural resources, by targeting sediment control strategies. Therefore, this research provided an extensively analysis of erosion in tropical soils. In article 1, it is shown how standard procedures can be employed to measure the erosion and how it can be affected by plant coverage. The plants involved cultivation of maize and jack beans, in a single scheme or intercropped. Soil coverage by plants was evaluated through the linear soil cover index. Its value reached the maximum at 70 days after seedling for all treatments. The rainfall erosivity of typical tropical rains were evaluated during three cropping seasons in Brazil. The erosivity was respectively 8.384, 5.962 and 4.050 MJ mm ha^{-1} h^{-1} $month^{-1}$. Due to such high erosivity values, soil losses occurred at all researched plots. Plant protection was efficient since at planted plots the soil losses were below the calculated tolerant limits. It can be verified that intercropping between maize and jack beans provided a better soil protection than single crop treatments. Despite correlated to erosivity, as expected, water losses were less influenced by plant cover and cultivation systems, revealing low influence of plants on surface drainage. In conclusion and extremely important, growers should perceive plant coverage that can be developed intensively and as fast as possible.

Procedures used at research described in article 1 are extremely laborious. Since tropical soils exhibit high and varied magnetic behaviour, this research investigated in article 2 its possible use for erosion studies, as worldwide, possibly for minimizing the requested efforts. Several magnetic parameters for three soil classes (Cambisol, Red-Yellow Latosol and Red

Latosol), and different particle sizes (clay, silt and sand) were measured. Approximately 14 thousand measurements were carried out and important findings were obtained. Curiously, despite the strong magnetism exhibited by tropical soils, low frequency magnetic susceptibility research, at least in Brazil, is still scarce. Measured values of this parameter revealed high values, mainly due to ferrimagnetic minerals presence. They varied among soil classes and soil fractions. Magnetism difference among soil classes could be attributed to soil formation factors such as parent material, relief, internal profile drainage and landscape position. Considering the variations detected at samples for all three soil classes, it was possible to conclude that such behaviour can be used as a fingerprinting technique to identify where a transported soil fraction can belong to.

Finally, at article 3, detailed investigation can be found to identify the origin of sediments. The hypothesis that magnetism can be used to correlate sediments to soil profile characteristics was confirmed in details at chapter three. This research is possibly the first one in Brazil or even at tropical soils to carry out fingerprinting techniques to identify the source of sediments common at bottom of reservoirs. Hence, tropical weathering lead to different Fe oxide minerals and high soil Fe oxide concentrations and magnetic variability can be deducted and precise comparisons can detect where sediments come from. For example, two soil classes described at Oxisol but different in Fe oxide contents (dystrophic Red-Yellow Latosol and dystroferric Red Latosol) were easily distinguished by magnetic properties. After analysing the sediments for the same properties, the sources of sediments were precisely identified.

The magnetic behaviour of tropical soils can, therefore, be more investigated. Properties such as low frequency susceptibility once compared from point to point, for example through fuzzy cluster analysis, can link consequence to origins. Although sediments from the bottom of reservoirs were investigated, it is possible that even suspended solids can be analysed and correlated to soil samples from different watersheds. If possible, isotope analysis should be performed even to investigate when the solids were transported.

In conclusion, magnetic mineralogy of soils and sediments are an important source of climatic and environmental information. A deeper analysis of erosion in tropical soils are critical in order to better understand and improve soil degradation conditions. This research might guide researches that can be used in the future not only to quantify erosion but also to identify their sources.

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SECOND PART – ARTICLES

Article elaborated according to standards of the scientific journal Revista Ciência e Agrotecnologia

ARTICLE 1 RELATION OF CROP SYSTEMS, SOIL COVER AND WATER EROSION AT SOUTHERN MINAS GERAIS, BRAZIL

Relação entre sistemas de cultivo, cobertura do solo e erosão no sul de Minas Gerais, Brasil

ABSTRACT

Several soil conservation practices have been developed in order to reduce water erosion and ensure a sustainable agriculture. An effective vegetative management system is intercropping, involving crops species and cover plants, especially for medium and small farmers. This practice is a system where two or more crops with different architectures and vegetative cycles are grown simultaneously in the same area. This research was carried out under natural rainfall conditions, at Lavras, Minas Gerais state, Brazil, including three cropping seasons (November to March) from 2011 to 2014. Four systems were used: bare soil, single maize cultivation, single jack-beans cultivation and intercropping involving these crops. The objectives of this research were: to quantify rainfall erosivity and soil and water losses from a dystrophic Red-Yellow Latosol (Oxisol); to determine soil cover index in different cultivation systems; as well as to integrate such parameters on soil losses interpretation. Rainfall erosivity in Lavras region was of 8,384, 5,962 and 4,050 MJ mm ha^{-1} h^{-1} month^{-1} for 2012, 2013 and 2014 seasons, respectively. Such elevated erosivity values directly influenced on soil and water losses at all researched treatments. At the third cropping season, bare soil produced higher soil losses than intercrop and single maize cultivation system. Water losses were directly related to erosivity and less influenced by soil cover and cultivation systems than soil losses. A linear maximum soil cover index value was achieved after 70 days of seedling. Intercropping presented a better soil cover than single crops. Therefore, initial crop development stage is critical and maximum soil cover should be achieved as early as possible.

Index terms: rainfall erosivity; Red-Yellow Latosol (Oxisol); soil losses; soil protection; water losses.

RESUMO

Diversas práticas de conservação do solo têm sido desenvolvidas com o intuito de reduzir a erosão hídrica e assegurar uma agricultura sustentável. Um sistema de manejo efetivo é o consórcio entre espécies de cultivos e plantas de cobertura, especialmente para pequenos e médios agricultores. Esta prática consiste em duas ou mais culturas, com diferentes arquiteturas e ciclos vegetativos, cultivadas simultaneamente no mesmo local. A presente pesquisa foi realizada sob condições de chuva natural, em Lavras, Minas Gerais, Brasil, durante 3 ciclos de cultivo (Novembro a Março) entre 2011 e 2014. Quatro sistemas foram utilizados: solo descoberto, plantio solteiro de milho, plantio solteiro de feijão-de-porco e consórcio entre ambas as espécies. Os objetivos deste trabalho foram: quantificar a erosividade da chuva e as perdas de água e solo em Latossolo Vermelho-Amarelo distrófico; determinar o índice de cobertura do solo em diferentes sistemas de cultivo; assim como integrar tais parâmetros na interpretação das perdas de solo. A erosividade da chuva para a região de Lavras foi de 8.384, 5.962 e 4.050 MJ mm ha^{-1} h^{-1} $mês^{-1}$ nos ciclos de 2012, 2013 e 2104, respectivamente. Tais valores elevados de erosividade influenciaram diretamente nas perdas de água e solo em todos os tratamentos. No terceiro ciclo de cultivo, o solo descoberto produziu perdas de solo maiores que os cultivos de milho solteiro e consórcio. As perdas de água foram diretamente relacionadas à erosividade da chuva e menos influenciadas pela cobertura do solo e sistemas de cultivo do que as perdas de solo por erosão. Valores máximos lineares do índice de cobertura do solo foram atingidos com 70 dias após a semeadura. O consórcio entre milho e feijão-de-porco apresentou uma melhor cobertura do solo que os demais tratamentos. Logo, o estádio de desenvolvimento inicial das culturas é crítico e uma cobertura da superfície do solo máxima deveria ser atingida o quanto antes.

Termos para indexação: erosividade da chuva; Latossolo Vermelho-Amarelo; perdas de solo; proteção do solo; perdas de água.

INTRODUCTION

Soil erosion is a natural phenomenon that can be accelerated by anthropic activities, causing, as consequence, a direct impact on the environment and food production (Pimentel et al., 1995; Lal, 2001). Erosion processes include the detachment, transport and deposition of soil particles. Rainfall detachment is the main starting cause of erosion, presenting increased rates when soil surface lacks vegetative cover (Lal, 2001; Pimentel, 2006; Zuazo; Pleguezuelo, 2008).

Several edaphic, mechanical and vegetative conservation practices and management systems have been developed and implemented in order to reduce soil erosion and ensure sustainable agriculture (Bertoni; Lombardi Neto, 2010; Powlson et al., 2011; Maetens; Poesen; Vanmaercke, 2012). Among different factors involved, maintenance of cover plants is vital (Lal, 2001; Ruiz-Colmenero et al., 2013). Vegetation will intercept rainfall, protecting the soil surface from direct impact of rainfall drops, and decrease runoff, promoting water infiltration and improving soil aggregates stability and cohesion (Zuazo; Pleguezuelo, 2008).

Single crop cultivation, such as maize (*Zea mays* L.), can be considered as non-protective crop. Aiming to avoid increase of erosion processes, alternative solutions have been proposed. One effective vegetative conservation practice is the intercropping involving cover plants and crop systems. This practice includes two or more crops with different architectures and vegetative cycles growing simultaneously. A most common practice in tropical areas, some of benefits from this practice include soil and water quality improvement, increasing nutrient cycling efficiency, as well as better protection against rain drop impact and consequent water erosion (Troeh; Hobbs; Donahue, 1980;

Connolly; Goma; Rahim, 2001; Snapp et al., 2005; Gómez et al., 2009; Maetens; Poesen; Vanmaercke, 2012; Chieza et al., 2013; Dias et al., 2013).

Among different intercropping combinations, systems which combine maize with cover plants have been effective to improve soil physical parameters and to control water erosion, reducing organic carbon, nutrients, soil and water losses (Debarba; Amado, 1997; Gilles et al., 2009; Silveira; Stone, 2010; Chen; Weil, 2011; Gabriel; Quemada, 2011; Freitas et al., 2012; Dias et al. 2013). The benefits of cover plants use were also demonstrated by Gómez et al. (2011), which concluded that they significantly reduced water erosion in comparison to traditional tillage practices in Southern France, Spain and Portugal. Cover plants with maize intercropping was recommended by Ngome, Becker and Mtei (2011), which stated that *Mucuna* and *Arachis* increased maize yields in Kenya.

Research investigations on soil and water losses by erosion often use standard sized plots, as proposed by Wischmeier and Smith (1978). These plots have been employed to measure erosion from different tillage systems through the world. The Universal Soil Loss Equation – USLE (Wischmeier; Smith, 1978) model integrates several parameters as follows:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where: A refers to soil losses (Mg ha^{-1}), R is the rainfall erosivity (MJ mm ha^{-1} h^{-1}), K is the soil erodibility (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the length slope factor, P is the conservation practice factor, and C, the soil cover factor (Wischmeier; Smith, 1978).

USLE parameters for different conditions of soil tillage and types have been object of review in the literature, such as Cogo, Leviens and Schwarz (2003), Mello et al. (2003), Vaezi et al. (2008), Castro et al. (2011), Cardoso et al. (2012) and Dias et al. (2013). USLE equation has become an important planning tool in United States, but needs to be calibrated locally, for example, to conditions in Brazil and in South America.

The Lavras region, Brazil, is highly dependent on agricultural activities. In addition to coffee and pasture for dairy cattle, agricultural production stands dominated by maize, with Minas Gerais state being responsible for approximately 8.13% of national production (Conab, 2015). In this region, soils are highly variable and high levels of erosion can be observed. Gomide, Silva and Soares (2011) stated that at this region large areas are subjected to advanced soil degradation by water erosion, specifically gully. Thus, to develop sustainable soil use and management, it is important to conduct research that considers different plants and management systems with the purpose of measuring soil and water losses.

Therefore, the objectives of this research were: 1) to quantify rainfall erosivity, soil and water losses from a dystrophic Red-Yellow Latosol in Lavras region; 2) to determine the soil cover index by different crop systems; and 3) to integrate such parameters on interpretation of soil losses.

MATERIAL AND METHODS

The experiment was located at Federal University of Lavras (UFLA), in Lavras county, Minas Gerais state, Brazil (21º13’20’’ S and 44º58’17’’ W), situated at 925 m altitude. Three cropping seasons (November to March) between 2011 and 2014 were studied. The climate, according to Köppen classification system, is classified as Cwa, with a dry winter and rainy summer (Alvares et al., 2013), with average annual rainfall of approximately 1,530 mm and mean annual temperature of 19.4 ºC (Dantas; Carvalho; Ferreira, 2007).

Rain erosivity (EI_{30}) was calculated from continuous monitoring of rainfall events, during the rainy season, from November to March, at the main weather station of Lavras, approximately 1 km apart from the research site. Over 10 mm rains were recorded with tolerance of 0.2 mm. Total kinetic energy was determined for each rain event according to the equation proposed by Wischmeier and Smith (1958), adapted for international units by Foster et al. (1981) as follows:

$$E = 0.119 + 0.0873 \log \mathrm{I} \tag{2}$$

where: E is the kinetic energy (MJ ha^{-1} mm^{-1}) and I is the rain intensity (mm h^{-1}).

This research considered individual rains, defined as those separated by at least 6 hours with rainfall less than 1 mm. Rain events with less than 10 mm of rain and 15 minutes duration but with intensity less than 24 mm h^{-1}, or kinetic energy less than 3.6 MJ, were considered as non-erosive ones (De Maria, 1994). The kinetic energy value multiplied by precipitation resulted in the kinetic energy expressed as MJ ha^{-1}. Values obtained were accumulated to obtain the total Kinetic energy for a given rain storm.

The EI_{30} index was obtained by multiplying the total kinetic energy by the maximum intensity in a 30 min period (I_{30}), accordingly to the method proposed by Wischmeier and Smith (1958). By summing the values for each rain storm along the month, it was possible to obtain the total erosivity for each month.

The soil was classified as dystrophic Red-Yellow Latosol according to Embrapa (2013), or as an Hapludox in the US Soil Taxonomy (Buol et al., 2011), with 12% slope. Its main soil properties (Embrapa, 1997) are presented at Table 2.1.

Table 1: General characterization of the soil at 0-20 cm depth.

Property	Soil
pH	5.5
P (mg dm^{-3})	2.6
K (mg dm^{-3})	97
Ca ($cmol_c$ dm^{-3})	2.0
Mg ($cmol_c$ dm^{-3})	0.4
Al^{+3} ($cmol_c$ dm^{-3})	0.2
t ($cmol_c$ dm^{-3})	2.8
T ($cmol_c$ dm^{-3})	5.5
SOM (g kg^{-1})	20.0
Sand (g kg^{-1})	460
Silt (g kg^{-1})	80
Clay (g kg^{-1})	460

t: effective cation exchange capacity; T: potential cation exchange capacity; SOM: soil organic matter.

Four experimental plots (4.0 m wide by 12.0 m long) were installed to evaluate soil and water losses at the first and second cropping season. At the third cropping season (2013-14) three replicates were used at each treatment. Soil erosion plots data presents a large variability, both naturally and due to measurements (Nearing; Govers; Norton, 1999). However, the required replication of such field experiment is likely to be far greater than it is possible for scientists to monitor in practical terms (Wendt; Alberts; Hjelmfelt, 1986; Deasy; Titman; Quinton, 2014). Therefore, although the present study does not have the field replications necessary to properly represent soil erosion losses, data obtained is important since it contributes to a large database from the authors of the present work.

All plots were limited by galvanized zinc metal plate, inserted 20 cm in the soil and leaving 20 cm above the soil surface. At the bottom of each plot, an outlet was installed for receiving eroded soil and water into two 250 liter reservoirs connected to each other by a GEIB divisor, dimensioned with 9 entries slots (Geib, 1933). Once the first reservoir was filled, one ninth of runoff was carried to the second reservoir (Aquino et al., 2012).

Soil and water losses were quantified after each erosive rain according to the method described by Cogo, Leviens and Schwarz (2003). After solid suspension was shaken, three aliquots at each erosive event per plot were collected and transferred to laboratory for decanting. Settled material was then oven-dried at 105 ºC, for 24 hours, and the dry weight determined to quantify soil erosion.

In order to evaluate cultivation systems adequacy, soil losses tolerance limits values were estimated. Soil profile methodology used considered rooting depth, soil permeability, organic matter content and textural ratio between B and A horizons (Lombardi Neto; Bertoni, 1975).

The treatments involved four systems (involving three plant systems): maize (*Zea mays* L.) hybrid cultivar AS1598PRO (MZ); jack beans (*Canavalia ensiformis* (L.) DC) (JB); intercropping involving of maize and jack beans (IC); and bare soil as plot control (BS). Hybrid maize was chosen once as it is frequently used in the region for grain production, due to its disease tolerance. A cover plant (jack beans) was used due its nitrogen fixing capacity, high vegetal mass production, ability to improve soil physical conditions and substantial soil cover (Castro et al., 2011; Maetens; Poesen; Vanmaercke, 2012; Chieza et al., 2013; Dias et al., 2013).

The seeds were sown in November of each cropping season, 0.70 m apart, when single crop was tested, and 0.35 m when intercropping every other row. Rows were established perpendicularly to the slope. Manually weeding was carried out before planting and all residues from previous crops were removed. Fertilizers were applied, equivalent to 300 kg ha^{-1}of NPK 10:20:30, and a topdressing fertilization of 100 kg ha^{-1} NPK 20:05:20 by according the soil analyses (Ribeiro; Guimarães; Alvarez, 1999). At 130 days after seedling, all plants were mowed and crop residues were left on the soil surface.

The historical of use of the area is presented at table 2.2, including different cover plants.

Table 2: Historical use of the area.

Period	Use historical	Reference
Before 2007	Area was previously cultivated with *Brachiaria decumbens*.	Freitas et al. (2012)
2007 to 2008	Sun hemp (*Crotalaria juncea* L.), jack beans (*Canavalia ensiformis* DC.) and millet (*Pennisetum sp* Rich.).	Cardoso et al. (2012)
2008 to 2009	Pigeon pea legumes (*Cajanus cajan* (L.) Huth), sun hemp (*Crotalaria juncea* L.), jack beans (*Canavalia ensiformis* DC.) and millet (*Pennisetum sp* Rich.).	Castro et al. (2011)
2010 to 2011	Pigeon pea legumes (*Cajanus cajan* (L.) Huth), jack beans (*Canavalia ensiformis* DC.) and millet (Pennisetum sp Rich.)., cultivated under different planting systems.	Dias et al. (2013)

The soil cover index (SCI) was established according to the methodology developed by Stocking (1988), which consists in an apparatus with 19 circle orifices of 9 mm diameter each, spaced 10 cm apart from each other, along a two meter rod placed 1.20 meters above soil surface. Random readings through crop rows were done, with three replications for each plot. A zero value was attributed for bare soil, 0.5 for any crop coverage detected inside the circle, and 1.0 when the circle was fully covered by crop leaves. The soil cover index was calculated as follows:

$$SCI\ (\%) = \frac{number\ of\ vegetable\ cover\ readings}{total\ number\ of\ readings} \times 100 \qquad \ldots\ldots.(3)$$

SCI measurements started at 10 days after seedling according to soil cover percentage (De Maria; Lombardi Neto, 1997; Souza et al., 2010). SCI values were fitted by quadratic polynomial equations for each crop system.

