Spatialization of soil quality index in the Sub-Basin of Posses, Extrema, Minas Gerais

Gabriela C. Lima[1], Marx L. N. Silva[1], Diego A. F. de Freitas[2],
Bernardo M. Cândido[3, 4], Nilton Curi[1] & Marcelo S. de Oliveira[5]

[1] Universidade Federal de Lavras/Departamento de Ciência do Solo. Lavras, MG. E-mail: gabslima@yahoo.com.br; marx@dcs.ufla.br; niltcuri@dcs.ufla.br
[2] Universidade Federal de Viçosa. Florestal, MG. E-mail: diego_ufla@yahoo.com.br
[3] Universidade Federal de Lavras. Lavras, MG. E-mail: bernardocandido@gmail.com (Corresponding author)
[4] Lancaster University. Lancaster, UK
[5] Universidade Federal de Lavras/Departamento de Ciências Exatas. Lavras, MG. E-mail: marcelo.oliveira@dex.ufla.br

Key words:
Kriging
SQI
Atlantic Forest

A B S T R A C T

This study aimed to determine and spatialize the soil quality index (SQI), in relation to chemical and physical attributes, and evaluate its use in the payment for environmental services in the Sub-Basin of Posses, Extrema-MG, Brazil, which represents the Atlantic Forest Biome. SQI values were influenced by both the replacement of native forests by stands of eucalyptus and by pastures and annual crops, reflecting in the reduction of soil quality in the sampled layer in the evaluated systems. The spatialization of SQI showed values ranging from 0.40 to 0.80, with some specific areas with high values and others with values above 1.00 (native forest). The reforestation with eucalyptus conditioned most of the soils with low chemical and physical deterioration, due to accumulation of litter. The lowest SQI values are associated with pastures. SQI adjusted to the exponential model, which allowed the use of ordinary Kriging. The SQI has a great potential of use in the payment to farmers who provide services of soil and water conservation.

Palavras-chave:
Krigagem
IQS
Mata Atlântica

Espacialização do índice de qualidade do solo na Sub-Bacia das Posses, Extrema, Minas Gerais

R E S U M O

Objetivou-se, com este estudo, determinar o índice de qualidade do solo (IQS), em relação a atributos químicos e físicos, e espacializá-lo, além de avaliar a utilização deste índice no pagamento por serviços ambientais na Sub-Bacia Hidrográfica das Posses, Extrema, Minas Gerais, representativa do Bioma Mata Atlântica. Os valores do IQS foram influenciados tanto pela substituição da mata nativa por povoamento de eucalipto, quanto por pastagens e culturas anuais, refletindo na redução da qualidade do solo na profundidade amostrada nos sistemas avaliados. A espacialização do IQS apresentou valores variando de 0,40 a 0,80, ocorrendo algumas áreas pontuais com elevados índices e algumas com índices superiores a 1,00 (mata nativa). O reflorestamento com eucalipto condicionou solos, em sua maioria, com baixas deteriorações físicas e químicas devido ao acúmulo de serrapilheira. Já os menores valores do IQS estão associados às pastagens. O modelo pelo qual o IQS se ajustou foi o exponencial, possibilitando a krigagem ordinária. O IQS apresenta grande potencial para uso no pagamento de agricultores que prestam serviços de conservação do solo e água.

INTRODUCTION

According to Doran & Parkin (1994), soil quality is defined as the capacity of the soil to function within the limits of the ecosystem, managed or natural, in order to sustain biological production and maintain environmental quality and the health of plants and animals. Therefore, it is the capacity of the soil to perform its functions in nature, acting as a medium for plant development; regulation and compartmentalization of water flow in the environment; stock and promotion of cycling of elements in the biosphere and as an environmental buffer in the formation, attenuation and degradation of compounds that are harmful to the environment (Vezzani & Mielniczuk, 2009).

