SOIL PROPERTIES, CONDITION AND SOIL LOSSES FOR SOUTH AND EAST BRAZILIAN FOREST AREAS

JUNIOR CESAR AVANZI

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Dissertation presented to the Federal University of Lavras as part of the requirements of the Soil Science Graduate Program to obtain the degree of "Doctor".

Major Professor:

Prof. Dr. Marx Leandro Naves Silva

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APROVED on July 09, 2009

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LAVRAS
MINAS GERAIS – BRAZIL

To God,
for all the works
made in my life

I OFFER

"My steps have held to your paths;
my feet have not slipped" **Psalm 17:5**

I DEDICATE

To my parents, João Leonardo and Maria Imaculada, for their love and for being always encouraging me to follow my dreams. For my wife "G" for understanding this step of my life; giving up her career to be with me. I LOVE YOU ALL!!!

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GENERAL ABSTRACT

AVANZI, Junior Cesar. **Soil properties, condition and soil losses for south and east Brazilian forest areas**. 2009. 76 p. Dissertation (Doctorate in Soil Science) – Federal University of Lavras, Lavras.[1]

Eucalyptus cultivation has increased in all Brazilian regions. In order to recommend good management practices it is necessary to understand differences in soil properties where eucalyptus is planted. In addition, aggregate stability analyses have proved to be a useful tool to measure soil effects caused by changes in management practices. Besides, the evaluation of soil erosion is an important tool for planning of conservationist management actions allowing appropriate changes on land-use and implementation of sustainable management strategies in the long-term. Thus, the objectives of this study were: i) to determine the main soil properties for different soil classes, and assess the relationship between aggregate stability and changes in soils under eucalyptus plantation, and ii) to predict the potential annual soil loss using the Universal Soil Loss Equation (USLE) coupled in a Geographical Information System (GIS). We studied representative soils within three eucalyptus cultivated regions. In the Espírito Santo state the soils selected were classified as dystrocohesive Yellow Argisol – PA1 (Hapludult), moderately rocky Yellow Argisol – PA2 (Hapludult), and dystrophic Haplic Plinthosol – FX (Phinthaquox). In the Rio Doce Valley, center-east region of Minas Gerais state, the samples were collected in dystrophic Red-Yellow Latosol – LVA (Haplustox) and dystrophic Red Latosol – LV (Haplustox). In the south region of Brazil the area encompasses eutrophic Red Argisol – PVe (Rhodudalf), dystrophic Red-Yellow Argisol – PVA (Hapludult), and dystrophic Haplic Cambisol – CXbd (Dystrudept). Physical, chemical, and mineralogical analyses were performed for the A horizon to characterize the predominant soil profiles. Aggregate stability was measured using the high-energy moisture characteristic (HEMC) technique. Aggregate stability ratio was greater than 50% for all soils. This fact shows for highly weathered soils with large amount of 1:1 clay minerals, that the aggregate stability index was high. In the Espírito Santo we performed the USLE model in order to evaluate soil erosion. All the USLE factors were generated in a distributed approach using GIS framework. Results showed that the average soil loss was 6.2 t ha^{-1} yr^{-1}. Relative to soil loss tolerance, 86% of the area presented erosion rate smaller than the tolerable value.

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[1] Guidance Committee: Marx Leandro Naves Silva – UFLA (Major Professor); L. Darrell Norton – USDA-ARS-NSERL/Purdue University; Nilton Curi – UFLA.

RESUMO GERAL

AVANZI, Junior Cesar. **Atributos do solo, ambientes e perdas de solo para áreas florestadas no sul e leste do Brasil**. 2009. 76 p. Tese (Doutorado em Ciência do Solo). Universidade Federal de Lavras, Lavras.[2]