Aiming to compare the interaction of factors studied (different systems, rainfall erosivity and soil cover index), statistical modelling was used to better understand the factors influencing soil losses. Referred to as LMM, the linear mixed model, such as used by Haskard, Rawlins and Lark (2010), Suuster et al. (2012), and Doetterl et al. (2013), has been successfully used in different soil science studies and is adopted here. Models were generated using methodology similar to that described in Gelman and Hill (2007) and Zuur, Ieno and Smith (2007). LMM with a season random term to account for the clustering was analysed, using the *lmer* function present in the package *lme4* (Bates et al., 2014) of R version 3.1.2 (R Core Team, 2014). Thus the influence of groups of variables on which model likelihood was compared. Variables that presented the greatest improvement to model likelihood were selected, according to the lowest Akaike's Information Criterion value. After statistical analyses, another set of variables representing different controls over function was then added and the process was repeated.

RESULTS AND DISCUSSION

Rainfall erosivity

Monthly rainfall during the study period ranged from 52 to 507 mm, with the highest monthly rainfall occurring in January of 2013 and the lowest in February of 2013 (table 2.3). The cropping season total values were 1,317, 1,063 and 621 mm respectively for the 2011/12, 2012/13 and 2013/14 years. This resulted in high erosivity values. During the first cropping season, erosivity values varied from 220 to 3,280 MJ mm ha^{-1} h^{-1} month^{-1}, while during the second cropping season, erosivity variation was of 359 to 3,245 MJ mm ha^{-1} h^{-1} month^{-1}, and in the third cropping season erosivity ranged from 124 to 1,672 MJ mm ha^{-1} h^{-1} month^{-1}. Such energy corresponds to 8,384; 5,962 and 4,050 MJ mm ha^{-1} h^{-1} month^{-1} during 2011/12, 2012/13 and 2013/14, respectively.

Table 3: Monthly total precipitation, non-erosive and erosive rains, and rain erosivity values during three cropping seasons between November and March of 2011 to 2012, 2012 to 2013 and 2013 to 2014 in Lavras, Brazil.

Month/year	Rainfall Precipitation			Erosivity
	Total	Non-erosive	Erosive	
	mm			MJ mm ha^{-1} h^{-1} month^{-1}
2011-2012				
Nov-11	173	14	159	1,168
Dec-11	498	11	501	3,280
Jan-12	431	9	408	3,147
Feb-12	80	5	75	220
Mar-12	134	24	110	571
Total	1,317	64	1,253	8,385
2012-2013				
Nov-12	153	17	136	1,034
Dec-12	156	6	150	693
Jan-13	507	15	492	3,245
Feb-13	75	9	66	359
Mar-13	172	16	156	631
Total	1,063	64	999	5,962
2013-2014				
Nov-13	177	68	109	927
Dec-13	209	24	185	1,672
Jan-14	52	12	39	131
Feb-14	64	4	60	124
Mar-14	120	29	91	1,196
Total	621	137	484	4,050

Erosivity value observed at the first cropping season was slightly higher than the 5,145 to 7,776 MJ mm ha^{-1} h^{-1} year^{-1} range for the Southern region of Minas Gerais, as reported by Aquino et al. (2012). The present research presented higher values in the first cropping season, and lower in the second and third cropping season than the ones presented by Val et al. (1986), that were the first ones to present erosivity values for Lavras region (6,837 MJ mm ha^{-1} h^{-1} year^{-1}), using a database of 22 years. Mello et al. (2007) found erosivity values for the same region ranging from 5,000 to 12,000 MJ mm ha^{-1} h^{-1} year^{-1}. Evangelista et al. (2006) presented an average erosivity value of 5,403 MJ mm ha^{-1} h^{-1} year^{-1} for Lavras region, similarly to erosivity data presented here.

Soil and water loss

Soil losses by water erosion for all crop systems are listed in table 2.4. Soil losses values presented a variation of 1.12 to 14.10 Mg ha^{-1} period^{-1}, with the highest monthly soil loss (10.88 Mg ha^{-1} month^{-1}) measured in December of 2013 in the bare soil plot and the lowest (null soil loss) in January 2014 in the maize, jack beans and intercrop plots, and in February 2014 in maize, jack beans and intercrop plots. The highest soil loss values were found for bare soil, followed by maize, jack beans, and maize intercropped with jack beans. On field observations, bare soil plots presented surface crusting which leads to soil surface sealing and consequent increase on soils and water losses by erosion. In the other hand, there was an absence of soil crusting in the crops plots.

Table 4: Soil losses by water erosion at three cropping systems between November and March of 2011 to 2012, 2012 to 2013 and from 2013 to 2014, in Lavras, Brazil.

	------------------------------Mg ha^{-1} period^{-1}------------------------------					
	November	December	January	February	March	Total
2011-2012						
BS	0.57	1.60	4.06	1.09	0.94	8.27
MZ	0.79	1.22	1.29	0.25	0.19	3.74
JB	0.69	0.54	1.29	0.10	0.03	2.65
IC	0.40	0.69	1.24	0.06	0.06	2.44
2012-2013						
BS	0.49	0.78	4.84	0.33	0.97	7.42
MZ	0.15	0.28	2.90	0.09	0.09	3.51
JB	0.38	0.38	1.58	0.04	0.17	2.54
IC	0.62	0.23	0.85	0.04	0.28	2.03
2013-2014						
BS	0.41	10.88	0.05	0.11	2.65	14.10a
MZ	0.09	2.56	0.00	0.00	0.00	2.65b
JB	0.04	3.28	0.00	0.00	0.08	3.40ab
IC	0.06	2.38	0.00	0.00	0.00	2.45b

BS: bare soil; MZ: maize only; JB: jack beans only; IC: maize intercropped with jack beans. Means followed by same letter in column does not differ significantly by Tukey test at 5% probability.

During the first cropping season, from November 2011 to March 2012, the months of December and January produced the highest soil loss values, due to high rainfall erosivity during the same period (table 2.3). In November some high soil loss values were measured in all treatments. Such results were probably related to a lack of soil cover, as this month corresponds to the initial phase of crop cultivation, from seedling to post-planting. Nevertheless, tillage previous to seedling can contribute to higher soil losses. In short term, it is clear that the presence of crop plants decreased soil loss, as bare soil plots produced two to four times more soil loss than the crop systems. The soil cover by aerial vegetation parts decrease erosion effects mainly by intercepting rainfall and protecting soil surface against direct impact of rainfall drops. In the other hand, the lack of a soil cover (bare soil) drastically increases detachment and transport of soil particles.

For the second and third cropping seasons (November 2012 to March 2013, and November 2013 to March 2014) treatments response to natural rainfall was similar to that of the first season. In the second season, the effect of the high rainfall erosivity in January was clear, leading to higher values of soil losses. After crop establishment and development (February and March), soil losses tended to reduce as rainfall drops were intercepted before reaching soil surface (table 2.4). Root growth improving stability of soil aggregates possibly also contributed to increase resistance to soil erosion (Chen; Weil, 2011).

While in the third cropping season, December and March had elevated soil losses, as a natural consequence of the elevated rain erosivity in those months. In March, all crops were already established leading to a dissipation of rainfall drops kinetic energy, of which only bare soil plot presented high erosion rates. Statistical difference was stated between crop systems used, in which bare soil presented higher values than maize single cultivation and intercrop system used.

Soil losses presented here are similar to others found in the literature for Brazil. Soil losses for jack beans in the present work are higher than the values presented by Cardoso et al. (2012) which found values of 1.59 Mg ha^{-1} for a single jack beans cultivation plot, with 0.5m rows spacing, at the same study area. Dias et al. (2013) measured soil losses values of 0.72 Mg ha^{-1} and 2.81 Mg ha^{-1}, for jack beans at different systems cultivation on a Latosol, in Lavras region, similar to soil loss values obtained here. Regarding bare soil plot control, similar results were determined by Dias et al. (2013) reaching 7.67 Mg ha^{-1} soil loss for a Latosol.

Tolerance limit values of soil losses obtained were 10.90 Mg ha^{-1} year^{-1}. As the present study was conducted at rainy season (November to March at each year) which corresponds to approximately to 75.81% of year total rainfall (Dantas; Carvalho; Ferreira, 2007), it is possible that bare soil plots soil losses values (7.42, 8.27 and 14.10 Mg ha^{-1} $period^{-1}$) exceed such soil losses tolerance limits when the whole year is considered. In the other hand is safe to assume that cultivation systems researched here are adequate as soil losses values are much lower than tolerance limit. Tolerance limits to Latosols at São Paulo state ranging from 9.6 to 15.0 Mg ha^{-1} $year^{-1}$ (Lombardi Neto; Bertoni, 1975), similar to tolerance value presented here.

Water losses (surface runoff) by water erosion for all crop systems are presented in table 2.5. Similar behaviour to soil losses was observed for surface runoff for each cropping season. Water losses by water erosion values presented variation of 41.72 to 212.59 mm ha^{-1} $period^{-1}$, with the highest monthly water loss (132.80 mm ha^{-1} $month^{-1}$) measured in January of 2013 for bare soil plot and the lowest (null soil loss) in January 2014 for maize, jack beans and intercrop plots, and in February 2014 for maize, jack beans and intercrop plots. Such results follow a trend similar for soil loss measurements (table 2.4). In bare soil plots, soil crusting directly contributed to high water losses by erosion.

Table 5: Water losses by water erosion under natural rainfall, during three cropping systems between November and March of 2011 to 2012, 2012 to 2013 and from 2013 to 2014, in Lavras, Brazil.

	--------------------------mm ha^{-1} period^{-1}----------------------------					
	November	December	January	February	March	Total
2011-2012						
BS	18.58	58.46	92.71	3.64	1.90	175.30
MZ	16.62	42.54	49.53	6.03	2.96	117.68
JB	1.59	29.60	38.52	13.97	5.08	88.76
IC	2.94	45.20	43.58	7.54	5.48	104.74
Rainfall	173.00	498.00	431.00	80.00	134.00	1,317.00
2012-2013						
BS	15.66	21.27	132.80	8.20	34.66	212.59
MZ	11.08	15.62	86.23	5.86	4.19	122.98
JB	6.37	8.74	80.79	1.83	2.12	99.85
IC	13.12	15.24	61.19	3.35	4.37	97.28
Rainfall	153.00	156.00	507.00	75.00	172.00	1,063.00
2013-2014						
BS	12.94	84.21	1.04	2.90	40.72	141.82a
MZ	1.83	63.94	0.00	0.00	0.11	65.88a
JB	1.50	64.51	0.00	0.00	1.55	67.56a
IC	1.10	40.51	0.00	0.00	0.11	41.72a
Rainfall	177.00	209.00	52.00	64.00	120.00	621.00

BS: bare soil; MZ: maize only; JB: jack beans only; IC: maize intercropped with jack beans.

At the first cropping season (November 2011 to March 2011), December and January months produced the highest water loss values, due to high rainfall erosivity registered for those months (table 2.3). In fact, maximum surface runoff percentage at the first season was observed for bare soil plot in January 2012, in which water loss collected at the plot corresponded to 21.51% of total month rainfall.

During the second cropping season, high water loss values in November and December were observed, probably due to a lack of soil cover, as this month corresponds to the initial phase of crop cultivation. The highest water loss values were measured for bare soil plot in January 2013, mainly due to high rainfall erosivity in that month. Water loss corresponded to 26.19% of total rainfall measured in January 2013.

In the third season, December 2013 presented the highest water loss percentage levels of all research period. Surface runoff was equivalent to almost 40% of total rainfall for bare soil plots. Only bare soil plot had water loss measured at January and February 2014. In those months, lower rainfall associated to already stablished crops resulting in elevated soil cover, were not enough to cause surface runoff. However, no statistical difference was stated between treatments analysed, possibly due to large variation on water losses events.

Different to the soil loss measurements, water losses were directly related to erosivity and less influenced by soil cover and management, once December and January months with elevated rainfall erosivity values presented high water runoff losses, despite crops were already being established. However, as a long-term effect, high vegetation density directly influences on water and sediments fluxes by increasing soil-aggregate stability and by improving water infiltration (Zuazo; Pleguezuelo, 2008).

Castro et al. (2011) and Dias et al. (2013) found smaller overland flow than this research, when studying jack beans single planting at the same soil on Lavras region, probably due to lower rainfall erosivity than values presented here. Debarba and Amado (1997) presented a high value of 24.93% surface runoff related to total rainfall, similar to results presented here.

Soil cover index

The Soil Cover Index (SCI) for the different systems for all cropping seasons are illustrated in figure 2.1. The values plotted were fitted by a quadratic polynomial model which related SCI values to days after seeding (DAS). All models treatments presented coefficient of determination higher than 90%, indicating an adequate data fitting.

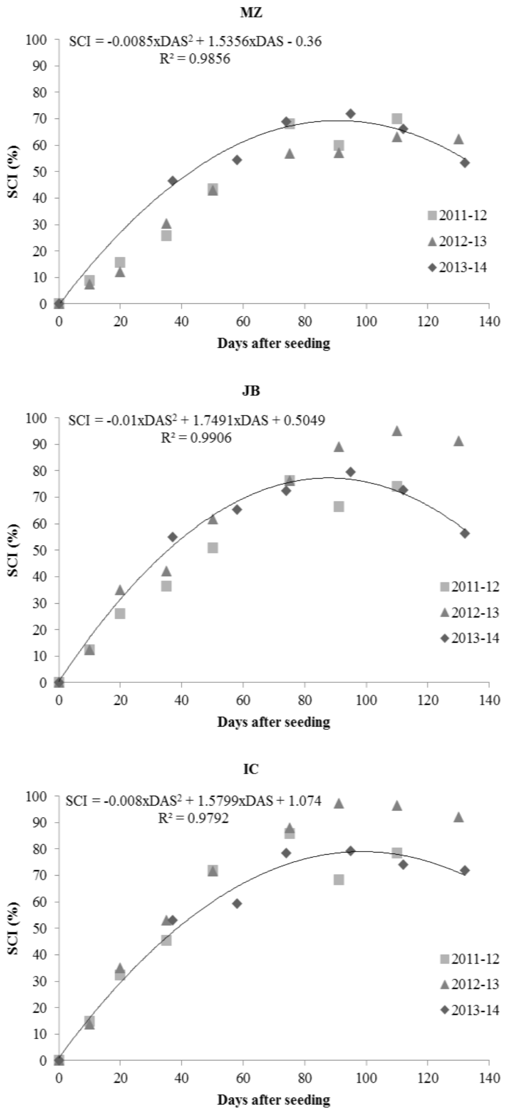

Figure 1: Soil cover index (SCI) for the three cropping seasons in a dystrophic Red-Yellow Latosol. MZ: maize only; JB: jack beans only; IC: maize intercropped with jack beans.

For 35 to 60 days after seedling (crop establishment), values were gradually increased up to establish a linear SCI value (from 60 to 80%) and consequently higher soil cover protection against direct impact of natural rainfall. Such elevated SCI values directly influenced on a decrease on soil and water losses (tables 2.4 and 2.5). Therefore, conservation practices are fundamental to protect soil against erosion processes, especially at initial plant growth where soil cover density is very low.

Intercropping presented a better soil cover than single crops with a maximum SCI (93.54%) obtained on the second cycle. As stated by Troeh, Hobbs and Donahue (1980), soil conservation is an important bonus from multiple cropping, especially after initial plant growth.

Comparing soil and water losses listed in tables 2.4 and 2.5 to the average SCI (table 2.6), it is clear that the greater the average SCI the lower the erosion losses, mainly due to rainfall drop intercept, protecting the soil surface against the impact of rainfall drops.

Table 6: Average soil cover index for the three cropping seasons between November and March of 2011 to 2012, 2012 to 2013 and 2013 to 2014 in Lavras, Brazil.

Cropping Season	Average Soil Cover Index (%)		
	MZ	JB	IC
2011/12	36.50	42.82	49.63
2012/13	36.98	55.91	60.88
2013/14	43.34	48.32	50.02

MZ: maize only; JB: jack beans only; IC: maize intercropped with jack beans.

The results obtained here are smaller than the values reported by Souza et al. (2010), when different varieties of maize were investigated. They found SCI maximum values of 80%, while 68.18% was the maximum value obtained here (figure 2.1). SCI values corroborate with Castro et al. (2011) which studied several cover crops, like jack beans. Freitas et al. (2012) and Dias et al. (2013), studying jack beans cultivation, strongly recommended it as promising soil cover plant for Lavras region.

Linear effects mixed model analysis

In order to predict soil loss, a fitted model (linear mixed models (LMM)) correlating rain erosivity (R), soil cover index (SCI), cultivation systems (CS) and interaction between those parameters, are presented in table 2.7. Model 5 was the one that presented the lowest Akaike's Information Criterion (AIC) value (187.81), and therefore it can be considered the best fitted model likelihood. Such model correlated the interaction of R and SCI to better estimate soil loss.

Table 7: Linear mixed models, correlating different parameters to predict soil loss, from a dystrophic Red-Yellow Latosol in Lavras, Brazil.

Models		DF	AIC
M1	R*CS + R*SCI + CS*SCI	14	274.81
M2	R*CS + R*SCI	12	250.58
M3	CS + R*SCI	9	201.72
M4	R + CS + SCI	8	222.31
M5	R*SCI	6	187.81
M6	R + SCI	5	209.51

R: Rainfall erosivity; CS: Cultivation System; SCI: Soil Cover Index; DF: degrees of freedom; AIC: Akaike's Information Criterion.

The model chosen to better correlate different parameters and predict soil losses was the one that presented the lowest AIC value. Therefore, Model 5 was chosen: interaction between rainfall erosivity and soil cover index, without the effects of cultivation system. Despite different plant physiology and soil water infiltration capacity between the treatments evaluated (Debarba; Amado, 1997), it is important to point out that cultivation systems is related to soil cover used at Model 5. Model 5 values were plotted at figure 2.2.