However, soil quality cannot be directly evaluated; it must be inferred from soil quality indicators that are used by farmers and scientists (Mairura et al., 2007). Thus, soil physical, chemical and biological attributes can be used as quality indicators, allowing the measurement of the capacity of the soil to perform its essential functions in favor of a sustainable management.

In this perspective, it is essential to select a minimum set of indicators that have characteristics such as easy evaluation, applicability on different scales, capacity of integration, adequacy to the research analysis level, utilization in the highest possible number of situations, sensitivity to variations in management and climate, and possibility of measurements through quantitative and/or qualitative methods.

Studies developed by Swanepoel et al. (2014) verified the importance of the evaluation of the soil quality index (SQI), in relation to the sustainability of agricultural systems, and confirmed low SQI values inadequately managed soils.

In the evaluation of different systems of planted forest and native cerrado, in different regions of the state of Minas Gerais, Freitas et al. (2012) obtained SQI values that prove that these forest management areas suffer a reduction in the indices compared with the evaluated native systems.

Some research lines have proposed, as soil quality indicators, the evaluation of soil physical, chemical and biological attributes (Lima, 2013; Nesbitt & Adl, 2014). Organic matter has also been included, for its importance in nutrient availability, soil structure and erosion control, water retention and the transport and immobilization of pollutants (Barrios et al., 2006; Fließbach et al., 2007).

According to Hazarika et al. (2014), soil quality can also be evaluated through the soil deterioration index, for which the deviations of soil chemical and physical properties of an area under anthropic action are compared with the baseline of an adjacent natural area or an area with similar conditions of soil and climate.

By establishing the indices in georeferenced points, it is possible to spatialize them using geostatistical tools, which provide better understanding on their variation and behavior in the environment. Studies on spatial variability of soil attributes are important not only in samplings or data interpretation, but also in soil survey and classification (Lima et al., 2010; Grego et al., 2011).

Therefore, the evaluation of soil quality in fragile biomes, such as the Atlantic Forest, is of great importance, because it concentrates a large portion of the Brazilian population

(70%) and with percentage of conserved forest remnants of only 7.26% (Brasil, 2007). Thus, SQI determination in areas with forest remnants, especially in the areas of water recharge of the Cantareira System, which supplies the state of São Paulo, constitutes a relevant tool in the implementation of adequate management practices that promote environmental sustainability.

In this context, this study aimed to determine and spatialize SQI and evaluate its use in the payment for environmental services in areas under agricultural use, forests, pastures and remnants of the Atlantic Forest in the Sub-Basin of Posses, Extrema-MG, Brazil.

MATERIAL AND METHODS

The studied area is located in the municipality of Extrema-MG, Brazil, in the Sub-Basin of Posses, at the UTM coordinates 374500 and 371500 E and 7468200 and 7474800 S (Datum SAD 69, Zona 23S) (Figure 1). The climate in the region is mesothermal, with mild summers and dry winters, Cwb, according to Köppen's climate classification.

The predominant vegetation is in the biome of the Atlantic Forest (ANA, 2008). The sub-basin is located in the Jaguari River Basin, one of the rivers that supply the reservoir of the Cantareira System in the state of São Paulo.

According to the classification of EMBRAPA (2013), the soil classes in the sub-basin are: Litholic Neosol (RL), Fluvic Neosol (RY), Red Yellow Argisol (PVA), Haplic Cambisol (CX) and Humic Cambisol (CH) (Figure 2A). Undulating and strongly undulating relief phases prevail in the studied area (Figure 2B).

Currently, the main soil use is pasture and most areas have been poorly managed; in addition, there are stands of eucalyptus, annual crops and native forest (Silva et al., 2013) (Figure 3 and Table 1).

Prior to sample collection, a stratified soil sampling grid was generated, with 150 points, spaced by 350 m and distributed in an area of approximately 1,200 ha (Figure 4), using the program ArcGIS 9.3. In areas with higher variability on the landscape, a larger number of sampling points was used, in order to increase their representativeness.