O cultivo de eucalipto tem aumentado em todas as regiões brasileiras. Para recomendar práticas de manejo adequadas é necessário o entendimento dos diferentes atributos do solo onde esta cultura está instalada. Além disso, a análise da estabilidade de agregados tem provado ser uma boa ferramenta para medir os efeitos causados no solo devido às mudanças nas práticas de manejo. Além disso, a avaliação do processo erosivo é um importante instrumento no planejamento do manejo conservacionista, permitindo realizar mudanças apropriadas no uso do solo e programar estratégias de manejo em longo prazo. Assim, os objetivos deste estudo foram: i) determinar os principais atributos do solo para as diferentes classes de solo e avaliar sua relação com a estabilidade de agregados em solos sob cultivo de eucalipto; e ii) estimar o potencial de perdas de solo anual através da Equação Universal de Perdas de Solo (EUPS) acoplada no Sistema de Informação Geográfica (SIG). Solos representativos de três regiões cultivadas com eucaliptos foram utilizados. No Espírito Santo os solos selecionados foram classificados como Argissolo Amarelo coesivo distrófico (PA1), Argissolo Amarelo moderadamente rochoso (PA2) e Plintossolo Háplico distrófico (FX). No Vale do Rio Doce, região centro-leste de Minas Gerais, as amostras foram coletadas em um Latossolo Vermelho Amarelo distrófico (LVA) e um Latossolo Vermelho distrófico (LV). Na região sul do Brasil a área abrange um Argissolo Vermelho eutrófico (PVe), um Argissolo Vermelho Amarelo distrófico (PVA) e um Cambissolo Háplico distrófico (CXbd). Análises físicas, químicas e mineralógicas foram realizadas nos horizontes A dos perfis de solo estudado. A estabilidade de agregados foi avaliada através da técnica *high-energy moisture characteristic* (HEMC). A estabilidade de agregados foi maior que 50% para todos os solos estudados. Este fato mostra que o índice de estabilidade de agregados foi elevado para solos altamente intemperizados com grandes quantidades de argilo-minerais 1:1. No Espírito Santo a avaliação do risco de erosão foi realizada por meio da EUPS. Os fatores da EUPS foram gerados de forma distribuídos utilizando a plataforma SIG. Os resultados mostraram uma perda de solo média de 6,2 t ha^{-1} ano^{-1}. Em relação à tolerância de perdas de solo, 86% da área apresentaram taxas de erosão abaixo dos valores de tolerância de perdas.

[2] Comitê Orientador: Marx Leandro Naves Silva – UFLA (Orientador); L. Darrell Norton – USDA-ARS-NSERL/Purdue University; Nilton Curi – UFLA.

CHAPTER 1

1 INTRODUCTION

Erosion and sedimentation are naturally occurring processes. However, human activities have accelerated these processes well beyond the rate allowed by nature. The erosion processes include three mechanisms: detachment, entrainment and transport of particles. For these processes be active the action of water and/or wind is required. When these active elements stop their action, the transported particles fall out on a surface. This process is called deposition. In Brazil the most important active element is the water. In this context, the water erosion can be considered one of the main problems linked to tropical soils management, constituting significant causes of environmental degradation. It may have an effect on both, the natural environment and the agricultural areas. Advanced erosion processes not only decrease land productivity but can also generate transport of nutrients, organic matter and agrochemical products that can contaminate and fill up water bodies.

The knowledge about soil erosion process as well as how fast soil is eroded is helpful in the planning of conservation management actions. Modeling can provide a quantitative and consistent approach to predict soil erosion and sediment delivery ratio under a wide range of conditions (Bhattarai & Dutta, 2007). In addition, it can be used to test hypotheses and to predict both the appropriate soil management and land use for each site (Beven, 1989; Grayson et al., 1992; Tucci, 1998).

The models can be defined as simplified approaches of the natural ecosystem (Batchelor, 1994) which try to better understand the essential aspect from a phenomenon. The models can be divided into empirical and physically-based models. Empirical model is a simple representation of a system or phenomenon that is based on measurements and/or observations. It usually establishes relationships between the variables. Examples of empirical-based models used for soil loss evaluation are the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978), the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). On the other hand, physical-based model uses physical variables that can describe a behavior with details of a physical phenomenon. Thus, it can be updated in real time, presenting a great improvement due to the fact that it can be extrapolated to other sites (Tucci, 1998). However, a big data-set should be constructed in order to calibrate the relatively large number of parameters. To do so, physically-based models have been used such as the Water Erosion Prediction Project (WEPP) (Flanagan & Nearing 1995), the Limburg Soil Erosion Model (LISEM) (De Roo et al., 1996), the European Soil Erosion Model (EUROSEM) (Morgan et al., 1998), the Geospatial interface for the Water Erosion Prediction Project (GeoWEPP) (Renschler, 2003), and the Soil and Water Assessment Tool (SWAT) (Gassman et al., 2007), among others.

2 LITERATURE REVIEW

2.1 The Universal Soil Loss Equation (USLE)

The most known, applied, and implemented approach for estimating long-term average annual soil loss is the Universal Soil Loss Equation (USLE) developed by Wischmeier & Smith (1978). It is a simple empirical equation based on factors representing the main processes causing soil erosion. It was developed as a conservation planning tool, and, in recent times it has become the

Soil Conservation Service's primary tool for enforcing conservation policy. For developing such model it were used data from 49 U.S. locations representing over 10,000 plots including measurements of runoff and soil erosion, which were compiled and studied at Purdue University (Wischmeier & Smith, 1978). Most of this data was collected between 1930 and 1950, and, the collection continued to grow into the late sixties. Using this information and the results from previous empirical studies of erosion, Wischmeier & Smith (1965) developed the following equation that estimates average annual soil loss using rainfall, soil, topographic, and management data:

$$A = R \times K \times L \times S \times C \times P \qquad \text{Eq. 1}$$

where A is the computed long-term average annual soil loss per unit area, R is the rainfall and runoff factor, K is the soil erodibility factor, LS is the topographic factor, C is the cover and management factor, and P is the support practice factor. Each of these factors is designed to account for critical processes that can affect the soil loss on a given slope.