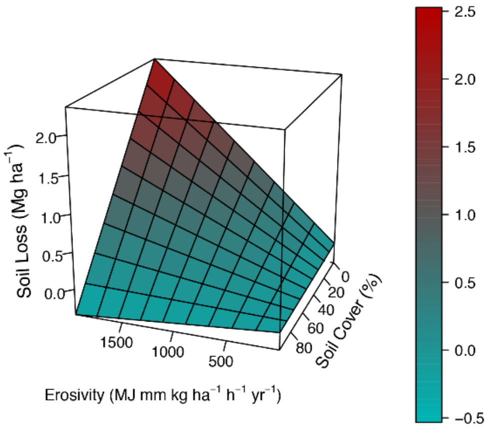

Figure 2: Fitted relationships between rain erosivity and soil cover index, using linear mixed model to predict soil loss from a Red-Yellow Latosol in Lavras, Brazil ($P < 0.001$).

The LMM presented demonstrates a strong correlation between R and SCI that possibly can be used to predict soil losses by erosion. However, such effect is considerably decreased when one of those parameters, R or SCI, is analysed separately, resulting in less influence on soil losses; for example, high rain erosivity (about 2,000 MJ mm kg ha^{-1} h^{-1} year^{-1}), when correlated to high SCI value (around 80%), would generate lower soil loss values than a situation where SCI is around 10%.

CONCLUSIONS

Rainfall erosivity in the Lavras region was 8,384, 5,962 and 4,050 MJ mm ha^{-1} h^{-1} month^{-1} at 2011/12, 2012/13 and 2013/14 cropping seasons, respectively. Such elevated erosivity values directly influenced soil losses at all researched treatments, wherein at the third cropping season, bare soil produced higher soil losses than intercrop and single maize cultivation system, enhancing the importance of soil cover.

Cultivation systems used were adequate once soil losses values were much lower than tolerance limits values estimated, in contrast to bare soil. Water losses were directly related to erosivity and less influenced by plant cover and cultivation systems then soil loss.

A linear maximum soil cover index value was achieved at 70 days after seedling for all treatments. Intercropping between maize and jack beans presented a better soil cover than single crops treatments. Therefore, initial crop development stage is critical and maximum soil cover must be achieved as early as possible, and consequently intercropping system is highly recommended once it does better protect soil surface against natural rainfall.

ACKNOWLEDGMENTS

Authors recognize their gratitude to CAPES (Coordination of Improvement of Higher Education Personnel), FAPEMIG (Research Foundation of Minas Gerais State) and CNPq (National Research and Development Council) for their financial support and scholarships. The authors are also thankful to the support given by UFLA's Professors Gabriel Carvalho and Renzo Von Pinho, and undergraduate students Endrew Santos, Wharley Santos and Fábio Gomes.

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Article elaborated according to standards of the scientific journal Geoderma

ARTICLE 2 Tropical soil characterisation by mineral magnetic measurements in Lavras, Brazil

Caracterização de solos tropicais por medição magnética de minerais em Lavras, Brasil

ABSTRACT

Interactions between tropical weathering conditions, long-duration soil-forming intervals and a range of different parent materials have often produced in Brazilian soils, both high soil Fe oxide concentrations and a range of different Fe oxide minerals. Such combination makes Brazilian soils an excellent environment to study magnetic properties. The objectives of this research were: to characterize magnetic properties from three toposequences in different land uses at Lavras region, Brazil; to evaluate possible influence of soil formation factors on magnetic properties of such soils; and to evaluate influence of soil particle size on magnetic properties. Soil samples were collected at three toposequences (Cambisol, Red-Yellow Latosol and Red Latosol). Unsurprisingly, parent material emerged as the factor with the highest influence among all soil factors on environmental magnetism. Relief and drainage also played major roles on soil formation and soils with high drainage conditions such as Latosol presented very high levels of magnetism. Elevated rainfall at Lavras region favoured Fe oxide formation/transformation. Weathering index suggested that the older soils (Latosols) exhibit higher magnetism levels than the younger ones (Cambisol). Considering the differences detected at samples obtained from the three soils studied, it is possible to infer that magnetic analysis of eroded soil particles can be successfully used as a fingerprint technique to identify the source of sediments.

Keywords: Environmental magnetism; Iron oxides; Magnetic properties; Soil formation factors; Tropical soils.

RESUMO

As interações entre os fatores de intemperismo em condições tropicais, as longas durações dos intervalos de formação de solo e a variação entre os materiais de origem levaram os solos brasileiros a exibir altas concentrações de óxidos de ferro e grande variabilidade dos minerais contendo esses óxidos o que faz dos solos brasileiros excelentes ambientes para estudos de propriedades magnéticas. Os objetivos desta pesquisa foram de caracterizar as propriedades magnéticas e como os fatores de formação de solo as influenciam, bem como o efeito do tamanho de partículas nas propriedades magnéticas. Amostras de solo foram coletadas em três toposequencias (Cambisolo, Latosolo Vermelho Amarelo e Latosolo vermelho). Como era esperado, entre os fatores de formação do solo, o material de origem foi o fator com maior influência nas propriedades magnéticas. O relevo e as condições de drenagem interna do perfil também se destacaram, fazendo com que solos como os latosolos exibissem altos níveis de magnetismo. A alta precipitação anual na região de Lavras favoreceu a formação e transformação dos óxidos de ferro. Os índices de intemperismo sugerem que solos mais velhos (Latosolos) pudessem exibir níveis de magnetismo superiores aos solos jovens (Cambisolos). Considerando as diferenças detectadas nas amostras obtidas das três classes de solo avaliadas, é possível inferir que a análise de parâmetros magnéticos em partículas erodidas possa ser usada como uma técnica de rastreamento para identificar a origem de sedimentos.

Palavras-chave: Fatores de formação de solo; Magnetismo ambiental; Óxidos de ferro; Propriedades magnéticas; Solos tropicais.

1. Introduction

Interactions between tropical weathering conditions, long-duration soil-forming intervals and a range of different parent materials have often produced in Brazilian soils, both high soil Fe oxide concentrations and a range of different Fe oxide minerals. Such combination makes Brazilian soils an excellent environment to study magnetic properties.

Therefore, the different soil classes still need to be investigated in relation to magnetic aspects. In fact, as soil classes exhibit different magnetic properties, Brazil's large territory stands out as very representative tropical research environment (Kämpf et al., 2012; Ker, 2013; Resende et al., 1986; Resende et al., 2014). For instance, approximately 31.61% of Brazilian soil are classified as Latosol (Oxisol as US Soil Taxonomy equivalent), and Cambisol represents 5.43% of total area (Inceptisol as US Soil Taxonomy equivalent) (Anjos et al., 2012; Buol et al., 2011; Embrapa, 2013).

Differences in soil magnetic properties can be used as a tool to better understand soil forming processes and the movement of soil by erosional processes (Armstrong et al., 2012; Dearing et al., 1986; Hatfield; Maher, 2009). All solid rocks, sediments and soils display some magnetic behavior, arising from different atomic and crystalline configurations. Such magnetic signatures can be easily measured and quantified (Costa and Bigham, 2009; Walden et al., 1999). For instance, Dearing (1999) measured a magnetic property (low frequency magnetic susceptibility) at different iron oxides (table 3.1) when submitted to an external magnetic field (Thompson; Oldfield, 1986). Differences on magnetic properties of ferromagnetic materials, for example by magnetite, and antiferromagnetic minerals, such as haematite, can be measured and used to identify the structure of iron oxides in sediments (Walden et al., 1999).

Table 1.
Minerals/materials classified by magnetic behaviour, chemical form, Fe content and low frequency magnetic susceptibility, adapted from Dearing (1994) and from Costa and Bigham (2009).

Magnetic Behaviour	Mineral/Material	Chemical Form	Fe ($g\ kg^{-1}$)	Low Frequency Magnetic Susceptibility ($10^{-8}\ m^3\ kg^{-1}$)
Ferromagnetic	Iron	Fe	1,000	27,600,000
Ferrimagnetic	Magnetite (0.012 - 0.069 μm)	Fe_3O_4	720	44,000 - 111,600
	Magnetite (1 - 250 μm)	Fe_3O_4	720	39,000 - 71,600
	Maghemite	γ-Fe_2O_3	700	28,600 - 50,000
	Titanomagnetite	Fe_2TiO_4	Variable	16,900 - 29,000
Antiferromagnetic	Haematite	α-Fe_2O_3	700	27 - 169
	Goethite	α-FeOOH	630	35 - 125
Paramagnetic	Ilmenite	$FeTiO_3$	370	170 - 200
	Lepidocrocite	γ-FeOOH	630	50 - 75
Diamagnetic	Quartz	SiO_2	0	-0.1
	Kaolinite	$Al_2Si_2O_5(OH)_4$	0	-0.01

The most important ferrimagnetic minerals occurring in soils and sediments are magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3) (Mullins, 1977). Such ferrimagnetic minerals naturally occurs in soils at trace concentrations (Maher, 2007). Both detrital and in situ (pedogenic) sources of Fe oxides are possible. Maghemite can be formed by oxidation of detrital magnetite (Cornell and Schwertmann, 2003; Fontes et al., 2000; Maher, 1998; Resende et al., 1986). In basalt-derived soils, as it is the case at most of Brazilian soils, maghemite occurrence in the soil profile is associated with hematite (Costa et al., 1999). In the other hand, in situ formation of ferrimagnetic minerals can occur, either by thermal transformation of other Fe oxides in the presence of organic matter (Le Borgne, 1960; Mullins, 1977; Schwertmann and Taylor, 1989) or by magnetotactic bacteria forming pedogenic magnetite (Fassbinder et al., 1990; Maher, 1998).

Moreover, ferrimagnetic minerals presence in soils is strongly related to soil particle size fractions. For instance, detrital magnetite tends to accumulate in the coarser fractions of soil, whereas detrital maghemite can be found at clay fraction (Kämpf and Curi, 2000). Therefore, for magnetic properties analyses soil particle size separation is strongly recommended (Armstrong et al., 2012; Costa and Bigham, 2009; Fontes et al. 2000; Hatfield and Maher, 2008; Maher et al., 1999).

Other important minerals present in concentration terms at tropical soils are haematite (αFe_2O_3) and goethite ($\alpha FeOOH$), which are presented in table 3.1. However, such minerals exhibit low magnetic susceptibility magnitude due to their antiferromagnetism magnetic behaviour (Fontes et al., 2000; Walden et al., 1999). The contrast in magnetic properties at different minerals found in nature provide key ways in which environmental magnetic measurements can be a diagnostic of the iron oxide assemblage within rocks, sediments or soils (Costa and Bigham, 2009; Dearing et al., 1996; Walden et al., 1999).

In Brazil, about 5% of the area is represented by magnetic latosols (Resende et al., 1986). At some areas, like Paraná state, magnetic soils represents almost 50% of total area, in which magnetic soils are defined as those having saturation magnetization greater than approximately 1 $Am^{-2}kg^{-1}$, so that they are easily attracted by a hand magnet (Costa et al., 1999; Resende et al., 1986). Surprisingly, our understanding of the magnetic properties of Brazilian soils is still scarce. In relation to other tropical and subtropical soils, several studies on magnetic properties have been developed recently aiming to better understand such soil environments and signatures. The studies involving environmental magnetism properties at Brazilian and global tropical soils are listed in table 3.2.

Table 2.

Summary of references on environmental magnetism at Brazilian and other tropical soils studies.

Soil research site	References
Brazil	Anami and Costa (2013), Araujo et al. (2014), Costa et al. (1999), Fontes et al. (2000), Matias et al. (2013), Matias et al. (2015), Moukarika et al. (1991), Oliveira et al. (2015), Paduani et al. (2009), Resende et al. (1986), Santos et al. (2011), Silva et al. (2010), Siqueira et al. (2010), Souza Júnior et al. (2010).
Other Global Tropical sites	Ananthapadmanabha et al. (2014), Balsam et al. (2004), Chen et al. (2005), Eyre and Shaw (1994), Fischer et al. (2008), Han et al. (1996), Lu (2000), Lu et al. (2008), Lu et al. (2012), Owliaie et al. (2006), Torrent et al. (2007), Van Dam et al. (2008), Zhang et al. (2007).

The soil magnetism variability worldwide help researchers to use it as a tool to interpret different soil environments and formation processes. In order to provide proper interpretation, use of Dokuchaev's (1883) soil formation factors, presented by Jenny (1994) equation are conventionally used, as soil formation depends on climate, organisms/vegetation, relief, parent material and time. Several research studies regarding soil formation factors to better understand environmental magnetism were published, as presented at table 3.3.

Table 3.
Summarized references of environmental magnetism and soil formation processes proposed by Jenny (1994) studies.

Formation Process	References
Climate	Ananthapadmanabha et al. (2014), Blundell et al. (2009), Dearing et al. (1996), Eyre and Shaw (1994), Fischer et al. (2008), Han et al. (1996), Maher et al. (1994), Maher (1998), Maher et al. (2002, 2003).
Organisms/vegetation	Blundell et al. (2009), Dearing et al. (1995), Hounslow and Chepstow-Lusty (2004), Mullins (1977), Neumeister and Peschel (1968), Schwertmann and Taylor (1989).
Relief	Blundell et al. (2009), De Jong et al. (2000), Hatfield and Maher (2009), Hanesch and Scholger (2005), Maher (1998), Matias et al. (2013), Schwertmann (1991).
Parent Material	Araujo et al. (2014), Blundell et al. (2009), Fontes et al. (2000), Hanesch et al. (2001), Hanesch and Scholger (2005), Hatfield and Maher (2009), Lu (2000), Lu et al. (2008), Lu et al. (2012), Silva et al. (2010).
Time	Blundell et al. (2009), Singer et al. (1992).

Magnetism can be also used to characterize the movement and deposition of eroded soil particles. In fact, the technique that uses magnetic properties as sediment tracer (fingerprinting) has been used also on non-tropical soils (Armstrong et al., 2012; Collins et al., 1997; Dearing et al., 2001; Guzmán et al.; 2010; Maher et al., 2009; Walling et al., 1979; Yu and Oldfield, 1993). The successful use of fingerprinting on Brazilian soils still depends however on further investigation of magnetic variations in tropical soils.

Studies correlating magnetic properties to soil formation factors along toposequences are rare, especially for tropical soils. Therefore, the objectives of this research were: 1) to characterize magnetic properties from three toposequences in different land uses at Lavras region, Brazil; 2) to evaluate possible influence of soil formation factors on magnetic properties of such soils; and 3) to evaluate influence of soil particle size on magnetic properties. It is possible that according to results, the potential use of magnetism as a fingerprinting tool in tropical soils can be evaluated.

2. Material and methods

The study area was at Federal University of Lavras (UFLA) campus, in Lavras, Minas Gerais state, Brazil. Local climate is classified according to Köppen classification system as Cwa, with a dry winter and temperate summer (Alvares et al., 2013), with average annual rainfall of approximately 1,530 mm and mean annual temperature of 19.4 ºC (Dantas et al., 2007).

Soil samples were collected at three toposequences in the Lavras region, as shown in table 3.4. The region exhibits the main Brazilian soil types (Curi et al., 1990; Marques Júnior et al., 1992). At the first transect, the soil was classified as dystrophic Tb Haplic Cambisol in the Brazilian System of Soil Classification, equivalent to an Inceptisol at US Soil Taxonomy Classification System. At the second transect, the soils were classified according to the Brazilian System of Soil Classification as: dystroferric Red Nitosol at one site (LA1), and as dystrophic Red-Yellow Latosol (remaining sites), equivalent to an Oxisol at US Soil Taxonomy Classification System. At the third transect, the soil was classified as dystroferric Red Latosol, also equivalent to an Oxisol at US Soil Taxonomy Classification System (Buol et al., 2011; Embrapa, 2013).

Table 4.
Soil sampling characterization.

Transect	Site	Land Use	Coordinates		Elevation
			Latitude	Longitude	
1st (CXbd)	C1	Native Forest	21°13'51"	44°59'11"	857
	C2	Native Forest	21°13'50"	44°59'10"	873
	C3	Crop Cultivation	21°13'48"	44°59'10"	878
	C4	Crop Cultivation	21°13'47"	44°59'09"	884
	C5	Crop Cultivation	21°13'46"	44°59'09"	892
2nd (NVdf and LVAd)	LA1	Native Forest	21°13'27"	44°58'09"	940
	LA2	Eucalyptus	21°13'25"	44°58'11"	933
	LA3	Crop Cultivation	21°13'22"	44°58'14"	922
	LA4	Crop Cultivation	21°13'20"	44°58'17"	912
	LA5	Native Pasture	21°13'16"	44°58'23"	906
3rd (LVDf)	LV1	Native Forest	21°13'43"	44°58'46"	909
	LV2	Native Forest	21°13'40"	44°58'46"	919
	LV3	Crop Cultivation	21°13'31"	44°58'46"	909
	LV4	Crop Cultivation	21°13'25"	44°58'46"	903
	LV5	Crop Cultivation	21°13'23"	44°58'46"	893

CXbd: dystrophic Tb Haplic Cambisol; NVdf: dystroferric Red Nitosol; LVAd: dystrophic Red-Yellow Latosol; LVdf: dystroferric Red Latosol.

Soils were sampled under different land uses: native forest as control treatment, crop cultivation, eucalyptus and pasture (table 3.4). Soils main properties (Embrapa, 1997) and soil erodibility (Wischmeier and Smith, 1978) were determined. Soil erodibility was determined through rainfall erosivity and soil loss relation at bare soil (Article 1). Soil erodibility values were corrected by slope (9%) and slope length (12m) trough Bertoni et al. (1975) and Wischmeier and Smith (1978) equations.

At each sampling site (table 3.4), triplicate undisturbed 1 m profiles samples using 50 millimeters diameter PVC (Polyvinyl chloride) core were taken. Soil cores were sliced into 10 cm layers in order to measure magnetic properties. As magnetic properties are strongly particle-size dependent (Armstrong et al., 2012; Fontes et al. 2000; Hatfield and Maher, 2008; Maher et al., 1999), samples were separated into three particle size fractions prior to analysis (sand, silt and clay). Samples were then treated with 1 N NaOH solution and moved to an ultrasonic bath in order to enhance particle dispersion. Soil samples were wet sieved to obtain sand size fraction. The remaining material was separated by settling in Atterberg columns into clay and silt. The separated fractions were dried at 40°C and packed into 10 cc plastic sample pots prior to magnetic analyses.

Mineralogy analysis was performed at the X-ray diffraction (XRD) Siemens D 5000 diffractometer, with CoKα radiation and Fe filter under 40 kV voltage and 25 mA current. Samples were prepared in non-oriented slides of concentrated iron oxide fraction (Norrish and Taylor, 1961; Singh and Gilkes, 1991).