The samples were collected in order to represent the five soil classes prevailing in the sub-basin and the main
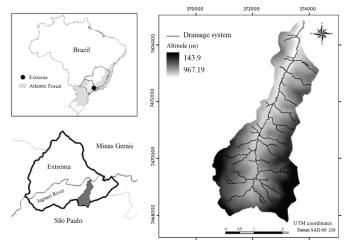

Figure 1. Sub-Basin of Posses in the municipality of Extrema-MG, Brazil. Adapted from Silva (2013)
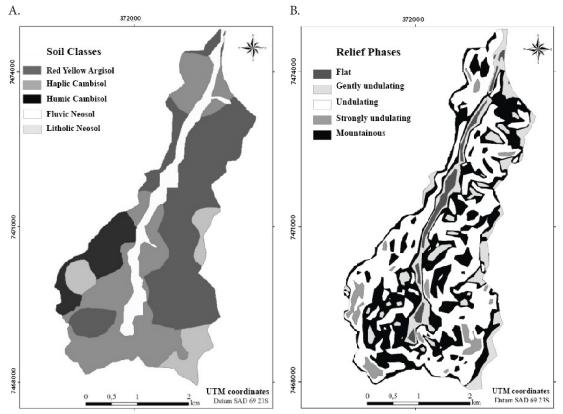
A.

B.

Figure 2. Map of soil classes (A) and relief phases (B) of the Sub-Basin of Posses, in municipality of Extrema-MG, Brazil. Adapted from Silva (2013)
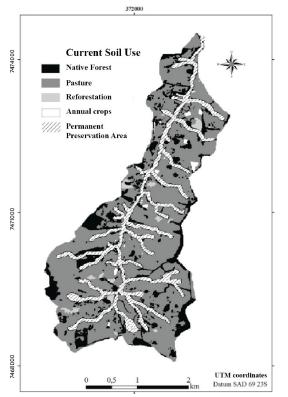

Figure 3. Current soil uses in the Sub-Basin of Posses, Extrema-MG, Brazil. Adapted from Silva (2013)

soil uses. The GARMIN eTrex Vista global positioning system (GPS) was used to mark the points at the field. Soil samples were collected in each point, in the layer of 0-0.20 m, according to Lemos & Santos et al. (2005), and the soils were classified according to EMBRAPA (2013).

Table 1. Characterization of the native reference systems and other evaluated systems in the Sub-Basin of Posses, Extrema-MG, Brazil. Adapted from Silva (2013)

Soil	Use	Description
PVA	NF	Original condition, reference of a system in equilibrium
	EUC	Eucalyptus with litter - 2 years under sampling
	P	Degraded pasture, with erosion
	SCS	Post-harvest corn - corn straw
CH	NF	Original condition, reference of a system in equilibrium
	EUC	Eucalyptus with litter - 2 years under sampling
	P	Degraded pasture
CX	NF	Original condition, reference of a system in equilibrium
	EUC	Eucalyptus with litter (regeneration)
	P	Degraded pasture
	SPP	Potato - soil tillage
RL	NF	Original condition, reference of a system in equilibrium
	P	Pasture in permanent preservation area
RY	NF	Original condition, reference of a system in equilibrium
	EUC	Eucalyptus with litter
	P	Pasture in permanent preservation area

NF - native forest; EUC - stand of eucalyptus; P - planted pasture; SCS - soil covered with corn straw; SPP - soil prepared for potato planting; PVA - Red Yellow Argisol; CH – Humic Cambisol; CX - Haplic Cambisol; RL - Litholic Neosol; RY - Fluvic Neosol

Representative soil profiles were dug, considering the class and current use of the soil for the collection of disturbed and undisturbed samples.