The rainfall and runoff factor (R) is designed to quantify the raindrop direct impact effect and provide relative information on the amount and rate of runoff likely to be associated with the rain. It represents the potential erosivity presented in the rainfall and runoff at the particular location and is defined empirically as a function of the total storm energy and the maximum 30-minute intensity. The soil erodibility factor (K) is used to represent the differences in the natural susceptibilities of soils to erosion. The slope length (L) and slope steepness (S) factors represent the topography of the terrain. They are designed to account for topographic factors which can affect the rate of energy dissipation. The C factor is the ratio of soil loss from land cropped under specific conditions to the corresponding loss from tilled, continuous fallow conditions. The correspondence of periods of highly erosive rainfall with periods of poor or good plant cover differs appreciably between climatic areas;

therefore, the value of C for a particular cropping and management system will not be the same for all parts of the world. Locally, the C values are derived using specific rainstorm-timing probabilities and research data that reflect the erosion reducing effectiveness of crops and management during successive periods within a rotation cycle (Wischmeier, 1972). The support practice factor, P, is similar to C, except that it is intended to account for additional effects such as contour farming, terraces, and strip cropping. By definition, P is the ratio of soil loss with a specific support practice to the corresponding loss with conventional up-and-down slope tillage.

The approach for determining these factors is based on the concept of the unit plot. This is a slope 20.1 m long with 9% slope, left fallow with regular up and down tillage. Using this standard condition (where LS, C and P all equal to one) and calculated values of R, measurements of the soil loss can be used to determine the value of K. From this baseline, the other factors can be determined by measuring the soil loss on plots where one of the factors is changed and the corresponding change in soil loss is evaluated against that under the standard conditions. The drawback of this model is that it is not capable of simulating deposition, sediment yield, channel erosion, and gully erosion. In addition, such equation makes no differentiation between rill and interrill erosion, predicting their combined effects. Despite the aforementioned limiting aspects, the USLE has presented consistent results when coupled with Geographical Information System (GIS) for estimating the magnitude and spatial distribution of soil loss.

3 FINAL CONSIDERATIONS

Models are essential tools to assess the erosion process. They can be used to simplify reality or to analyze a system to be constructed (diverse scenarios). Modeling provides support in decision making and can give us more security to recommend a specific management practice, specially, when modeling in a distributed approach, which shows a global view about what is happening into the watershed. In erosion studies there are empirical and physical based models, both with advantages and disadvantages. However, these models do not compete with each other, but they can be treated as complementary models because they are applied in different situations. While empirical-based model is simple and needs few parameters, physical-based model is more complex and needs more parameters. Thus, the adoption of a particular model depends on the amount of available data for a give region.

4 SUGGESTIONS FOR FUTURE RESEARCH

4.1 The WEPP Model

The WEPP hillslope model is a physically-based continuous simulation model (Flanagan & Nearing, 1995). It uses fundamental hydrological and erosion mechanics as opposed to the empirically-based USLE model. It is based on a two-dimensional hillslope profile approach and it is able to predict deposition and erosion along the soil profile as well as sediment delivery from the profile.

The WEPP hillslope model does not have a slope length and slope gradient factor as in USLE. Instead, the slope gradient and length inputs of WEPP are deeply integrated into the hydrological and erosion components of the model. This means that the measurements of slope length and slope gradient are not limited to affect L and S factors as in USLE, but instead they affect the calculations of runoff, friction, transport capacity and various other factors (Flanagan & Nearing, 1995).

The slope length of the WEPP profile is defined as the distance from the top of the hillslope to the end of the hillslope (usually ending in a channel or impoundment). Selection of the length and slope profile in WEPP is thus easier than in USLE in the case of a single hillslope. Since WEPP is able to calculate both detachment and deposition along the hillslope profile, it is therefore important that an accurate representation of the slope profile (length and gradients) be used.

Applications of the WEPP models include all those of the USLE as well as many additional applications beyond the scope of USLE. According to Lane et al. (1992) some of the applications include: i) location of sediment detachment on a slope, either for individual storms or for long-time averages; ii) evaluation of complete land treatment, including waterways, terraces, tillage systems and management on soil detachment within a field; iii) evaluation of range management and treatment alternatives on soil erosion and sediment delivery from rangeland areas; iv) effect of road design and construction in forests on sediment delivery from forest lands; v) effect of ridge height on sediment delivery from a field; vi) evaluation of grassed waterways; vii) appraisal of Natural Resource Inventory (NRI) sites for estimates of sediment delivery from fields and farms; viii) use of NRI sites and real-time weather to make same-day estimates of soil loss; ix) effect of autumn stubble management on the capture of snow and its consequent effect on soil erosion. These effects would include those due to increased soil moisture, altered hydraulics due to crop residue, and increased runoff during thawing periods. On the other hand, the major disadvantages of the WEPP model are: i) it needs extensive data sets as input and many calibration parameters; ii) it requires either complex laboratory analyses or difficult and expensive field data collection, which may be unfeasible in many developing countries; and iii) in spite of having some calibration parameters, the model does not have an optimization method embedded in the software.