Magnetic parameters measured were: low frequency magnetic susceptibility (χ_{LF}), high frequency magnetic susceptibility (χ_{HF}) and stepwise acquisition of isothermal remanent magnetization (IRM). Magnetic susceptibility were measured at 0.47 kHz (low frequency) and at 4.7 kHz (high frequency) on a Bartington MS2B Susceptibility Sensor. IRM was acquired in DC fields of 10, 20, 50, 100 and 300 mT, using a Molspin Pulse Magnetizer and at 1,000 mT (referred as 'Saturation' IRM (SIRM)) using a Newport Electromagnet. Samples were then demagnetized in AC fields of 5, 10, 15 and 100 mT. Remanence measurements were made on a Molspin Minispin (noise level of 2.5 10^{-5} A/m). All measurements were expressed on a mass-normalized basis. From these measurements, frequency dependent susceptibility ($\chi_{FD\%}$) was calculated, as described by Dearing et al. (1997).

3. Results and discussion

3.1 Soil characterization

Mean soil chemical and physical characteristics, soil erodibility and slope are presented in table 3.5. Weathering degree, parent material and relief are the main reason to differences among soils. The Red Latosol transect was formed from a gabbro intrusion in a flat relief, whereas Cambisol and Red-Yellow Latosol transects both come from a leucocratic granite gneiss, except first site at the second transect (Nitosol) that is originated from a gabbro intrusion with granite gneiss fragments. Difference between first (Cambisol) and second (Red-Yellow Latosol) transect is due to its relief (a smoothed slope at Red-Yellow Latosol and a more pronounced one at Cambisol) and due to its landform (linear landform at the Red-Yellow Latosol and a convex landform at the Cambisol). Such combination make pedogenesis/erosion rate relatively higher at the Red-Yellow Latosol, resulting in deeper soil with relatively higher gibbsite and iron oxide contents in clay fraction when compared to Cambisol (Kämpf et al., 2012).

Table 5.
General characterization of the soils at 0-20 cm depth.

Property	CXbd	LVAd	LVdf
pH	5.0	5.7	5.0
P (mg dm^{-3})	0.84	0.56	0.56
K (mg dm^{-3})	28.0	18.0	30.0
Ca (cmol$_c$ dm^{-3})	0.5	3.1	0.5
Mg (cmol$_c$ dm^{-3})	0.3	0.2	0.1
Al^{+3} (cmol$_c$ dm^{-3})	0.7	0.1	0.2
H+Al (cmol$_c$ dm^{-3})	4.04	2.90	4.52
t (cmol$_c$ dm^{-3})	1.57	3.45	0.88
T (cmol$_c$ dm^{-3})	4.91	6.25	5.20
BS (%)	17.76	53.54	13.02
SOM (g kg^{-1})	12.9	14.1	16.4
Sand (g kg^{-1})	480	460	260
Silt (g kg^{-1})	160	80	120
Clay (g kg^{-1})	360	460	620
[1]Erodibilidity (Mg h MJ^{-1} mm^{-1})	0.0355*	0.0041**	0.0032*
[1]Slope (%)	12.71	8.50	5.48

CXbd: dystrophic Tb Haplic Cambisol; LVAd: dystrophic Red-Yellow Latosol; LVdf: dystroferric Red Latosol; t: effective cation exchange capacity; T: potential cation exchange capacity; BS: base saturation; SOM: soil organic matter. *Data obtained from Silva et al. (2009). **Data obtained by the authors of the present work. [1]0-20 cm depth characterization does not apply.

Cambisol typically does present low Fe oxides contents (Resende et al. 2014). In fact, Cambisol has been exposed to limited weathered to partially change its parent material (leucocratic granite gneiss). Horizon Bi (B incipient) already presents colour and typical soil structure, but still holds many fragments of parent material (Embrapa, 2013).

Mineralogical composition was variable in the 2nd transect (Red-Yellow Latosol), once soil sites were classified as Nitosol and Red-Yellow Latosol. Leucocratic granite gneiss mineral weathering, which lead to a Red-Yellow Latosol formation, had a clear coloration, with quartz, feldspars and muscovite mineral predominating. On the other hand, a gabbro intrusion with granite gneiss fragments, that formed Nitosol of dark coloration, provides some ferromagnesian minerals, such as augite, hornblende, biotite and magnetite (Marques Júnior et al., 1990).

In the 3rd transect (Red Latosol), low or no quartz presence in the parent material added to long exposure time of this soil to bioclimatic agents facilitated by a smoothed slope, provided higher pedogenesis/erosion rates. As a consequence very deep soils were formed, with more gibbsite and sesquioxide mineralogy featuring very old soils (Kämpf et al., 2012).

Sulphuric acid digestion data and Ki and Kr indexes, which indicate oxidic mineralogy, obtained at control site (forest) and at an anthropic site of each soil are presented in table 3.6. The 3rd transect have the lowest Ki and Kr values when compared to other soils due to latolization formation process at Latosol, in which elevated weathering and efficient drainage conditions directly resulted in high Fe oxides. Accentuated removal of silica and other elements occurs by mineral weathering, leading to Fe and Al oxides enrichment (Kämpf and Curi, 2003; Resende et al., 2014).

Table 6.
Sulphuric acid digestion of soil samples studied.

Attribute	First Transect		Second Transect		Third Transect	
	CXbd	CXbd	NVdf	LVAd	LVdf	LVdf
	Control	Anthropic	Control	Anthropic	Control	Anthropic
SiO_2 (%)	19.00	16.58	23.08	17.67	14.46	15.19
Al_2O_3 (%)	21.53	23.55	23.16	22.38	27.91	28.34
Fe_2O_3 (%)	3.66	3.86	19.09	7.25	22.82	24.8
TiO_2 (%)	0.667	0.553	3.014	1.231	2.29	3.84
P_2O_5 (%)	0.014	0.008	0.07	0.026	0.056	0.055
Ki	1.50	1.20	1.69	1.34	0.88	0.91
Kr	1.35	1.08	1.11	1.11	0.58	0.58
Al_2O_3/Fe_2O_3	9.23	9.59	1.9	4.85	1.92	1.79

CXbd: dystrophic Tb Haplic Cambisol; NVdf: dystroferric Red Nitosol; LVAd: dystrophic Red-Yellow Latosol; LVdf: dystroferric Red Latosol.

Elevated maghemite presence was detected in the clay fraction of X-ray diffraction analysis (figure 3.1) for the Red Latosol samples (LV1 and LV4), and as expected, such mineral presence occurred associated with haematite (Costa et al., 1999). Red-Yellow Latosol control site (LA1) also has a considerable amount of maghemite possibly due to its parent material formation, slope and weathering conditions (tables 3.5 and 3.6) (Kämpf and Curi, 2000).

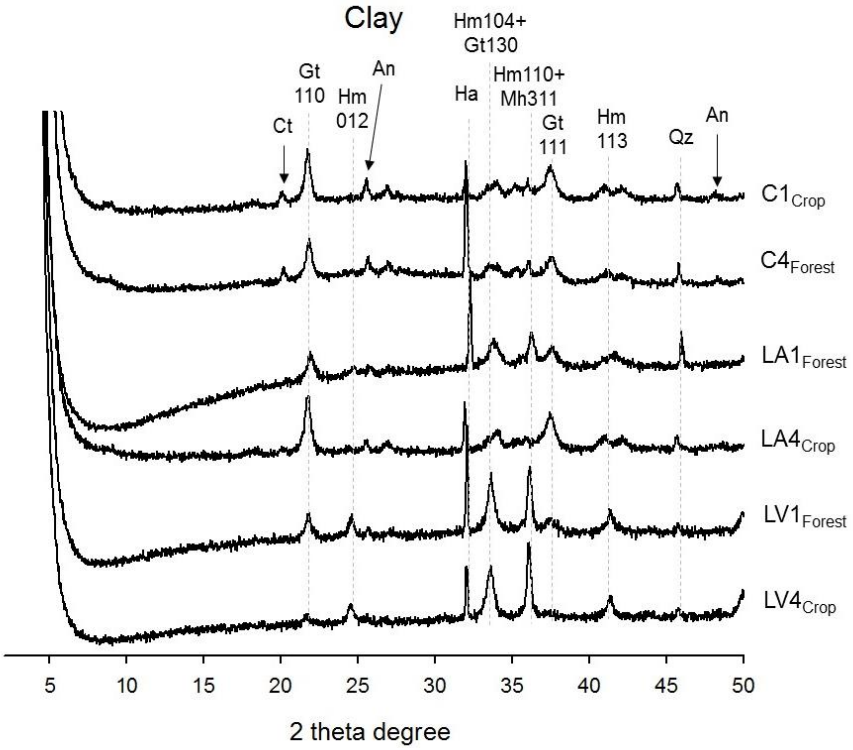
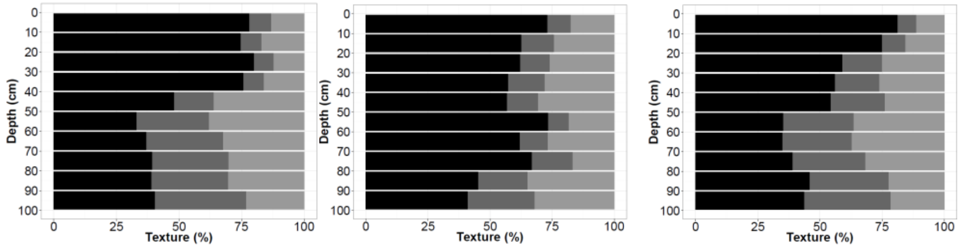
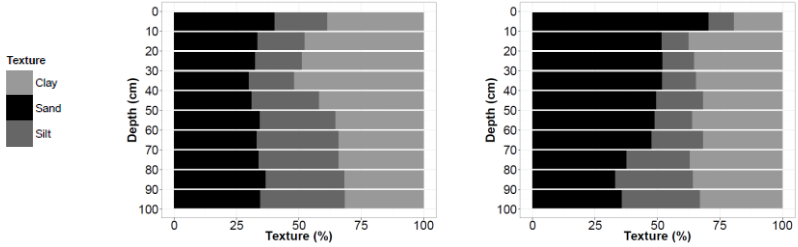


Fig. 1. X-ray diffraction of oriented samples of natural clay soil horizons. Qz = quartz, Gt = goethite, Hm = haematite, An = anatase, Ha = halite*, Mh = maghemite. *10% of halite was added due to methodology used.

Particle size distribution (sand, silt and clay) for each sample site is illustrated as different soil classes present varied proportions (figures 3.2, 3.3 and 3.4). Cambisol (1st transect) profiles had smaller clay contents then other soil classes due to several factors, such as its more accentuated landscape slope and high soil erodibility (table 3.5), consequently resulting in elevated sand content throughout the profile. The 2nd transect (Red-Yellow Latosol) profiles did not present texture variations when compared to the control situation (native forest) and remaining land uses. Moreover, 3rd transect (Red Latosol) profiles had a small clay increase with depth, and as expected, had a fine texture (presenting up to 80% of clay) than the remaining soil classes, as a result of intense weathering (Curi and Kämpf, 2012; Kämpf et al., 2012; Ker, 2013; Resende et al., 2014).

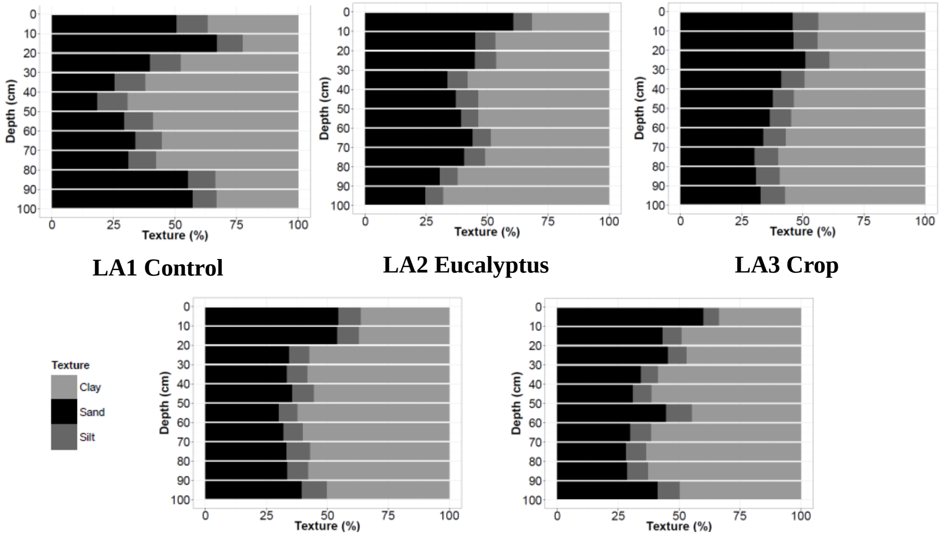


C5 Control **C4 Control** **C3 Crop**



C2 Crop **C1 Crop**

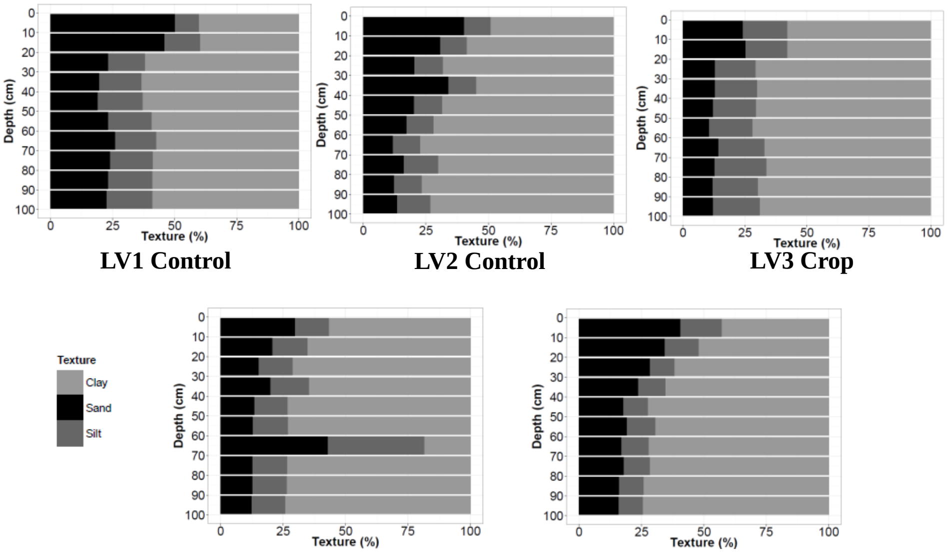
Fig. 2. Particle size distribution (sand, silt and clay) of Cambisol transects, 1 meter down profiles, divided in 10 cm layers, at different sites.



LA1 Control **LA2 Eucalyptus** **LA3 Crop**

LA4 Crop **LA5 Pasture**

Fig. 3. Particle size distribution (sand, silt and clay) of Red-Yellow Latosol transects, 1 meter down profiles, divided in 10 cm layers, at different sites.



LV1 Control **LV2 Control** **LV3 Crop**

LV4 Crop **LV5 Crop**

Fig. 4. Particle size distribution (sand, silt and clay) of Red-Latosol transects, 1 meter down profiles, divided in 10 cm layers, at different sites.

3.2 Magnetic parameters

At first, low frequency magnetic susceptibility, one of the main magnetic parameters in environmental magnetism were measured at each one centimetre in cores. Such measurements were made using three replicates at each site in order to ensure statistical difference between soil types investigated and land uses (figure 3.5).

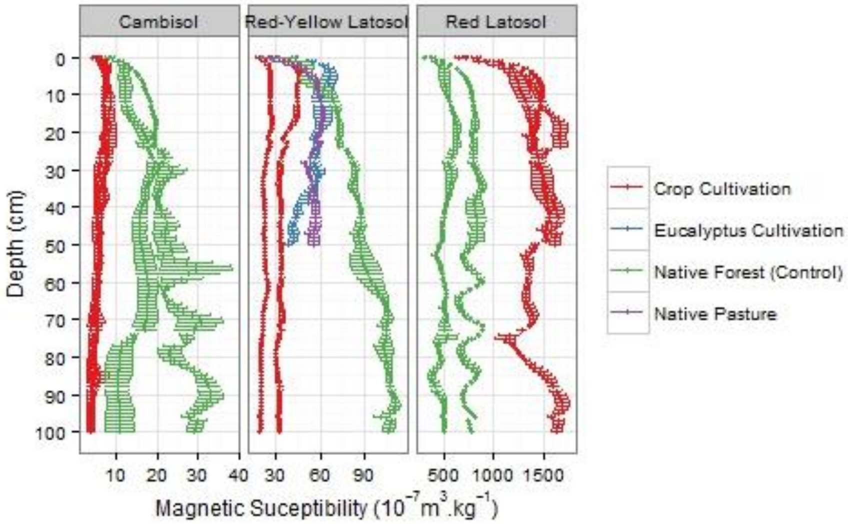


Fig. 5. Average low frequency magnetic susceptibility (10^{-7} m^3 kg^{-1}) at 1 meter down profiles for three soils (Red Latosol, Red-Yellow Latosol and Cambisol) from Lavras, Brazil.

Once magnetic susceptibility variability is mainly associated to the Fe oxides assemblage within a soil, measurements of χ_{LF} from the soils analysed clearly reflected their different parent material characteristics.

Elevated weathering of Fe from Red Latosol parent material (gabbro intrusion) and high drainage conditions directly resulted in high Fe oxides content. Soils developed from basalt rocks, like Red Latosol, are often characterized by higher χ_{LF} values (Costa et al., 1999; Lu et al., 2008; Silva et al., 2010).

In the other hand, low χ_{LF} values are strongly related with Cambisol formation process, in which soil has suffered enough weathering to change only partially its parent material, leucocratic granite gneiss, which is a rock that contain low levels of iron oxides, generating soils low in iron oxides levels (Silva et al., 2010). Analysing χ_{LF} for the Red-Yellow Latosol samples, there is a values magnitude increase when compared to the Cambisol values, despite both soils originate from the same parent material. The main difference between Cambisol and Red-Yellow Latosol magnetic values are related to slope gradient: the LVAd landscape (10.10%) is softener than CXbd (5.48% slope) facilitating exposure to bioclimatic agents, resulting in higher iron oxides level contents at LVAd, as determined by sulphuric acid digestion (table 3.6).

3.2.1. First Transect – Cambisol (CXbd)

Elevation, in meters, of the five sites, under crop cultivation or native forest (control) sampled at the CXbd transect, as well as low frequency magnetic susceptibility (χ_{LF}) (10^{-7} m^3 kg^{-1}) at different particle size (clay, sand and silt) at 1 meter down profile are presented at figure 3.6.