The evaluation of soil quality was performed through the SQI, using the model suggested by Islam & Weil (2000). According to Araújo et al. (2007), for the application of the model, a few basic assumptions must be made: the natural ecosystems, characterized by minimum anthropic intervention and expected equilibrium, are considered as a reference; two categories of soil quality attributes (chemical and physical) contribute equitably to soil quality and the same weighted value
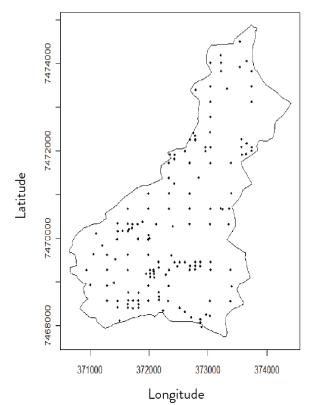
Figure 4. Sampling points in the Sub-Basin of Posses, Extrema-MG, Brazil

is attributed to each category; their respective indicators have the same relative importance.

For SQI determination, the attributes involved in the main functions performed by the soil (Table 2) were considered. The analysis of soil chemical and physical attributes were performed by Lima et al. (2014).

Table 2. Soil functions and quality indicator attributes

Soil functions	Attributes
Receive, store and supply water	Soil water permeability
	Microporosity
	Soil organic matter
	Soil density
Promote root growth	Soil organic matter
	Soil density
	Sum of bases
	Effective CEC
	Aluminum saturation
Store, supply and cycle nutrients	Soil organic matter
	Sum of bases
	Aluminum saturation
	pH
Promote soil conservation	Geometric mean diameter
	Soil water permeability
	Macroporosity
	Total volume of pores
	Soil organic matter
	Soil density

SQI was calculated in two steps:

$$Q_a = \left[\frac{\left(\dfrac{w1-k1}{k1}\right) + \left(\dfrac{w2-k2}{k2}\right) + \left(\dfrac{w3-k3}{k3}\right) + \left(\dfrac{wn-kn}{kn}\right)}{n} \right] \quad (1)$$

$$SQI = 1 - \left(\frac{Qca + Qpa}{2} \right) \quad (2)$$

where:

Q_a - mean of the deviations of the indicators of each attribute in relation to the reference;

w - value of the indicator measured in the studied systems;

k - value of the indicator measured in the reference system;

n - number of indicators constituting each set of attributes;

Qca - mean of the deviations of soil chemical attributes; and

Qpa - mean of the deviations of soil physical attributes.

After one SQI was generated for each sampled point, the deterioration indices of soil chemical and physical attributes and the SQI corresponding to each soil class and main uses were determined. The deterioration is considered as the chemical and physical variations of the managed areas in comparison to the native ones. The R program (R Core Team, 2014) was used for the descriptive analysis for each soil class, which provided: mean, standard deviation, coefficient of variation and asymmetry.

The adjustment parameters of the experimental semivariogram for SQI, as well as the geostatistical analysis, were obtained using the R program (R Core Team, 2014), in the GeoR package (Ribeiro Júnior & Diggle, 2001), performed through the analysis of semivariograms based on the assumptions of intrinsic hypothesis, in which the spatial dependence ratio is the same at any "h" position inside a certain range of the spatial continuity.

For each soil attribute, the semivariances γ(h) were calculated in all directions, meeting the hypothesis of isotropy. After adjusting the mathematical model, the following parameters were defined: nugget effect (C0), γ value when h is zero; range (a), value of h when γ stabilizes close to a constant value; (C1), structural variance and sill (C1 + C0), value of γ when a constant value is obtained close to the variance of the data. The spatial dependence ratio (SDR) between samples was determined according to Cambardella et al. (1994).

After obtaining the data necessary for Kriging, the maps were constructed using the R program (R Core Team, 2014).

Results and Discussion

The deterioration suffered by soil chemical and physical attributes for each soil use and each soil class, and the respective soil quality indices, are shown in Table 3.