4.2 The GeoWEPP Interface

The need of a spatially distributed erosion prediction model capable of using larger and more detailed data sets, usually managed with geographic information system (GIS) or precision farming software packages, has led to the development of the Geospatial interface for WEPP (GeoWEPP) (Renschler, 2003).

The GeoWEPP model is a continuous simulation, process-based model that allows simulation of small watersheds and hillslope profiles for evaluating land use management. The GeoWEPP prepares WEPP model inputs automatically through a GIS-based wizard, runs the WEPP hillslope and watershed model, and analyzes the model output. The GeoWEPP utilizes digital geo-referenced information such as Digital Elevation Model (DEM) and topographical maps to derive and prepare valid model input parameters and defaults to start site-specific soil and water conservation planning for a small watershed with a single soil and land use for each sub-watershed (Renschler & Flanagan, 2008). In addition, the automatic delineation procedure of the drainage networks and slope shapes is favored in comparison to a manual delineation of hillslopes and channels in watersheds (Nearing et al., 2005). Despite of the WEPP channel routing algorithms for the watershed simulation (Ascough II et al., 1997; Lui et al., 1997) was originally designed to simulate channel processes in watersheds smaller than 260 ha (Flanagan & Nearing, 1995), the GeoWEPP allows delineation of larger watersheds beyond the recommended watershed size for WEPP watershed simulations (Renschler, 2004).

The goal of the GeoWEPP project is to provide a series of interfaces for users with different levels of GIS knowledge that are capable to utilize these different data sources in a standard format provided by GIS users, by precision farmers with Global Positioning Systems (GPS) databases and/or through accessing commonly readily available U.S.-nationwide data sets that are free of charge (GeoWEPP, 2009).

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CHAPTER 2

SOIL PROPERTIES AND HEMC FROM SOILS CULTIVATED WITH EUCALYPTUS, BRAZIL

1 ABSTRACT

Eucalyptus cultivation has increased in all Brazilian regions. In order to recommend good management practices it is necessary to understand differences in soil properties where eucalyptus is planted. In addition, aggregate stability analyses have proved to be a useful tool to measure soil effects caused by changes in management practices. Thus, the objectives of this study were to determine the main soil properties for different soil classes, and assess the relationship between aggregate stability and changes in soils properties under eucalyptus plantation. We studied representative soils within three eucalyptus cultivated regions. Physical, chemical, and mineralogical analyses were performed for the A horizon to characterize the predominant soil profiles. Aggregate stability was measured using the high-energy moisture characteristic (HEMC) technique. The X-ray diffraction patterns showed kaolinite as predominant crystalline mineral for all soils, whereas, a small amount of hydroxy-interlayered vermiculite was found in some profiles. Aggregate stability ratio was greater than 50% for all soils. This fact shows, for highly weathered soils with large amount of 1:1 clay minerals, that the aggregate stability index was high. In these soils, the stability ratio did not show a good relationship with clay content, soil organic matter, or Fe_o/Fe_d ratio. Aggregate stability differences under eucalyptus plantings are not directly related to soil properties but are due to other possible feature.

2 RESUMO

O cultivo de eucalipto tem aumento em todas as regiões brasileiras. O conhecimento dos diferentes atributos do solo nestes sistemas é necessário para uma boa recomendação das práticas de manejo. Além disso, a análise de estabilidade de agregados tem mostrado ser uma boa ferramenta para medir os efeitos no solo causados pelas mudanças nas práticas de manejo. Deste modo, objetivou-se com este estudo determinar os principais atributos do solo para diferentes classes de solo e avaliar a relação entre a estabilidade de agregados e estes atributos nos solos sob o cultivo do eucalipto. Foram estudados solos representativos de três regiões com cultivo de eucalipto. Análises físicas, químicas e mineralógicas foram realizadas nos horizontes A para caracterização dos solos. A estabilidade de agregados foi analisada por meio do método *high-energy moisture characteristic* (HEMC). As análises dos difratogramas de raio-X mostraram que a caulinita foi o mineral predominante em todos os solos, enquanto uma pequena quantidade de vemiculita com hidroxi-intercamada foi encontrada em alguns perfis. A estabilidade de agregados foi maior que 50% para todos os solos estudados. Este fato mostrou que para solos com grande quantidade de minerais de argila 1:1, o índice de estabilidade de agregados foi alto. Para estes solos, a estabilidade de agregados não mostrou boa correlação com o conteúdo de argila, com a matéria orgânica ou com a razão molecular Fe_o/Fe_d. As diferenças na estabilidade de agregados para plantios de eucalipto não estão relacionadas diretamente com os atributos do solo, mas possivelmente devido a outras variáveis.