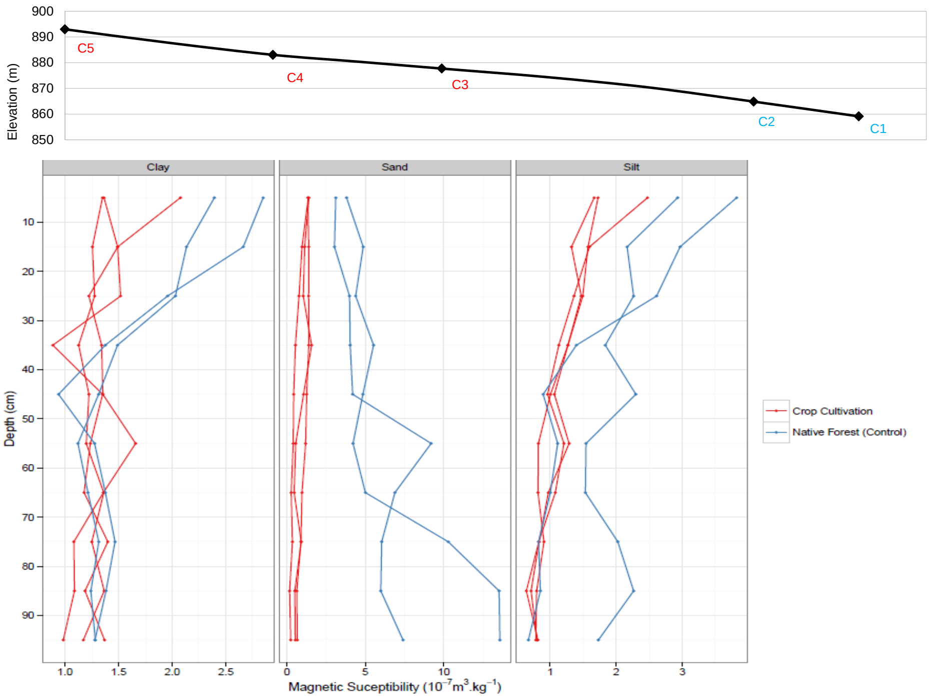


Fig. 6. Elevation (m) of sampling sites and low frequency magnetic susceptibility (10^{-7} m^3 kg^{-1}) for three different particle sizes (sand, silt and clay) in a Cambisol profile from Lavras, Brazil, with different land uses.

Elevated relief combined with lack of surface soil protection at crop scenarios will generate an enhanced natural erosion process, which will carry out thinner and lighter material. Such erosion process is predominantly laminar, facilitating water erosive action and thus detachment and transport of soil particles, promoting soil loss accumulation at control sites (C1 and C2), located in a lower landscape position. Eroded soil accumulation at forest sites is justified by a less erodible scenario at forest soil cover. Commonly, magnetic susceptibility increases downslope at upper layers (Blundell et al., 2009; De Jong et al., 1998).

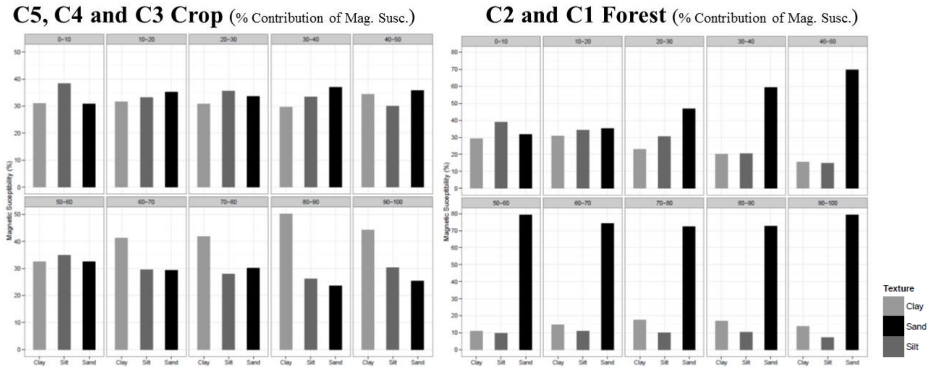


Fig. 7. Particle size contribution of low frequency magnetic susceptibility (%) in a CXbd from Lavras, Brazil, at different soil depths (0 – 100 cm) and sampling sites.

Figure 3.7 also suggests that at the beginning of Cambisol soil formation process, climate and relief conditions favoured erosion of the lighter material/minerals. Since the parent material of Cambisol is granite gneiss, among one of those such lighter minerals, biotite eroded first to lower parts of landscape, and eventually other minerals were eroded downslope, being deposited on top of C1 and C2 sites. Biotite is a mineral with paramagnetic behaviour, weak, but positive magnetic susceptibility (Walden et al., 1999). Therefore, biotite deposition produces an elevated percentage contribution on χ_{LF} of sand fraction at deeper layers of C1 and C2 sites.

In order to confirm paramagnetic (biotite) presence at lower parts of landscape (C1 and C2), SIRM/χ_{LF} ratio was calculated (figure 3.8). A lower ratio, as values presented here, suggests a greater proportion of diamagnetic and paramagnetic minerals (Oldfield et al., 1985; Walden et al., 1999).

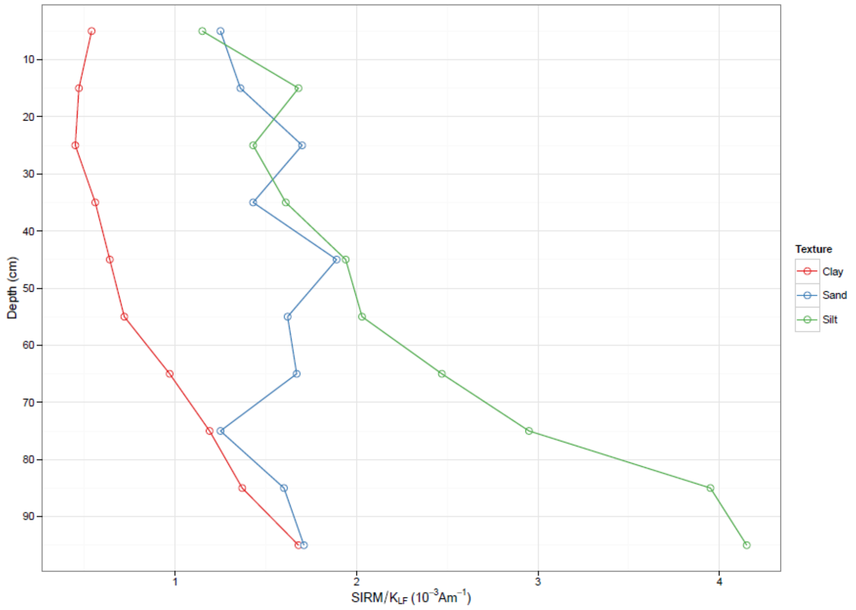


Fig. 8. SIRM/ /χ_{LF} ratio values (C1 site values) in 10^{-3} Am^{-1} for three different particle sizes (sand, silt and clay) in a 1 meter down profile from Lavras, Brazil.

Cambisol χ_{LF} values presented here are similar to values found by Owliaie et al. (2006) in Inceptisol soils in Iran, with values varying from 0.16 to 0.35 10^{-7} m^3 kg^{-1}. Araújo et al. (2014) presented much higher Cambisol χ_{LF} values of 92.4 and 102.9 x 10^{-7} m^3 kg^{-1} at A horizon (0 to 18 cm depth) and Bi horizon (18 to 100 cm depth), respectively, in Minas Gerais state, Brazil. Those higher values are related to higher ferrimagnetic content in the soils researched by those authors when compared to Cambisol from present study.

'Saturation' IRM (SIRM$_{1T}$) values for the three different particle sizes (sand, silt and clay) in the 1st transect were similar to all sampling sites (C1, C2, C3, C4 and C5 values) (figure 3.9). Regarding sand samples, most remanence is acquired at fields of 10-100 mT (~50%), while clay and silt samples most remanence acquisition (~40%) were at higher fields (300-1000 mT). Such magnetic behavior indicates predominance of 'hard' minerals (e.g. goethite) at the finer soil fractions (silt and clay), corroborating with low χ_{LF} values (figure 3.7), characterized when ferrimagnetic minerals are not present.

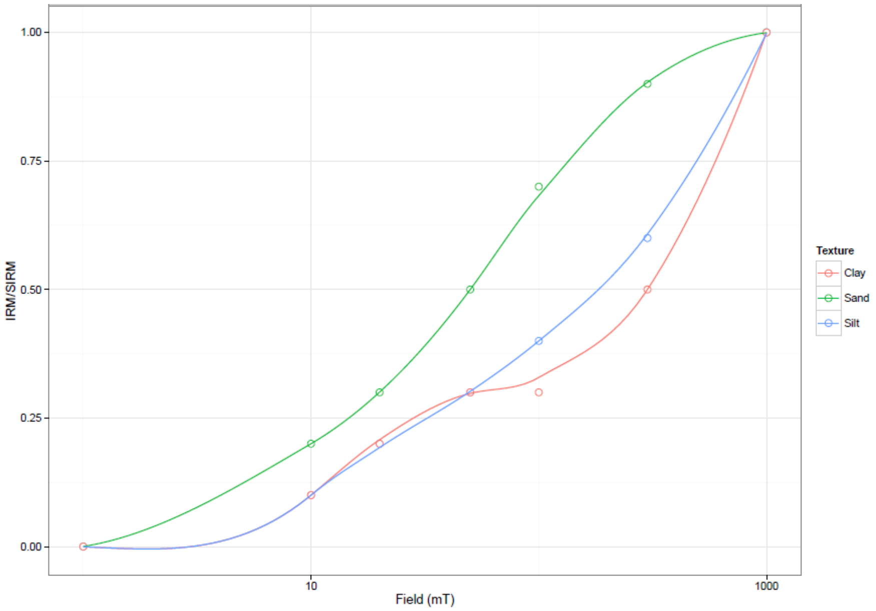


Fig. 9. Average IRM acquisition values (C1, C2, C3, C4 and C5 site values) at different applied field (mT) for three different particle sizes (sand, silt and clay) in a CXbd profile from Lavras, Brazil.

3.2.2. Second Transect – Red-Yellow Latosol (LVAd)

Elevation (meters) of the five sites sampled under different cultivation system or native forest (control) at the LVAd transect, as well as χ_{LF} (10^{-7} m^3 kg^{-1}) at different particle size (clay, sand and silt) at 1 meter down profile are presented at figure 3.10.

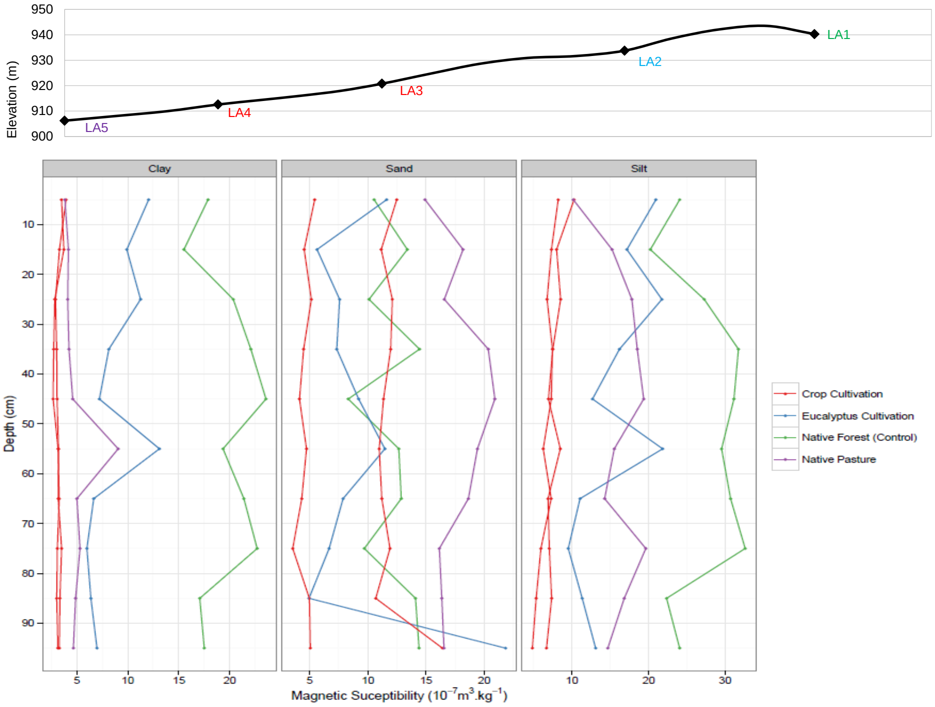


Fig. 10. Elevation (m) of sampling sites and low frequency magnetic susceptibility (10^{-7} m^3 kg^{-1}) for three different particle sizes (sand, silt and clay) in a Red-Yellow Latosol profile from Lavras, Brazil, with different land uses.

LA1 soil sampling site was originated from a gabbro intrusion with granite gneiss fragments, in which it can provide some ferromagnesian minerals, such as augite, hornblende, biotite and magnetite (Marques Júnior et al., 1990). Such elevated iron content directly influence χ_{LF} (figure 3.10), especially in the clay fraction where maghemite presence was detected by X-ray diffraction analysis (figure 3.1). In the other hand, other sites on this Red-Yellow Latosol transect were originated from a leucocratic granite gneiss mineral, predominating with quartz, feldspars and muscovite minerals. Those minerals are characterized as having none or very low magnetic susceptibility (Walden et al., 1999).

In order to confirm maghemite presence in the clay fraction, SIRM demagnetization curves are presented at figure 3.11. When a sample gets to its magnetic saturation (SIRM), a series of fields is applied in an opposite direction so the demagnetization behaviour of the assemblage can be identified. Red-Yellow Latosol clay samples presents an easy demagnetization, once magnetic saturation value (SIRM) is reduced by 50% before 15 mT field is applied. Such behaviour is common at ‘soft’ minerals that did not hold a strong remanence, indicating an elevated maghemite presence, especially at LA1 and LA2 soils as mentioned above (Walden et al., 1999).

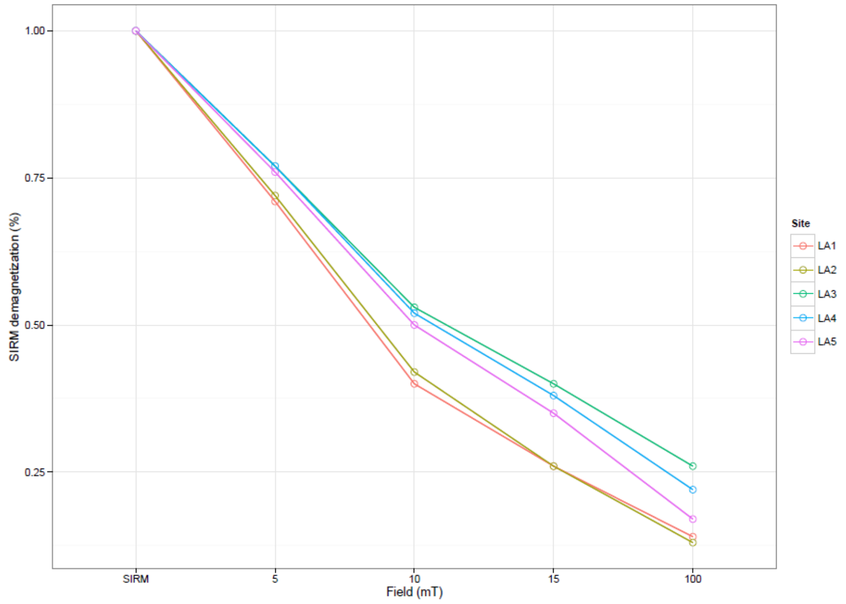


Fig. 11. Demagnetization of SIRM (Saturated IRM) in %, in clay fraction in Red-Yellow Latosol profile sites from Lavras, Brazil.

Similar χ_{LF} values (ranging from 17.1 to 23.9 10^{-7} m^3 kg^{-1}) to χ_{LF} values presented here, were determined in a soil originated from a gneiss rock from Minas Gerais state, Brazil (Araujo et al., 2014). In Paraná state, Brazil, soils originated from granite and gneiss rocks presented low χ_{LF} values, in which authors also justified it by low ferrimagnetic minerals concentration (Silva et al., 2010).

Percentage of frequency difference ($\chi_{FD\%}$), clearly distinguishes clay magnetic behaviour samples and sand samples (figure 3.12). As sand fraction presents low $\chi_{FD\%}$ (<2%), virtually no superparamagnetic grains are expected (Dearing, 1999), corroborating with X-ray diffraction analysis which indicates no magnetite presence, often associated with sand fraction of soil (Kämpf and Curi, 2000).

Clay particle size fraction presenting high $\chi_{FD\%}$ (10-14%), indicating virtually all superparamagnetic grains, and easy demagnetization of SIRM curves (figure 3.11) are magnetic parameters behaviours that evidence in situ (pedogenic) formation of maghemite (Walden et al., 1999). Indeed, Costa et al. (1999) also suggests pedogenic maghemite formation in Brazil, stating that its formation source is by oxidation of lithogenic magnetite.

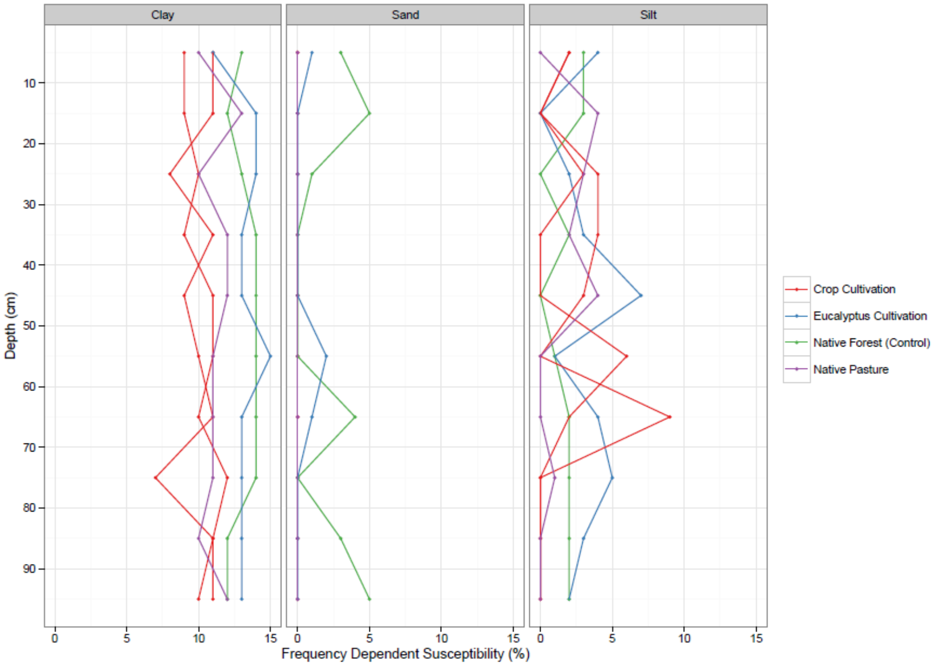


Fig. 12. Elevation (m) of sampling sites and percentage frequency difference (%) for three different particle sizes (sand, silt and clay) in an Red-Yellow Latosol profile from Lavras, Brazil, with different land uses.