The SQI values calculated from the deviations of soil properties in the systems of reforestation, annual crops and pastures, compared with the reference natural system (native forest), were influenced by both the replacement of native forest by the stand of eucalyptus and pasture and annual crops, reflecting in the reduction of soil quality in the sampled layer in the evaluated systems.

Cardoso et al. (2011) observed, in the superficial soil layer, the highest contents of organic matter, which mainly came from the deposition of organic substrate in the litter, where the effect of animal trampling was more pronounced and the activity of soil microbiota on the decomposition and mineralization of

Table 3. Deterioration of soil chemical and physical attributes in relation to the reference native systems and soil quality indices for different systems of soil use and management in the Sub-Basin of Posses, Extrema-MG, Brazil

Soil	Use	Deterioration		SQI
		Physical	Chemical	
PVA	NF	-	-	1
	EUC	-0.759	-0.387	0.697
	P	-0.88	-0.568	0.276
	SCS	0.248	-0.406	0.821
CH	NF	-	-	1
	EUC	-0.065	-0.519	0.708
	P	-0.201	-0.424	0.688
CX	NF	-	-	1
	EUC	0.15	-0.012	1.069
	P	-0.109	-0.543	0.674
	SPP	-0.017	0.001	0.992
RL	NF	-	-	1
	P	-0.298	-0.125	0.888
RY	NF	-	-	1
	EUC	-0.151	0.339	1.094
	P	-0.309	-0.123	0.784

SQI - Soil quality index; NF - Native forest; EUC - Stand of eucalyptus; P - Planted pasture; SCS - Soil covered with corn straw; SPP - Soil prepared for potato planting; PVA - Red Yellow Argisol; CH - Humic Cambisol; CX - Haplic Cambisol; RL - Litholic Neosol; RY - Fluvic Neosol

the organic matter was more intense. Therefore, in this layer, soil chemical and physical attributes were more sensitive to the alterations imposed by anthropic action.

The alterations in the chemical attributes consisted of deteriorations in relation to the reference (NF) for all soil classes and uses, except for the chemical attributes in the uses of annual crops in area of CX and reforestation in area of RY.

The preparation of the soil for potato cultivation involves fertilization with nutrients that promote better soil fertility; in this case, soil quality improved 0.1% in relation to NF. However, for soil physical attributes, potato cultivation in the CX promoted a deterioration of 1.7% in relation to NF, certainly due to the management during harvest, which may have affected soil structure.

Potato cultivation is frequently performed in soils with moderate to high declivity, as the situation in the Sub-Basin of Posses, and the soil is intensively prepared and susceptible to losses by water erosion, compaction, reduction in water infiltration rates and a consequent decrease in water table recharge, which damage the environment and even make it difficult to obtain high yields.

The area with eucalyptus reforestation in RY showed improvement of 3.39% in soil chemical attributes, in relation to NF; this is due to the soil correction performed before eucalyptus was planted and the significant CEC variations in soils under eucalyptus cultivation (Effgen et al., 2012). Studies have shown the accumulation of N, P, K, Ca and Mg in leaves, branches and barks, contributing to the increase of litter, nutrient cycling and organic residues (Stape et al., 2010).

As to the physical attributes, a deterioration of approximately 15% occurred for the eucalyptus reforestation in RY. The eucalyptus plantations in the Sub-Basin of Posses generally occur in areas of degraded pastures and this previous soil use can influence the deterioration of soil physical attributes, especially in RY areas.

The soil use with pasture, which represents more than 70% of the Sub-Basin of Posses, showed the lowest SQI compared with NF and the other uses, in all the evaluated soil classes, showing the highest deteriorations in both chemical and physical attributes. The lowest SQI value (0.276) corresponds to the use under pasture in PVA. In this situation, areas with degraded pasture were found, i.e., areas with occurrence of laminar erosion, usually in areas with undulating to strongly undulating landscape.