3 INTRODUCTION

Eucalypt plantations play an important role at economy of several countries. In Brazil, Eucalyptus plantations area reached 4.3 million hectares in 2008, with an increase of 7.3% compared to 2007 (Associação Brasileira de Produtores de Floresta Plantada - ABRAF, 2009). Despite of great amount of cultivated area, little is known about how this kind of cultivation management system affects soil properties. In addition, soil chemical and physical properties can be greatly modified by different soil land use and management practices.

Aggregate stability influences several aspects of a soil physical behavior (Le Bissonnais, 1996). However, many physical and chemical properties and agriculture management practices can affect aggregate stability (Levy & Mamedov, 2002; Levy et al., 2003; Norton et al., 2006; Ruiz-Vera & Wu, 2006). The breakdown of aggregates can be governed by: (i) slaking, i.e., breakdown caused by compression of entrapped air during fast wetting; (ii) breakdown by differential swelling during fast wetting; (iii) breakdown by raindrops impact; and (iv) physical-chemical dispersion due the osmotic stress upon wetting with low electrolyte water. These mechanisms differ in many ways including the type of forces involved, interactions with soils properties, size of aggregates involved in the breakdown process, and intensity of disaggregation (Le Bissonnais, 1996).

The three soil properties that are most often mentioned affecting aggregate stability are (i) exchangeable-sodium-percentage, (ii) iron and aluminum oxides (a general term that includes oxides, oxydroxides and hydroxides in this paper) that cement aggregates, particularly for tropical soils, and (iii) organic matter which is a bonding agent between mineral soil particles, which may protect the surface against raindrop impact, improve water infiltration and impart hydrophobic characteristics that reduces wetting rate and slaking (Le Bissonnais, 1996). In addition, soil texture and other factors play an important role in aggregation. For example, interaction between aggregation and clay content and its mineralogy have been reported by many researchers such as Reichert & Norton, 1994; Levy & Mamedov, 2002; Lado et al., 2004; Denef & Six, 2005; Ruiz-Vera & Wu, 2006; Norton et al., 2006; and Mamedov et al., 2007. Thus, an increase in clay content in the soil could increase slaking forces during soil wetting. Under faster wetting, an increase in clay content in the aggregate also increases the extent of differential swelling and the volume of entrapped air that, in turn, can increase aggregate slaking. Therefore, an increase in clay content in the soil might have two opposite effects on seal formation: (i) an increase in aggregate stability and a reduction in seal formation, and/or (ii) increase in aggregate slaking, upon wetting, and an increase in soil susceptibility to sealing (Lado et al., 2004). Thus, an increase in clay content does not always result in increased stability, since clay type is an important factor in aggregation (Reichert & Norton, 1994).

Aggregation by iron oxides is evident in the Oxisols on Tertiary age sediments. This indicates that remobilization of iron during soil formation is essential for iron playing a role in aggregation. These findings suggest that the mode of formation and iron mineralogy affect aggregation (Muggler et al., 1999). In Brazilian Oxisols, the presence of Al-oxides (gibbsite) conferred a good correlation with aggregate stability, conversely, kaolinite showed a strong negative relationship (Ferreira et al., 1999).

Soil organic matter (OM) is expected to be the primary binding agent in 2:1 clay-dominated soils because polyvalent-organic matter complexes form bridges between the negatively charged clay platelets. In contrast, soil OM is not the only binding agent in oxides and 1:1 clay dominated soils (Six et al., 2000b). The electrostatic interaction between kaolinite, oxides, and vermiculite seem to result in a soil stability not as dependent on soil OM content as soils dominated by 2:1 clays. Due to the binding of particles by electrostatic interactions, soil OM does not have to function as critical binding agent (Six et al., 2000a). This is supported by the observation of aggregate size in kaolinitic soil (Six et al., 2000b). For the more weathered kaolinitc soils (1:1 type clay minerals), soil OM and biological processes played only a partial role in the binding of aggregates (Denef & Six, 2005).

The aforementioned facts showed aggregate stability can be affected by many factors such as texture (Levy & Mamedov, 2002; Lado et al., 2004; Norton et al., 2006; Mamedov et al., 2007), clay mineral type (Reichert &

Norton, 1994; Six et al., 2000a; Denef & Six, 2005; Ruiz-Vera & Wu, 2006; Norton et al., 2006), soil organic matter (Six et al., 2000a; Denef & Six, 2005), sodium adsorption ratio (Levy et al., 2003; Ruiz-Vera & Wu, 2006), antecedent moisture content (Reichert & Norton, 1994; Lado et al., 2004; Ruiz-Vera & Wu, 2006; Mamedov et al., 2006), Fe- and Al-oxides (Pinheiro-Dick & Schwertmann, 1996; Ferreira et al., 1999; Muggler, et al., 1999; Ajayi et al., 2009), polyacrylamide (PAM) molecular weight (Mamedov et al., 2007), redox potential (De-Campos et al., 2009) and others not related also can affect aggregate stability. Thus, the interaction of soil chemical and physical properties suggests that aggregate stability is a complex function (Levy & Mamedov, 2002; Levy et al., 2003). In addition, soil management and type of vegetation also can change soil aggregation, because of different organic compounds that are deposited in the soil.