3.2.2. Third Transect – Red Latosol (LVdf)

Measurements of χ_{LF} from the soils analysed (figures 3.6, 3.10 and 3.13) clearly reflected their different parent material characteristics. χ_{LF} values for the 1st (0.18 to 13.58 x 10^{-7} m^3 kg^{-1}) and 2nd transects (2.43 to 31.91 x 10^{-7} m^3 kg^{-1}) were much lower than 3rd transect (58.99 to 587.31 x 10^{-7} m^3 kg^{-1}).

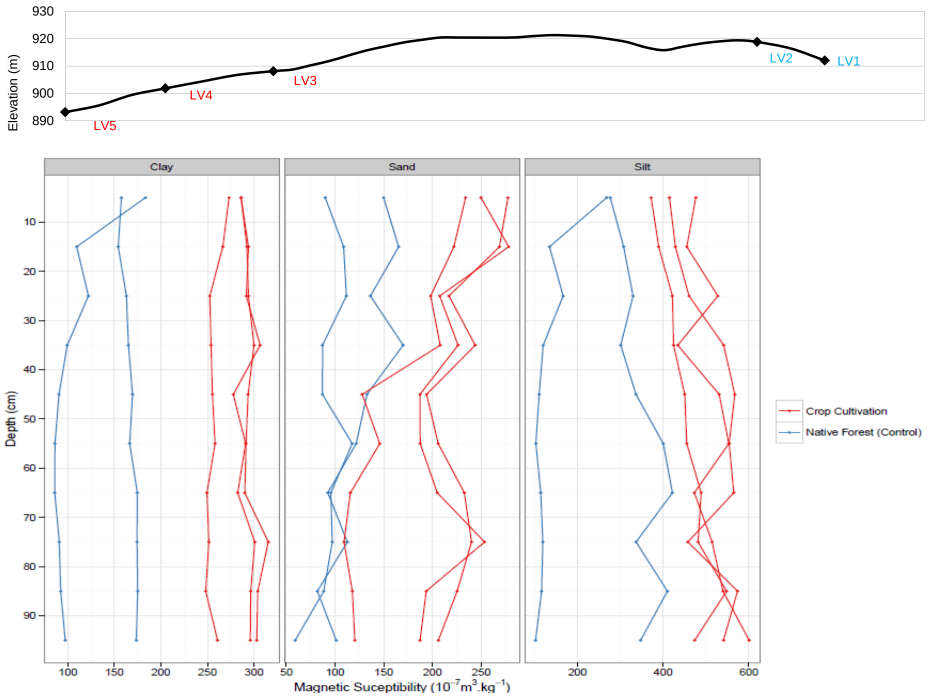


Fig. 13. Elevation (m) of sampling sites and low frequency magnetic susceptibility (10^{-7} m^3 kg^{-1}) for three different particle sizes (sand, silt and clay) in a Red Latosol profile from Lavras, Brazil, with different land uses.

Other researchers have carried out experiments that support high Fe oxides (like clay-sized maghemite) and consequent higher χ_{LF} values presented here. For example, Lu et al. (2008) presented values varying from 900 to 8,830 x 10^{-7} m^3 kg^{-1} for soils formed on basalt, and 900 to 8,830 x 10^{-7} m^3 kg^{-1} for soils formed on basalt. According to Lu et al. (2008), such difference on χ_L values is due to magnetic properties of soils formed on parent materials with elevated initial magnetic susceptibility. For instance, basalt parent material results in different soils than parent material sedimentary rocks soils, presenting a low initial magnetic susceptibility. Araujo et al. (2014) also presented elevated χ_{LF} values, varying from 892.2 to 1,405.9 x 10^{-7} m^3 kg^{-1} for a Latosol formed from gabbro intrusion. Costa et al. (1999) also stated that soils developed from basalt have higher χ_{LF} values than acid-intermediate rocks, like quartz latite or rhyodacite. Silva et al. (2010) measured basalt originated soils from Paraná state, Brazil, and presented values of 22.5 to 779 x 10^{-7} m^3 kg^{-1}, similar to those presented here.

Red Latosol $\chi_{FD\%}$ values (figure 3.13) suggests maghemite presence in the clay particle size fraction, as it presents a high $\chi_{FD\%}$ (10-14%), indicating virtually all superparamagnetic grains (Dearing, 1999). Maghemite quantities were high enough so XRD identification of this mineral was possible (figure 3.1).

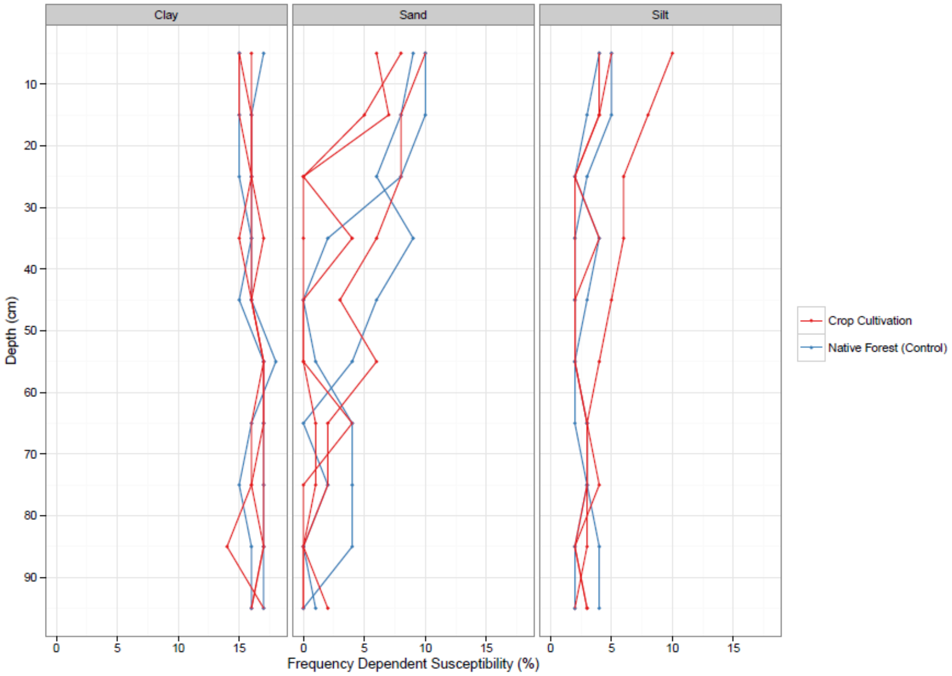


Fig. 14. Elevation (m) of sampling sites and percentage frequency difference (%) for three different particle sizes (sand, silt and clay) in an LVdf profile from Lavras, Brazil, with different land uses.

Figures 3.14 and 3.15 presents a magnetic behaviour of an elevated $\chi_{FD\%}$ at clay fraction and easy demagnetization of SIRM, reaching less than 50% of its saturation value before 10 mT field is applied. This magnetic behaviour combination evidences in situ (pedogenic) formation of maghemite at Red Latosol sites, as it happened in Red-Yellow Latosol transect (Walden et al., 1999), justifying high χ_{LF} values, once magnetic susceptibility magnitude is mainly associated to the Fe oxides assemblage within a soil.

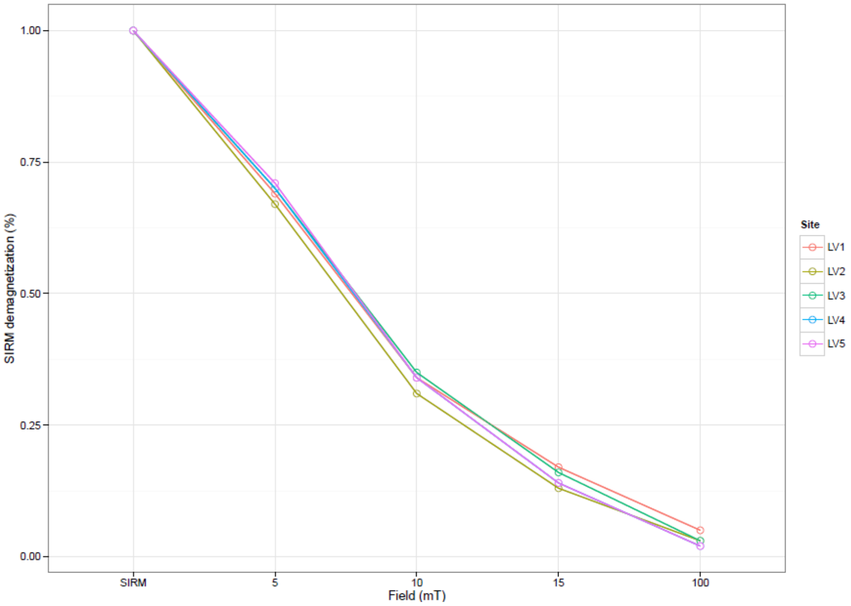


Fig. 15. Demagnetization of SIRM (Saturated IRM) in %, in clay fraction in Red Latosol profile sites from Lavras, Brazil.

'Saturation' IRM ($SIRM_{1T}$) values for the three different particle sizes (sand, silt and clay) in the 3rd transect were similar to all sampling sites (LV1, LV2, LV3, LV4 and LV5 values) (figure 3.16). Most remanence was acquired at fields of 10-100 mT (~70%), wherein clay fraction acquired all remanence at 100 mT applied field. Such magnetic behaviour also indicates a predominance of ‘soft’ mineral maghemite over ‘hard’ minerals (e.g. haematite), justifying strong magnetic susceptibility as mentioned at discussion above (figure 3.13).

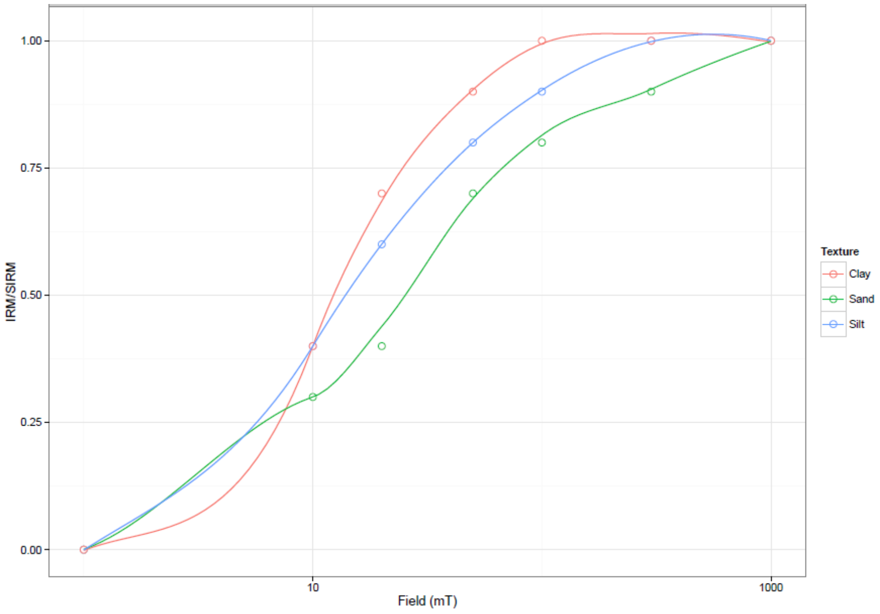


Fig. 16. Average IRM acquisition values (LV1, LV2, LV3, LV4 and LV5 site values) at different applied field (mT) for three different particle sizes (sand, silt and clay) in a LVdf profile from Lavras, Brazil.

3.3. Soil formation factors

Association of soil formation factors, proposed by Jenny (1994), with magnetic parameters and soil attributes, suggests the influence of each one of soil factors on environmental magnetism of tropical soils, as it follows. **Parent material:** unsurprisingly**,** parent material emerged as the factor with the highest level of influence of soil factors on magnetism. Such observation is due to different magnetism magnitude at soils studied, once gabbro produced soils (Red Latosol) are more magnetic enriched then granite gneiss soils (Cambisol and Red-Yellow Latosol). High magnetic values are related to elevate ferrimagnetic concentrations, originated from parent material, like at gabbro's case (plutonic rock formed by magma cooling of basaltic composition). **Relief and drainage:** relief factor had a major role on soil formation and consequently magnetic properties. Such observation was made once soils originated from the same parent material (Cambisol and Red-Yellow Latosol) presented different magnetic behaviours. A more accentuated relief (Cambisol) was critical to decrease ferrimagnetic minerals detrital formation at sampling sites, once it did provide a higher soil erodibility. Soils with high drainage conditions (Red Latosol) presented very high levels of magnetism, once accentuated removal of silica and other elements directly resulted on detrital ferrimagnetic minerals production and accumulation. Another important observation is that sites located at the lowest part of the landscapes were more susceptible to present magnetic enhancement due to eroded particles accumulation, like at Cambisol. **Climate:** annual elevated rainfall at Lavras region (1,530 mm) has a great influence on environmental magnetism enhancement, especially at Red Latosol (high drainage conditions), once natural conditions did favoured Fe oxides formation/transformation (Ker, 2013). **Time:** as Ki, weathering index at table 3.6 suggests that older soils contain higher magnetism levels then younger soils, once natural alteration process of rock and mineral alterations/transformations will generate more iron oxides. At this case, Red Latosol presented higher magnetism values then Red-Yellow Latosol and Cambisol. **Organisms and vegetation:** land use apparently did not directly affected a variability in magnetic parameters such as the remaining soil formation factors. However, the lack of soil cover vegetation directly resulted on soil particles erosion by natural rainfall, transporting enhanced soil material, and consequently depositing it over the landscapes.

4. Conclusions

Low frequency magnetic susceptibility was determined for sand, silt and clay fractions, for three transects at Lavras region, Brazil, for three different soil classes (Cambisol, Red-Yellow Latosol and Red Latosol). Values varied according to soil fractions and to soil classes. Although well studied worldwide, low frequency magnetic susceptibility research in tropical soils is still scarce and the present research at Brazilian soils evidenced that this property presents high values, especially for Latosols, mainly due to in situ formed ferrimagnetic minerals presence.

Magnetism difference among soil classes can be attributed to soil formation factors. Apparently, parent material, relief, internal profile drainage and landscape position play a major role to influence environmental magnetic behaviour. Considering the differences detected at samples obtained from the three soils studied, it is possible to infer that magnetic analysis of eroded soil particles can be successfully used as a fingerprint technique to identify the source of sediments.

5. Acknowledgements

Authors recognize their gratitude to CAPES (Coordination of Improvement of Higher Education Personnel – Process number 12082/13-9), FAPEMIG (Research Foundation of Minas Gerais State) and CNPq (National Research and Development Council – Process number 143437/2011-9 and 167089/2014-5) for their financial support and scholarships. The authors are also thankful to the support given by Lancaster University’s Vassil Karloukovski and UFRGS’s Professor Alberto Inda Júnior.

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Article elaborated according to standards of the scientific journal Geoderma

ARTICLE 3 Magnetic fingerprinting of deposited sediments as a tool for tracing eroded tropical soils of reservoirs

‘Fingerprinting’ magnético de sedimentos depositados como uma ferramenta para traçar solos tropicais erodidos em reservatórios

ABSTRACT

Water erosion promotes water quality variation and siltation of streams and reservoirs. Finding the origin of the sediments can ensure high agricultural productivity with preservation of natural resources, by targeting sediment control strategies. This research investigated for the first time potential sediment sources in Brazil through fuzzy clustering techniques quantifying magnetic parameters and identifying the origin of sediments at two reservoirs in a watershed at upper region of Rio Grande Basin, Brazil. The main objective was to verify the potential use of this magnetic fingerprinting technique for erosion studies. Research processes to identify possible route of sediments in watersheds involving magnetic properties have been widely carried out in temperate environments, at Northern latitudes, but there have been very few studies in tropical regions. This research provides one of the first demonstrations of the use of sediment fingerprinting using magnetic parameters to identify possible sediment sources in a tropical environmental, especially in the Brazilian setting. Hence, tropical weathering conditions lead to different Fe oxide minerals with high soil Fe oxide concentrations, favouring magnetic variability, allowing precise comparisons and identification of possible source of deposit sediments at reservoirs by magnetic fingerprinting. Specifically, although both soils are classified as Oxisol, two soil classes (dystrophic Red-Yellow Latosol and dystroferric Red Latosol) could be clearly distinguished by magnetic properties evaluation and the origin of sediments of downstream reservoirs precisely allocated to their source.

Keywords: Fuzzy clustering; Natural resources; Sediments sources; Tropical environment; Water erosion.

RESUMO

A erosão hídrica promove uma variação na qualidade da água e assoreamento de córregos e reservatórios. Encontrar a origem dos pode garantir uma alta produtividade agrícola com a preservação dos recursos naturais, através de estratégias de controles de sedimentos. A presente pesquisa investigou pela primeira vez no Brasil possíveis fontes de sedimentos através de técnicas por ‘fuzzy clustering’ quantificando parâmetros magnéticos e identificando a origem dos sedimentos em dois reservatórios em uma bacia hidrográfica na região da bacia do Alto Rio Grande, Brasil. O objetivo principal é verificar o uso potencial da técnica ‘fingerprinting’ magnética em estudos de erosão. Pesquisas de identificação de possíveis rotas de sedimentos em bacias hidrográficas envolvendo propriedades magnéticas tem sido amplamente utilizadas em ambientes de clima temperado, em latitudes ao Norte, sendo que houveram poucos estudos em climas tropicais. Esta pesquisa provém uma das primeiras demonstrações do uso de ‘fingerprinting’ de sedimentos utilizando parâmetros magnéticos na identificação de possíveis fontes de sedimentos em ambiente tropical, especialmente no cenário brasileiro. Portanto, as condições de intemperismo em clima tropical levaram a formação de diferentes óxidos de Fe com elevada concentração em solos de óxidos de Fe, favorecendo uma variação magnética, permitindo comparações precisas e identificação de possíveis fontes de sedimentos depositados em reservatórios através do ‘fingerprinting’ magnético. Especificadamente, apesar de ambos os solos serem classificados como Latossolos, duas classes de solo (Latossolo Vermelho-Amarelo distrófico e Latossolo Vermelho distroférrico) podem ser claramente distintos através da avaliação das propriedades magnéticas e a origem dos sedimentos dos reservatórios a jusante precisamente atribuída a sua origem.