One of the main causes of pasture degradation is the reduction of soil fertility due to the loss of nutrients through the production process (animal feeding), erosion, leaching and volatilization (Fonte et al., 2014). In addition, one of the main effects caused by the animals on pastures is compaction, which increases soil density and decreases macroporosity, hampering soil water movement and root growth (Swanepoel et al., 2014).

Therefore, SQI can become an instrument to be used by the authorities in the payment for environmental services. Areas that maintain better SQI have lower degradation degree of soil chemical and physical attributes, and farmers must be valued. Thus, the index has the potential to reflect the state of conservation or deterioration of a small farm, allowing the use of rewards or penalties according to its value.

Based on the adjustment parameters of the semivariogram (Table 4), the obtained value of SDR indicates a moderate spatial dependence of SQI, according to Cambardella et al. (1994). Thus, it was possible to interpolate values in any position of the studied area, constructing maps through ordinary Kriging and using structural properties of the semivariogram of the sampled sites (Figure 5).

Table 4. Adjustment parameters of the semivariogram for the soil quality index (SQI) of the Sub-Basin of Posses, Extrema-MG, Brazil

Variable	Model	C_0	C_1	$C_0 + C_1$	a	SDR
SQI	Exponential	0.02	0.03	0.05	870.84	40.00

SQI - Soil quality index; C_0 - Nugget effect; C_1 - Structural variance; $(C_0 + C_1)$ - Sill; a - Range; SDR - Spatial dependence ratio
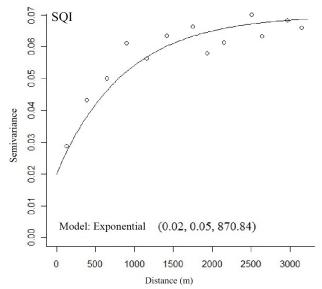

Figure 5. Semivariogram of the soil quality index (SQI) in the Sub-Basin of Posses, Extrema-MG, Brazil

The spatial distribution of the indices in the sampled area can be observed in the map of distribution obtained through data interpolation by the Kriging method (Figure 6).

Values from 0.40 to 0.80 prevailed in the distribution of SQI in the Sub-Basin of Posses. Some areas showed high indices, even higher than 1.00, as in native forest areas, while the lowest SQI values refer to the soil use with pasture.

The map indicated areas with low SQI in the Sub-Basin compared with NF, mainly due to the management. Because the region has more than 70% of the area occupied by pasture, intermediate soil quality indices prevailed.

Therefore, since the Sub-Basin of Posses is located in area with remnants of the Atlantic Forest and is part of the Cantareira System, the improvement of its soil quality is of great importance to protect ecosystems and recover degraded areas, contributing to the sustainability of the local activities in favor of soil and water conservation.
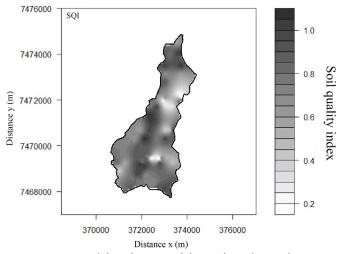

Figure 6. Map of distribution of the soil quality index (SQI) in the Sub-Basin of Posses, Extrema-MG, Brazil

Conclusions

1. The spatialization of soil physical and chemical attributes in the Sub-Basin of Posses showed that the lowest soil quality indices are related to pasture areas.

2; The reforestation with eucalyptus conditioned most of the soils with low physical and chemical deterioration, probably due to the accumulation of litter.

3. The soil quality index adjusted to the exponential model, allowing the use of ordinary Kriging.

Acknowledgments

Literature Cited

ANA - Agência Nacional das Águas. Programa produtor de água superintendência de usos múltiplos. Brasília: Ministério do Meio Ambiente, 2008. 60p.