The objective of this study was: (i) determine the main soil properties for representative soil classes from different eucalyptus growing regions of Brazil, and (ii) evaluate the relationship between aggregate stability and soil properties for Brazilian areas under eucalyptus plantation.

4 MATERIAL AND METHODS

4.1 The Study Area and Soil Description

The areas chosen for this study represent the dominant soils used for eucalyptus cultivation in three Brazilian regions (Espírito Santo, Minas Gerais and Rio Grande do Sul states). In the soil description below, soil classifications are according to Embrapa (2006), and soil classifications according to Soil Survey Staff (1999), the latter appearance in parenthesis. In the Espírito Santo state the soils selected were classified as dystrocohesive Yellow Argisol – PA1 (Hapludult), moderately rocky Yellow Argisol – PA2 (Hapludult), and dystrophic Haplic Plinthosol – FX (Phinthaquox), which represent more than 80% of soils from Coastal Plain region. In the Rio Doce Valley, center-east region of Minas Gerais state, the samples were collected in dystrophic Red-Yellow Latosol – LVA (Haplustox) and dystrophic Red Latosol – LV (Haplustox), which are the main soils there. In the south of Brazil the area encompasses eutrophic Red Argisol – PVe (Rhodudalf), dystrophic Red-Yellow Argisol – PVA (Hapludult), the main soils in Rio Grande do Sul state, and dystrophic Haplic Cambisol – CXbd (Dystrudept) which represents the shallow soils there. Espírito Santo soils were developed from tertiary age sediments above Precambrian crystalline rocks (Brasil, 1970); in Minas Gerais they were developed from granitic gneisses from Precambrian time (Celulose Nipo

Brasileira - Cenibra, 2001); and Rio Grande do Sul soils were formed from younger parent material, sediments form the tertiary-quaternary and quaternary period (Ramgrab, 1997), being considered lesser developed pedogenetically.

4.2 Soil Analyses

Soil samples were taken from the A horizons from the soils described above. The samples were characterized for particle size distribution using the hydrometer method (Gee & Or, 2002); it was also determined bulk density (Blake & Hartge, 1986a), particle density (Blake & Hartge, 1986b), total porosity (Danielson & Sutherland, 1986), cation-exchange capacity (CEC) using sodium acetate procedure, organic matter (OM) content by potassium dichromate oxidation and ferrous sulfate titration (Walkley & Black, 1934), iron extracted by dithionite-citrate-bicarbonate (Fe_d) (Mehra & Jackson, 1960), ammonium oxalate (Fe_o) (Schwertmann, 1964), and sulfuric attack (Fe_s) according to Embrapa (1997), through sulfuric attack we also extracted silicon, aluminum, titanium and phosphorus. The molecular ratio SiO_2/Al_2O_3 and $SiO_2/(Al_2O_3 + Fe_2O_3)$ was calculated according to Vettori (1959) and Embrapa (1997), using Si, Al and Fe from sulfuric attack extraction. The X-ray diffraction (XRD) was performed on a Siemens D500 diffractometer, with a generator settings of 40 kV and 35 mA and CoKα radiation (1.7890 Å). The mean geometric diameter (MGD) of stable aggregates was determined by wet sieving

(Kemper & Rosenau, 1986) of air-dried aggregates for size from 4.75 to 8.00 mm. The soil losses (A_{USLE}) and erodibility (K factor) were obtained by USLE-plots from previously studies performed by Martins (2005), Oliveira (2006), and Oliveira (2008).

4.2.1 High-Energy Moisture Characteristic (HEMC)

a) Technique

The high-energy moisture characteristic (HEMC) method was first proposed by Childs (1940), later modified by Collins-George & Figueroa (1984), Pierson & Mulla (1989), and finally by Levy & Mamedov (2002). In this method, the wetting process of the aggregates is accurately controlled, and the energy of hydration and entrapped air are the only forces responsible for aggregation breakdown. According to previous studies, the HEMC has been reported as a useful method for determining of aggregate stability of arid and humid zone soils with different stability levels (Pierson & Mulla, 1989; Levy & Miller, 1997; Levy & Mamedov, 2002; Levy et al., 2003; Norton et al., 2006), and also has been noted for its ability to detect small differences in aggregate stability (Pierson & Mulla, 1989).