Palavras-chave: Ambiente tropical; Erosão hídrica; Fonte de sedimentos; ‘Fuzzy clustering’; Recursos naturais.

1. Introduction

Water erosion is a major cause of land degradation and consequent reduction in agricultural production (Pimentel et al., 1995). Other negative effects of this phenomenon include the change in water quality and siltation of streams and reservoirs. Finding the origin of the sediments sources can ensure high agricultural productivity and preservation of natural resources, by targeting sediment control strategies.

Erosion rate quantification is an essential part of monitoring agricultural practices to determine how soil management system affect water and sediments runoff (Zhang et al., 2004). Traditionally, research investigations on soil and water losses by erosion often use standard plots (Wischmeier and Smith, 1978). Despite being extremely important in terms of erosion process understanding, especially in tropical conditions, the research plots are size limited and difficult to maintain.

Alternatively, use of soil tracers in soil erosion has been proposed. Methodologies are based on the principle that suspended sediments retain some of the properties acquired at their origin such that a sediment sample transported through the landscape can be compared to those of potential sources within its watershed. This technique is nominated "fingerprinting" (Armstrong et al., 2012; Collins and Walling, 2002; Walling, 2013).

There are two types of soil tracing methods (Armstrong et al., 2012). The first one considers existing soil properties, such as the concentration of variables such as soil radionuclides (^{137}Cs, ^{210}Pb, ^{7}Be), magnetic properties, metals, base cations and organic constituents. The second tracing method adds foreign material or labels to the natural soil, such as rare earths, artificial magnetic particles, fluorescent glass particles, steel nuts and radioactive elements. Summarized references of the erosion studies with tracers are presented at table 4.1, adapted from Guzmán et al. (2013).

Table 1.

Summary of references on erosion studies with tracers, adapted from Guzmán et al. (2013).

Tracer type	References
Fallout radionuclides	[a]Benninger et al. (1998), Dai et al. (2011), Kronvang et al. (1997), Li et al. (2010), Porto et al. (2011), Walling et al. (2000), Zhang and Walling (2005);
	[b]Bacchi et al. (2000), Chiu et al. (2008), di Stefano et al. (1999), Estrany et al. (2010), Lu and Higgitt (2000), Mabit et al. (2009), Mizugaki et al. (2008), Montgomery et al. (1997), Walling and He (1999), Walling et al. (1999), Wilson et al. (2008), Yang et al. (2006), Yin and Li (2008);
	[c]Belyaev et al. (2010), Fifield et al. (2010), Hassouni and Bouhlassa (2006), Higgitt et al. (2000), Li et al. (2009), Mabit et al. (2008), Olson et al. (2008), Quine et al. (1999a), Schuller et al. (2000), Wallbrink et al. (2002), Walling et al. (2009), Zhang et al. (1998);
	[d]Quine et al. (1999b), Syversen et al. (2001).
Rare earth elements	[a]Mahler et al. (1998);
	[b]Kimoto et al. (2006a), Polyakov et al. (2009);
	[c]Deasy and Quinton (2010), Matisoff et al. (2001), Stevens and Quinton (2008), Yang et al. (2008);
	[d]Kimoto et al. (2006b), Li et al. (2006), Michaelides et al. (2010), Polyakov and Nearing (2004), Pu-Ling et al. (2004), Zhang et al. (2003).
Soil magnetism and magnetic substances	[a]Dearing et al. (2001), Maher et al. (2009), Slattery et al. (2000), Walling et al. (1979), Yu and Oldfield (1993);
	[b]Hardy et al. (2000), Royall (2001);
	[d]Armstrong et al. (2010), Armstrong et al. (2012), Guzmán et al. (2010), Ventura et al. (2002).
Other tracers	[d]Bennett et al. (2010), Mentler et al. (2009), Plante et al. (1999), Sharma et al. (2009), Spencer et al. (2011), Yu et al. (2011).
Fingerprinting studies	[a]Barcellos et al. (1997), Collins and Walling (2002), Collins et al. (1998), Cunha et al. (2006), de Junet et al. (2009), Devereux et al. (2010), Fox and Papanicolaou (2008a, b), Juracek and Ziegler (2009), Kouhpeima et al. (2011), Martínez-Carreras et al. (2010a, b), Miller et al. (2005), Minella et al. (2008), Motha et al. (2003), Nosrati et al. (2011), Poulenard et al. (2009), Rhoton et al. (2008), Russell et al. (2001), Rustomji et al. (2008), Schoonover et al. (2007), Walling et al. (2008);
	[b]Fox and Papanicolaou (2007), Miguel et al. (2014), Poleto et al. (2009);
	[c]Bellanger et al. (2004).

[a] Studies made at large catchments (>100 ha); [b] Studies made at small catchments (<100 ha); [c] Studies made at hillslope scale; [d] Studies made at small plot or laboratory scale.

One of the main tracer types is the magnetic tracing, which is based on the principle that soils, sediments and rocks present magnetic properties that can be easily quantified. Different substances present different magnetic properties, enabling mineral identification and classification as well as lithological process identification. Several factors can directly influence variables that can be used for tracing the sources, such as magnetic properties at tropical soils. Soil parent material can be considered the main factor which directly influences soil iron oxides quantity. Other factors include relief, landscape position, weathering conditions and climate (Article 2). Magnetic environmental fingerprinting can be successfully used on sediment source identification (Walden et al., 1999). Several magnetic properties can be used as a fingerprinting tool; a short summary of possible environmental magnetic properties is presented at table 4.2 (Maher et al., 2009).

Table 2.
Short summary of environmental magnetic properties, adapted from Maher et al. (2009).

Magnetic susceptibility (normalized to mass) *Magnetic concentration*	Ratio of magnetic moment in a sample to the intensity of the applied magnetizing field. Measured in a small AC or DC field (typically 0.1mT). Directly proportional to strongly magnetic (e.g. magnetite and maghemite) minerals concentration. Weakly magnetic minerals (e.g. hematite) have much lower susceptibility values. Water, organic matter have negative susceptibility values.
Anhysteretic remanent magnetization (ARM) or anhysteretic susceptibility (χ_{ARM}) *Ultrafine magnetite*	Sample subjected to a decreasing AC field with a small DC field superimposed, acquiring an anhysteretic remanence. ARM is sensitive both to concentration and grain size of ferrimagnetic grains (e.g. magnetite), highest for grains close to lower single domain (SD) boundary and lowest for coarser multidomain (MD) magnetic grains (e.g. >5 μm in magnetite). If ARM normalized for the DC field strength, it is termed anhysteretic susceptibility.
Saturation remanence (SIRM) *Magnetic concentration*	Highest level of magnetic remanence that can be induced by application of a 'saturating' magnetic field (e.g. DC field 1 T) in order to saturate magnetite but not hematite or goethite. SIRM indicates concentration of magnetic minerals but also responds to magnetic grain-size.
Remanence ratios (IRM_{nmT}/SIRM (%)) *Degree of magnetic 'softness' or 'hardness'*	A 'soft' mineral (e.g. coarse MD magnetite) will acquire remanence easily at low fields (e.g. IRM_{20mT}/SIRM of 90%). In the other hand a 'hard' mineral (e.g. hematite) will magnetize only at high fields (e.g. IRM_{20mT}/SIRM of <5%).
Demagnetisation ratios (MDF_{IRM}) *Degree of magnetic 'softness' or 'hardness' (MD vs SD magnetite; magnetite vs hematite)*	SIRM subsequent demagnetization of a sample (e.g. SIRM−100mT) in increasing AC fields determine magnetic 'softness' and magnetic 'hardness'. The Median Destructive Field (MDF) of (S)IRM is the field at which a SIRM is demagnetized to 50% of its original value. Helps discriminate between MD magnetite and SD magnetite and or magnetite and hematite.

Hatfield and Maher (2009) had successfully used magnetic properties for sediment fingerprint at two sub catchments feeding Bassenthwaite Lake, in northwest England. Differences in soil magnetic mineralogy reflect differences in geology and soil particle size separation are crucial to distinguish between soil groupings from different areas of the catchment (Hatfield and Maher, 2008; Hatfield and Maher, 2009). Natural selection of soil particle size during erosion process will influence microorganisms, nutrient losses and contaminant transport (Armstrong et al., 2012; Oliver et al., 2007; Quinton et al., 2001; Quinton and Catt, 2007).

Although tropical weathering conditions lead to different Fe oxide minerals with high soil Fe oxide concentrations favouring magnetic variability, research in Brazil involving environmental magnetism as fingerprinting technique is relative scarce and mainly applied to understand geological formation processes. For example, a large scale research involving magnetic mineralogy fingerprinting in Southern Brazil detected a shift in sediment delivery at the estuary of Paraná River into distinct sources of sediments, from fine grained magnetite to coarse grained (hematite) derived from basalt (Mathias et al., 2014). Also, in a watershed at south of part of the country, significant importance of crops and roads in sediment yield was stated (Minella et al., 2007; Minella et al., 2009).

This research was concentrated at the upper region of Rio Grande Basin, a tributary of Parana River, mainly to evaluate soil sediments from the bottom of small reservoirs and compare them to the magnetic characteristics of upstream regions in order to trace their origin. Therefore, this research investigated potential sediment sources through fuzzy clustering techniques quantifying magnetic parameters and identifying the origin of sediments at a watershed in Brazil. The main objective is to confirm the potential use of this magnetic fingerprinting technique for erosion studies. To the authors knowledge, similar studies did not have been carried out in Brazil.

2. Material and methods

To understand potential sources, soil samples were collected at Federal University of Lavras (UFLA), in Lavras, Minas Gerais State, Brazil. The climate is classified as Cwa, with a dry winter and temperate summer, according to Köppen classification system (Alvares et al., 2013), with average annual rainfall of approximately 1,530 mm and mean annual temperature of 19.4 ºC (Dantas et al., 2007).

Soil samples were collected from two toposequences, as shown at table 4.3, under different land uses: native forest, crop cultivation, eucalyptus and pasture.

Table 3.
Soil sampling characterization.

Transect (soil)	Land Use	Coordinates		Elevation
		Latitude	Longitude (W)	
Dystrophic Red-Yellow Latosol	Native Forest	21°13'27"	44°58'09"	940
	Eucalyptus	21°13'25"	44°58'11"	933
	Crop Cultivation	21°13'22"	44°58'14"	922
	Crop Cultivation	21°13'20"	44°58'17"	912
	Native Pasture	21°13'16"	44°58'23"	906
Dystroferric Red Latosol	Native Forest	21°13'43"	44°58'46"	909
	Native Forest	21°13'40"	44°58'46"	919
	Crop Cultivation	21°13'31"	44°58'46"	909
	Crop Cultivation	21°13'25"	44°58'46"	903
	Crop Cultivation	21°13'23"	44°58'46"	893

The soils were classified according to the Brazilian System of Soil Classification as: dystrophic Red-Yellow Latosol; and as dystroferric Red

Latosol (Embrapa, 2013). Both soils classes are equivalent to an Oxisol by the US Soil Taxonomy Classification System (Buol et al., 2011).

Drainage area for two reservoirs (reservoirs A and B) were determined by processing a 30 m resolution Digital Elevation Model (DEM) obtained from shuffle radar topographic mission (SRTM) imagery. Flow direction and flow accumulation were calculated with the hydrology toolset for ArcGIS 10.1 (ESRI, 2011). Four points were assigned to the cell with highest flow accumulation within the reservoirs and the watershed function from the hydrology toolset delimitated the respective drainage areas.

At each soil sampling site, triplicate undisturbed 1 m profiles using 50 millimetres diameter PVC (Polyvinyl chloride) core were taken. Soil profiles cores were sliced into 10 cm layers in order to measure magnetic properties. Similarly, sediments from two reservoirs were sampled, also using 50 millimetres diameter PVC cores. Those samples were collected nearby the embankment of each reservoir (figure 4.1). Sediment profile cores from reservoirs were then sliced into 2 cm layers in order to measure magnetic properties.

As magnetic properties are strongly particle-size dependent (Armstrong et al., 2012; Fontes et al. 2000; Hatfield and Maher, 2008; Maher et al., 1999), samples were separated into three particle size fractions prior to analysis (sand, silt and clay). Samples were then treated with 1 N NaOH solution and moved to an ultrasonic bath in order to enhance particle dispersion. Soil samples were wet sieved to obtain sand size fraction. The remaining material was separated by settling in Atterberg columns into clay and silt. The separated fractions were dried at 40°C and packed into 10 cc plastic sample pots prior to magnetic analyses.

Magnetic parameters measured were: low frequency magnetic susceptibility (χ_{LF}), high frequency magnetic susceptibility (χ_{HF}), susceptibility of anhysteretic remanent magnetization (χ_{ARM}) and stepwise acquisition of isothermal remanent magnetization (IRM). Magnetic susceptibility was measured at 0.47 kHz (low frequency) and 4.7 kHz (high frequency) on a Bartington MS2B Susceptibility Sensor. χ_{ARM} was obtained using a Molspin Demagnetizer with ARM attachment at 80 mT, in a 0.10 mT DC biasing field, and then stepwise demagnetized, in AC fields of 5, 10 and 15 mT. IRM was acquired in DC fields of 10, 20, 50, 100 and 300 mT, using a Molspin Pulse Magnetizer and at 1,000 mT (referred as saturation IRM (SIRM)) using a Newport Electromagnet. Samples were then demagnetized in the same steps as in χ_{ARM}, with an additional demagnetisation step of 100mT AC. Remanence measurements were made on a Molspin Minispin (noise level of 2.5 10^{-5} A m^{-1}). All measurements are expressed on a mass-normalized basis. From these measurements, concentration-independent, interparametric ratios were calculated. All magnetic measurements were conducted at the Centre for Environmental Magnetism and Palaeomagnetism (CEMP) at Lancaster University.

Statistical matching of soils and reservoir sediments was performed by the use of fuzzy clustering technique (Hanesch et al., 2001; Hatfield and Maher, 2008; Hatfield and Maher, 2009). Fuzzy clustering aims to classify a discrete sample in multivariate space. The analysis estimates the degree of affinity between a sample and all other clusters, instead of categorical assign the samples to one cluster, as is the case in conventional hierarchal cluster analysis (Hatfield and Maher, 2009). Therefore, fuzzy clustering calculates a membership value for each sample in each cluster, ranging from 0 (no similarity) to 1 (identical). Cluster membership values variation is highly recommended once sediment source tracing samples often consists of a mixture of source materials. At first reservoir sediments were classified into clusters, then those sediments were matched with both soils sources. Kolmogorov–Smirnov (K–S) test was used in order to ensure that the data could be fitted by a normal statistical distribution function. In addition, in order to decrease the possibility of spurious matches, magnetic properties were evaluated by the non-parametric Spearman's Rank correlation coefficient to ensure that different properties were not auto-correlated (table 4.5) (Hatfield and Maher, 2008; Hatfield and Maher, 2009). Furthermore, removal of outliers in the dataset (samples values higher than 3 standard deviations from the mean) were performed, as proposed by Hanesch et al. (2001). Only properties and samples that satisfied those criteria were made available for fuzzy clustering analysis.

3. Results and discussion

Average main soil properties (Embrapa, 1997) are presented at table 4.4. A more pronounced relief and its landform make pedogenesis/erosion rate relatively higher at the dystroferric Red Latosol, resulting in deeper soil with relatively higher gibbsite and iron oxide contents in clay fraction when compared to dystrophic Red-Yellow Latosol (Kämpf et al., 2012). Soil erodibility is slighter higher at dystrophic Red-Yellow Latosol, making it a more probable sediment source.

Table 4.

General characterization of the soil at 0-20 cm depth.

Property	dystrophic Red-Yellow	dystroferric Red
pH	5.7	5.0
P (mg dm^{-3})	0.56	0.56
K (mg dm^{-3})	18.0	30.0
Ca (cmol$_c$ dm^{-3})	3.1	0.5
Mg (cmol$_c$ dm^{-3})	0.2	0.1
Al^{+3} (cmol$_c$ dm^{-3})	0.1	0.2
H+Al (cmol$_c$ dm^{-3})	2.90	4.52
t (cmol$_c$ dm^{-3})	3.45	0.88
T (cmol$_c$ dm^{-3})	6.25	5.20
BS (%)	53.54	13.02
SOM (g kg^{-1})	14.1	16.4
Sand (g kg^{-1})	460	260
Silt (g kg^{-1})	80	120
Clay (g kg^{-1})	460	620
^{1}Erodibilidity (Mg h MJ^{-1} mm^{-1})	0.0041*	0.0032**
^{1}Slope (%)	8.50	5.48

t: effective cation exchange capacity; T: potential cation exchange capacity; BS: base saturation; SOM: soil organic matter. *Data obtained from Article 2. **Data obtained from Silva et al. (2009). ^{1}0-20 cm depth characterization does not apply.

Drainage area for reservoirs A and B are shown in figure 4.1. Relief and consequent flow direction suggests a strong potential influence from Red-Yellow Latosol in reservoir A. However, for reservoir B, there is no clear potential sediment source due to a large drainage area and Red Latosol transect proximity.

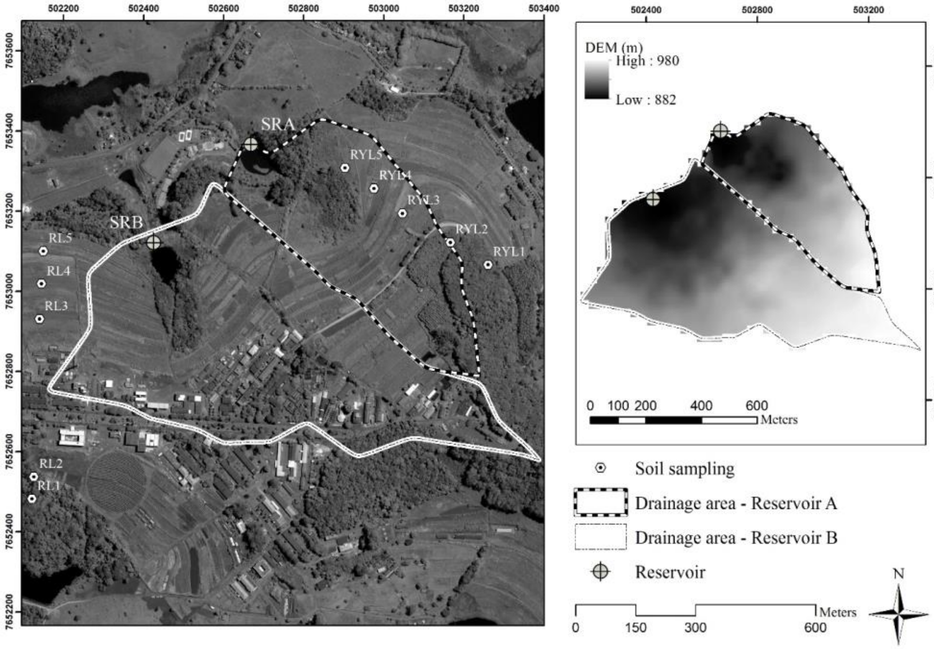

Fig. 1. Soil sampling transects (dystrophic Red-Yellow Latosol (RYL) and dystroferric Red Latosol (RL)), drainage area for the two reservoirs (SRA and SRB) and Digital Model Elevation (DEM) of the study area in Lavras region, Minas Gerais, Brazil.