Araújo, R.; Goedert, W. J.; Lacerda, M. P. C. Qualidade de um solo sob diferentes usos e sob cerrado nativo. Revista Brasileira de Ciência do Solo, v.31, p.1099-1108, 2007. http://dx.doi.org/10.1590/S0100-06832007000500025

Barrios, E.; Delve, R. J.; Bekunda, M.; Mowo, J.; Agunda, J.; Ramisch, J.; Trejo, M. T.; Thomas, R. J. Indicators of soil quality: A South-South development of a methodological guide for linking local and technical knowledge. Geoderma, v.135, p.248-259, 2006. http://dx.doi.org/10.1016/j.geoderma.2005.12.007

Brasil. Levantamento da cobertura vegetal nativa do bioma Mata Atlântica. Rio de Janeiro: Ministério do Meio Ambiente, 2007. 84p.

Cambardella, C. A.; Moorman, T. B.; Novak, J. M.; Parkin, T. B.; Karlen, D. L.; Turco, R. F.; Konopka, A. E. Field-scale variability of soil properties in Central Iowa Soils. Soil Science Society of America Journal, v.58, p.1501-1511, 1994. http://dx.doi.org/10.2136/sssaj1994.03615995005800050033x

Cardoso, E. L.; Silva, M. L. N.; Curi, N.; Ferreira, M. M.; Freitas, D. A. F. de. Qualidade química e física do solo sob vegetação arbórea nativa e pastagens do Pantanal sul-matogrossense. Revista Brasileira de Ciência do Solo, v.35, p.612-622, 2011. http://dx.doi.org/10.1590/S0100-06832011000200030

Doran, J. W.; Parkin, T. B. Defining and assessing soil quality. In: Doran, J. W.; Coleman, D. C.; Bezdicek, D. F.; Stewart, B. A. Defining soil quality for a sustainable environment. Madison: Soil Science Society of America, 1994. cap.1, p.3-21. http://dx.doi.org/10.2136/sssaspecpub35.c1

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. Sistema brasileiro de classificação de solos. 3.ed. Brasília, DF: EMBRAPA, 2013. 353p.

Effgen, E. M.; Nappo, M. E.; Cecílio, R. A.; Mendonça, A. R. de; Manzole, R.; Bocarte, M. Atributos químicos de um Latossolo Vermelho-Amarelo distrófico sob cultivo de eucalipto e pastagem no sul do Espírito Santo. Scientia Forestalis, v.40, p.375-381, 2012.

Fließbach, A.; Oberholzer, H.; Gunst, L.; Mader, P. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agriculture, Ecosystems and Environment, v.118, p.273-284, 2007. http://dx.doi.org/10.1016/j.agee.2006.05.022

Fonte, S. J.; Nesper, M.; Hegglin, D.; Velásquez, J. E.; Ramirez, B.; Rao, I. M.; Bernasconi, S. M.; Bünemann, E. K.; Frossard, E.; Oberson, A. Pasture degradation impacts soil phosphorus storage via changes to aggregate-associated soil organic matter in highly weathered tropical soils. Soil Biology & Biochemistry, v.68, p.150-157, 2014. http://dx.doi.org/10.1016/j.soilbio.2013.09.025

Freitas, D. A. F. de; Silva, M. L. N.; Cardoso, E. L.; Curi, N. Índice de qualidade do solo sob diferentes sistemas de uso e manejo florestal e cerrado nativo adjacente. Revista Ciência Agronômica, v.43, p.417-428, 2012. http://dx.doi.org/10.1590/S1806-66902012000300002

Grego, C. R.; Coelho, R. M.; Vieira, S. R. Critérios morfológicos e taxonômicos de Latossolo e Nitossolo validados por propriedades físicas mensuráveis analisadas em parte pela geoestatística. Revista Brasileira de Ciência do Solo, v.35, p.337-350, 2011. http://dx.doi.org/10.1590/S0100-06832011000200005

Hazarika, S.; Thakuria, D.; Ganeshamurthy, A. N.; Sakthivel, T. Soil quality as influenced by land use history of orchards in humid subtropics. Catena, v.123, p.37-44, 2014. http://dx.doi.org/10.1016/j.catena.2014.07.006

Islam, K. R.; Weil, R. R. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. Journal of Soil and Water Conservation, v.55, p.69-79, 2000.