The procedure is based on the following main steps. Aggregates were wetted either slowly and rapidly in a controlled manner, and a soil moisture content (MC) curve at high energies is constructed (Figure 1). An index of aggregate stability was obtained by quantifying differences in MC curves between fast and slow wetting (Figure 2a). For a given wetting rate, a structural index (SI) is defined by Collis-George & Figueroa (1984) using the following express:

$$SI = \frac{VDP}{MS} \quad \text{Eq. 1}$$

where VDP is the volume of drainable pores, and MS is the modal suction.

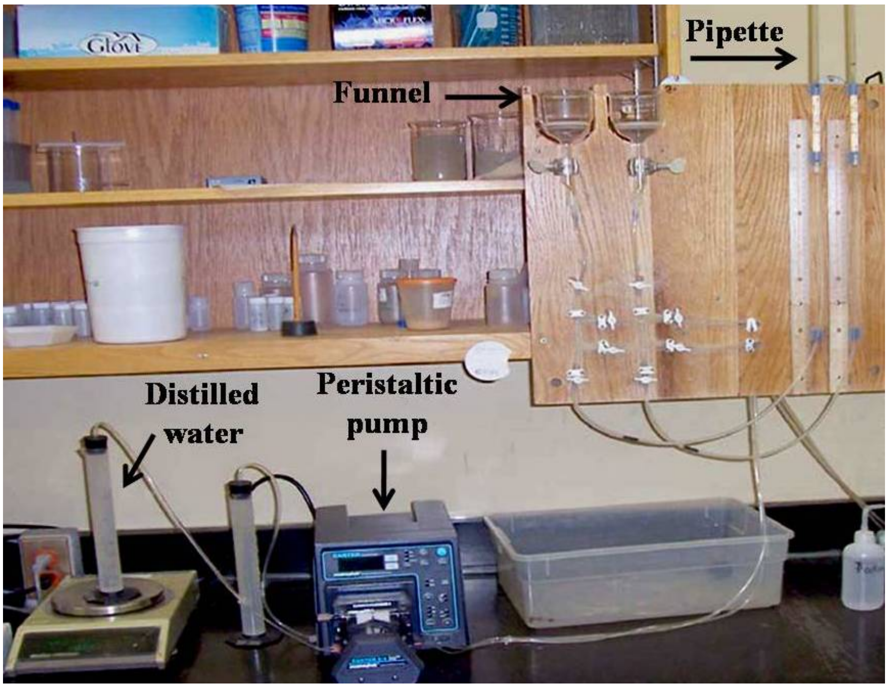

FIGURE 1 High-energy moisture characteristic (HEMC) apparatus.

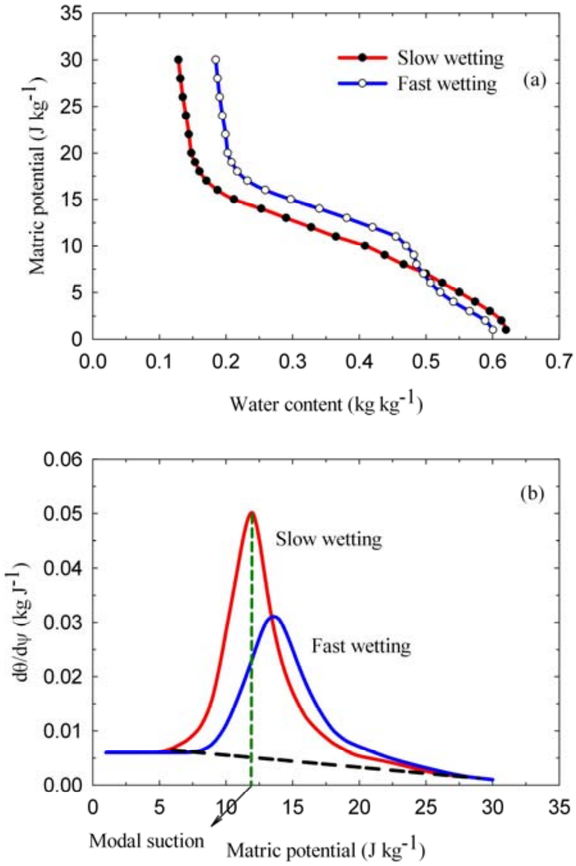

FIGURE 2 Schematic representation of (a) moisture release and (b) specific water capacity curves for fast and slow wetting. The dashed line in the specific water capacity curve represents soil shrinkage line for slow wetting.

The modal suction corresponds to the mactric potential (ψ, J kg^{-1}) at the peak of the specific water capacity curve ($d\theta/d\psi$), where θ is the water content (kg kg^{-1}) (Figure 2b). The VDP is the integral of the area under the specific water capacity curve and above the dotted baseline (Figure 2b). The dotted baseline represents the rate of water loss due to aggregate shrinkage rather than pore emptying (Collis-George & Figueroa, 1984).