Non-parametric Spearman's Rank correlation coefficient test results showing magnetic parameters correlation significant at a level of 5% probability are presented at table 4.5. The statistical test is performed to identify low correlation (not parametric) between two sets of properties, so that such data can properly be used on fuzzy clustering analysis. Several sets of parameters (denoted at table 4.5) were considered able to be used at fuzzy clustering analysis. Magnetic properties combination that presented the lowest Spearman's Rank correlation coefficient test results (rho) value statistically significant at 5% probability were χ_{HF} (in 10^{-7} m^3 kg^{-1}) versus χ_{ARM} (normalised with respect to the IRM_{100mT}) (in 10^{-5} m A^{-1}), as well as χ_{LF} (in 10^{-7} m^3 kg^{-1}) versus χ_{ARM} (normalised with respect to the IRM_{100mT}). Once χ_{LF} is the magnetic property mostly used in environmental magnetism research worldwide (Walden et al., 1999), its correlation with χ_{ARM} (normalised with respect to the IRM_{100mT}) was chosen to represent soil and sediment samples behaviours. Moreover, such properties relation were used at fuzzy clustering analysis showing differentiation between sources and dominant cluster affiliation of reservoirs sediments.

Table 5.
Non-parametric Spearman's Rank correlation coefficient test results (rho) showing magnetic parameters correlation significant at a level of 5%.

Magnetic property/ratio	IRM_{20}/ SIRM	IRM_{50}/ SIRM	$SIRM_{100mT}$/ $HIRM_{0.1\text{-}1.0T}$	$HIRM_{100\text{-}300mT}$/ SIRM	χ_{ARM}/ IRM_{100mT}	HIRM $_{20\text{-}50mT}$/ SIRM	SIRM/ χ_{LF}	χ_{ARM}/ SIRM	$HIRM_{50\text{-}100mT}$/ SIRM	$\chi_{FD\%}$	χ_{LF}/ χ_{ARM}	χ_{LF}/ SIRM	IRM_{300} /SIRM	$HIRM_{300\text{-}1000mT}$/ SIRM	MDF $_{ARM}$	SIRM	χ_{HF}	χ_{ARM}	χ_{LF}	MDF $_{IRM}$
IRM_{20}/SIRM	-																			
IRM_{50}/SIRM		-																		
$SIRM_{100mT}$/$HIRM_{0.1\text{-}1.0T}$			-	*-0.057																
$HIRM_{100\text{-}300mT}$/SIRM			*0.057	-																
χ_{ARM}/IRM_{100mT}					-								*-0.041	*0.041			*-0.005	*0.076	*0.017	
$HIRM_{20\text{-}50mT}$/SIRM						-					*-0.057									
SIRM/χ_{LF}							-									*-0.067				
χ_{ARM}/SIRM								-							*-0.027					
$HIRM_{50\text{-}100mT}$/SIRM									-		*0.014					*-0.058				*-0.058
$\chi_{FD\%}$										-					*0.077					*-0.025
χ_{LF}/χ_{ARM}						*0.057			*-0.014		-									*0.038
χ_{LF}/SIRM												-				*0.073				
IRM_{300}/SIRM					*0.041								-							
$HIRM_{300\text{-}1000mT}$/SIRM					*-0.041									-						
MDF_{ARM}								*0.027		*-0.077					-	*-0.045		*-0.059		
SIRM							*0.067		*0.058			*-0.073			*0.045	-				
χ_{HF}					*0.005												-			
χ_{ARM}					*-0.076										*0.059			-		
χ_{LF}					*-0.017														-	
MDF_{IRM}									*0.058	*0.025	*-0.038									-

* Rho value statistically significant at 5% probability.

The magnetic measurements appear to differentiate between the two major potential suspended sediment (dystrophic Red-Yellow Latosol and dystroferric Red Latosol) inputs to both reservoirs (Article 2). Figures 4.2 and 4.3 summarizes some of these observed magnetic contrasts, making sediment source identification possible by comparing both soils sediment signatures with those of the reservoirs sediments.

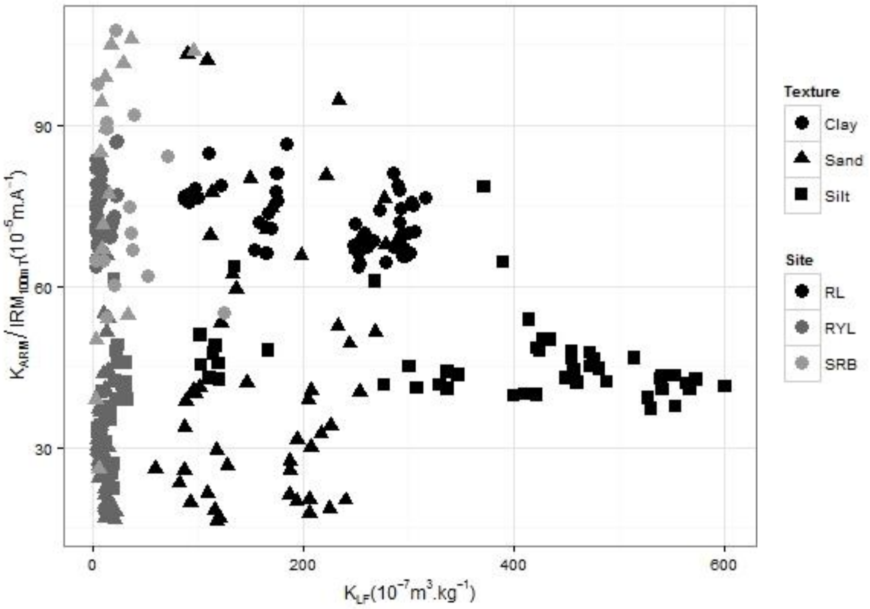

Fig. 2. χ_{LF} (in 10^{-7} m^3 kg^{-1}) versus χ_{ARM} (normalised with respect to the IRM_{100mT}) (in 10^{-5} m A^{-1}) bi-plot of two soils/sediment source (dystrophic Red-Yellow Latosol (RYL) and dystroferric Red Latosol (RL)) and of sediments of Reservoir A (SRA) for three different particle sizes (sand, silt and clay).

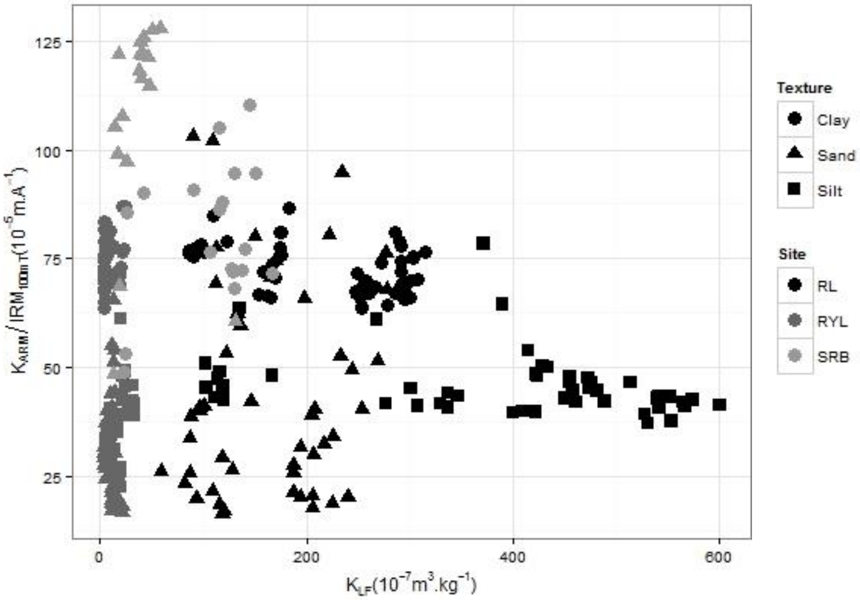

Fig. 3. χ_{LF} (in 10^{-7} m^3 kg^{-1}) versus χ_{ARM} (normalised with respect to the IRM_{100mT}) (in 10^{-5} m A^{-1}) bi-plot of two soils/sediment source (dystrophic Red-Yellow Latosol and dystroferric Red Latosol) and of sediments of Reservoir B for three different particle sizes (sand, silt and clay).

The χ_{ARM} (anhysteretic (hysteresis-free) remanent magnetization) used in figures 4.2 and 4.3, is a key magnetic property, in which magnetization cycles around progressively smaller hysteresis loops, gradually reducing the amplitude of an alternating magnetic field, while superimposing a small steady field (Maher, 2007). The χ_{ARM} / IRM_{100mT} ratio is often used in comparison to χ_{ARM} / SIRM, in which soft minerals (e.g. coarse MD magnetite) will acquire magnetisation easily at low fields (20/100mT), once hard minerals (e.g. haematite) will magnetize only at high fields (300/1000 mT) (Walden et al., 1999).

Both, the Red-Yellow Latosol (RYL) and Red Latosol (RL) soil samples, display narrow ranges of low χ_{ARM} / IRM_{100mT} values (figures 4.2 and

4.3). High χ_{ARM} values are often related to single domain ferrimagnets, such as magnetotactic bacteria (Fassbinder et al., 1990; Maher, 1998), while moderate χ_{ARM}, are common to fine, but non-concatenated grains, present in magnetically enhanced soils (Maher, 1988; Maher et al., 2003), and low χ_{ARM} values, as values presented here, are related to larger, multidomain magnetic grains (Maher et al., 2003). The difference stated here in χ_{ARM} values between the reservoirs sediments and the soil samples most likely reflects the presence in soils of haematite that carries very low χ_{ARM} values (Maher, 2007). Reduced oxygen conditions, such as at the bottom of the reservoirs favours iron oxides reduction, like haematite (Schwertmann, 1991).

Therefore, such difference is mainly stated at χ_{LF} values (in 10^{-7} m^3 kg^{-1}). Values range from 2.43 to 31.91 x 10^{-7} m^3 kg^{-1} were measured at Red-Yellow Latosol samples, as from 58.99 to 601 x 10^{-7} m^3 kg^{-1} were stated at the Red Latosol samples. Red Latosol samples are characterized as presenting high magnetic values due to parent material (gabbro intrusion). Elevated weathering of iron from its parent material and high drainage conditions directly resulted in high Fe oxides presence (like clay-sized maghemite). Soils developed from basalt rocks, like Red Latosol, are often characterized by higher χ_{LF} values, such as stated by several authors (Costa et al., 1999; Lu et al., 2008; Silva et al., 2010). In the other hand, Red-Yellow Latosol originated from a leucocratic granite gneiss mineral, predominating with quartz, feldspars and muscovite minerals. Those minerals are characterized as having none or very low magnetic susceptibility (Walden et al., 1999).

Figures 4.2 and 4.3 also illustrates the strong particle size dependence of the soils/sediments. Soils coarser samples present lower χ_{ARM} / IRM_{100mT} values, most possibly due to its associations with haematite mineral (Kämpf and Curi, 2003; Maher, 2007). These data variation emphasize the need for magnetic characterization of sediments and possible sources on a particle size basis (Hatfield and Maher, 2008).

In figures 4.4 and 4.5, results of the fuzzy clustering analysis showing differentiation between sources are presented (dystrophic Red-Yellow Latosol and dystroferric Red Latosol) and the dominant cluster affiliation of both reservoirs sediments identified.

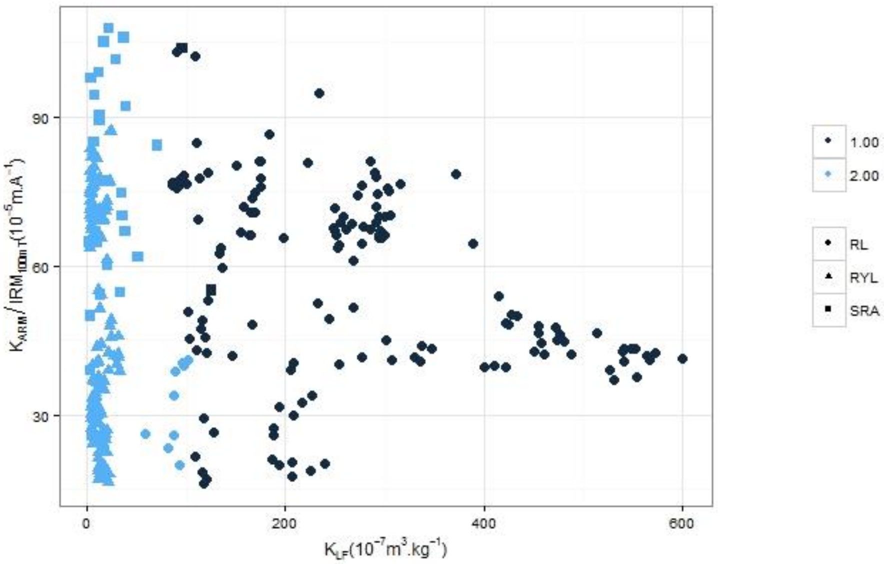

Fig. 4. Results of the fuzzy clustering analysis showing differentiation between sources (dystrophic Red-Yellow Latosol (RYL) and dystroferric Red Latosol (RL)), and the dominant cluster affiliation of the Reservoir A sediments (SRA).

Cluster fuzzy analysis indicates a dominant dystrophic Red-Yellow Latosol sediment source at reservoir A. Approximately 93.34% of the sediments sampled at reservoir A presented higher cluster affiliation to Red-Yellow Latosol samples, once reservoir A sediments are also characterized by low χ_{LF}.

Clustering results corroborates with drainage area indicated at figure 4.1, which was delimitated near the Red-Yellow Latosol transect sampled.

The proportion that each source contributes to the mixture varies in time and space, a result of erosion processes that are currently taking place in the watershed. Interaction between climate, natural relief and soil type, intensified by constant agricultural activities at the site, promotes elevated erosion rates for Red-Yellow Latosol (article 1), and consequent high sediment production.

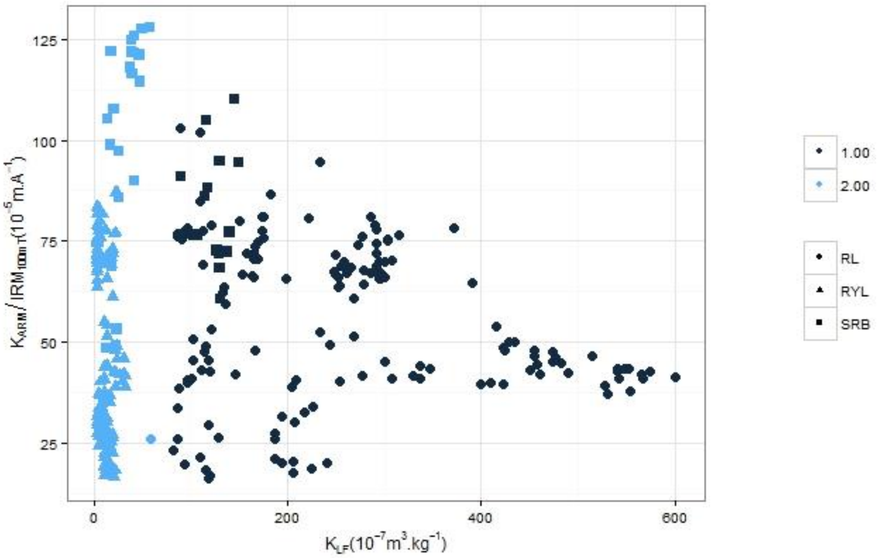

Fig. 5. Results of the fuzzy clustering analysis showing differentiation between sources (dystrophic Red-Yellow Latosol (RYL) and dystroferric Red Latosol (RL)), and the dominant cluster affiliation of the Reservoir B sediments (SRB).

In figure 4.5, the clustering analysis shows that sediments from both soils, dystrophic Red-Yellow Latosol and dystroferric Red Latosol, show affinity to the reservoir B sediments, indicating that they both do contribute significantly to sediment load. About 41.67% of reservoir sediments presented a higher cluster affiliation to Red Latosol samples, as 58.33% present a similar behaviour to Red-Yellow Latosol samples, demonstrating a higher cluster affiliation to this soil.

Soils with higher clay content, as Red-Latosol, produce higher sediment yield (Vahabi; Nikkami, 2008). Therefore, despite steeper relief and higher soil erodibility at Red-Yellow Latosol, both soils contribute with sediments to reservoir B. As in drainage area of reservoir A, constant agricultural activities at the site promotes elevated erosion rates, highlighting the importance of training programs and conservation management practices implementation in crop areas.

4. Conclusions

Research processes to identify possible route of sediments in watersheds involving magnetic properties have been widely carried out in temperate environments, at Northern latitudes, but there have been very few studies in tropical regions. This research provides one of the first demonstrations of the use of sediment fingerprinting using magnetic parameters to identify possible sediment sources in a tropical environmental, especially in the Brazilian setting.

Hence, tropical weathering conditions lead to different Fe oxide minerals with high soil Fe oxide concentrations, favouring magnetic variability, allowing precise comparisons and identification of possible source of deposit sediments at reservoirs by magnetic fingerprinting. Specifically, although both soils are classified as Oxisol, two soil classes (dystrophic Red-Yellow Latosol and dystroferric Red Latosol) could be clearly distinguished by magnetic properties evaluation and the origin of sediments of downstream reservoirs precisely allocated to their source.

5. Acknowledgements

Authors recognize their gratitude to CAPES (Coordination of Improvement of Higher Education Personnel – Process number 12082/13-9), FAPEMIG (Research Foundation of Minas Gerais State) and CNPq (National Research and Development Council – Processes number 143437/2011-9 and 167089/2014-5) for their financial support and scholarships. The authors are also thankful to the support given by Lancaster University's Vassil Karloukovski.

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