Lemos, R. C.; Santos, R. D.; Santos, H. G.; Ker, J. C.; Anjos, L. H. C. Manual de descrição e coleta de solos no campo . 5. ed. Viçosa, MG: SBCS, 2005. 92p.

Lima, A. C. R.; Brussaard, L.; Totola, M. R.; Hoogmoed, W. B.; Goede, R. G. M. de. A functional evaluation of three indicator sets for assessing soil quality. Applied Soil Ecology, v.64, p.194-200, 2013.

Lima, G. C.; Silva, M. L. N.; Oliveira, M. S. de; Curi, N.; Silva, M. A. da; Oliveira, A. H. Variabilidade de atributos do solo sob pastagens e mata atlântica na escala de microbacia hidrográfica. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, p.517-526, 2014. http://dx.doi.org/10.1590/S1415-43662014000500008

Lima, J. S. de S.; Souza, G. S. de; Silva, S. A. Amostragem e variabilidade espacial de atributos químicos do solo, em área de vegetação natural em regeneração. Revista Árvore, v.34, p.127-136, 2010. http://dx.doi.org/10.1590/S0100-67622010000100014

Mairura, F. S.; Mugendi, D. N.; Mwanje, J. I.; Ramisch, J. J.; Mbugua, P. K.; Chianu, J. N. Integrating scientific and farmers' evaluation of soil quality indicators in Central Kenya. Geoderma, v.139, p.134-143, 2007. http://dx.doi.org/10.1016/j.geoderma.2007.01.019

Nesbitt, J. E.; Adl, S. M. Differences in soil quality indicators between organic and sustainably managed potato fields in Eastern Canada. Ecological Indicators, v.37, p.119-130, 2014. http://dx.doi.org/10.1016/j.ecolind.2013.10.002

R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, 2014. http://www.R-project.org.15 Nov 2013

Ribeiro Júnior, P. J.; Diggle, P. P. GeoR: A package for geostatistical analysis. R. News, v.1, p.15-18, 2001.

Silva, M. A.; Freitas, D. A. F. de; Silva, M. L. N.; Oliveira, A. H.; Lima, G. C.; Curi, N. Sistema de informações geográficas no planejamento de uso do solo. Revista Brasileira de Ciências Agrárias, v.8, p.316-323, 2013. http://dx.doi.org/10.5039/agraria.v8i2a2289

Stape, J. L.; Binkley, D.; Ryan, M. G.; Fonseca, S.; Loos, R. A.; Takahashi, E. N.; Silva, C. R.; Silva, S. R.; Hakamada, R. E.; Ferreira, J. M. de A.; Lima, A. M. N.; Gava, J. L.; Leite, F. P.; Andrade, H. B.; Alves, J. M.; Silva, G. G. C.; Azevedo, M. R. The Brazil eucalyptus potential productivity project: Influence of water, nutrients and stand uniformity on wood production. Forest Ecology and Management, v.259, p.1684-1694, 2010. http://dx.doi.org/10.1016/j.foreco.2010.01.012

Swanepoel, P. A.; Preez, C. C. du; Botha, P. R.; Snyman, H. A.; Habig, J. Soil quality characteristics of kikuyu-ryegrass pastures in South Africa. Geoderma, v.232-234, p.589-599, 2014. http://dx.doi.org/10.1016/j.geoderma.2014.06.018

Vezzani, F. M.; Mielniczuk, J. Uma visão sobre qualidade do solo. Revista Brasileira de Ciência do Solo, v.33, p.743-755, 2009. http://dx.doi.org/10.1590/S0100-06832009000400001