As aggregate slake and the pore sizes distribution changes, the modal suction increases and the volume of drainable pores decrease. These changes cause the value of the structural index decreases (Pierson & Mulla, 1989). Figure 2 shows typical changes in the modal suction value and the volume of drainable pores.

The stability ratio (SR) value was also calculated for each soil sample using Equation 1 and the following express (Pierson & Mulla, 1989):

$$SR = \frac{SI_{fast\ wet}}{SI_{slow\ wet}} \qquad \text{Eq. 2}$$

The stability ratio was used to compare the resistance of aggregates to slaking on a relative scale from zero to one. Since the SR is a dimensionless value, soil samples of different size fractions and soil types can be compared if identical wetting rates and sample handling procedures are used for each sample (Pierson & Mulla, 1989).

b) Procedure

It was used sieved soil with a size of 0.5-1.0 mm. Fifteen grams air-dried aggregates were placed in a 60 mm i.d. funnel (Figure 1) to form a thick bed of about 5 mm (Collis-George & Figueroa, 1984; Levy & Mamedov, 2002), which it provides accurate and quick results (Pierson & Mulla, 1989). The fritted disk had a nominal maximum pore size of 20 to 40 µm. Saturation of the fritted disk was ensured prior to placing aggregates in the funnel. The funnel was connected from its bottom via a tubing to a peristaltic pump (Figure 1), which was then used to wet the aggregates in the funnel either fast (100 mm h^{-1}) or slowly (2 mm h^{-1}). At the end of wetting, aggregates were covered by standing water to ensure saturation (Levy & Mamedov, 2002). In order to obtain water closest to the rainfall water quality, distilled water was used for wetting the aggregates in the funnel.

Once the aggregates had been saturated (either slowly or rapidly), a MC curve ($\theta = f(\psi)$), at a matric potential (ψ) range of 0 to -3.0 J kg^{-1}, was obtained using a hanging water column (Figure 1), whereby height of the meniscus in the pipette was decreased in increments of 0.1 to 0.2 J kg^{-1}, thereby increasing the suction applied. Volume of water that drained from the aggregates at each matric potential was recorded after 2 min of equilibrium period and corresponding water content of the aggregates was calculated (Levy & Mamedov, 2002). Each treatment was duplicated.

c) Data analyses

To accurately calculate VDP and MS, modeling of MC curves was carried out with the following seven-parameter modified van Genuchten model (Pierson & Mulla, 1989).

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha\psi)^n\right]^{(1/n - 1)} + A\psi^2 + B\psi + C \qquad \text{Eq. 3}$$

where θ_s and θ_r are "pseudo" saturated and residual gravimetric water contents, respectively; α and ψ control location and steepness of the S-shape inflection of the MC curve, respectively; and A, B, and C are the quadratic terms added by Pierson & Mulla (1989) to improve fitting of the model to the MC curve. The term pseudo was added to saturated and residual water contents owing to modification of the original van Genuchten model (van Genuchten, 1980). Values of θ_s and θ_r can no longer be physically interpreted in terms of saturated and residual water contents (Pierson & Mulla, 1989).

Specific water capacity curve ($d\theta/d\psi$), needed for obtaining the value of modal suction, was computed by differentiating Equation 3 with respect to matric potential, and had the explicit form:

$$(d\theta/d\psi) = (\theta_s - \theta_r)\left[1 + (\alpha\psi)^n\right]^{(1/n - 1)}\left(\frac{1}{n} - 1\right)(\alpha\psi)^n \left(n/\left\{\psi\left[1 + \alpha\psi^n\right]\right\}\right) + 2A\psi + B \qquad \text{Eq. 4}$$

The VDP, that is, the area under the specific water capacity curve and above the soil shrinkage like (Figure 2b), was calculated by subtracting the terms for pore shrinkage ($2A\psi$ + B) from Equation 4, and analytically integrating the reminder of that equation.

5 RESULTS AND DISCUSSION

The soil clay mineralogy results were separated by region (Figures 3, 4, and 5). Within each region, soil mineralogy did not show great differences among the profiles. This would be expected because in each place the soil did not differ very much in pedogenetic development and the parent material was the same. The XRD patterns showed kaolinite as the dominant crystalline mineral for all soils (Figures 3, 4, and 5), which is the most abundant clay mineral at Brazilian soils (Kämpf & Curi, 2003). The diffractograms obtained for Espírito Santo soils (Figure 3) also contained a small amount of goethite, quartz, anatase, rutile and HIV (hydroxy-interlayered vermiculite). Differential thermal analysis performed by Duarte et al. (2000) in soils from that region indicated that those soils have a kaolinitic matrix with around 85%; with gibbsite contributions (around 5%); and small amounts of quartz, anatase, and HIV. The analyses also showed goethite as dominant Fe-oxide (Duarte et al., 2000). The soil mineralogical composition from Rio Grande do Sul, obtained by XRD patterns (Figure 4), was kaolinite, quartz, goethite, hematite, and HIV. However, HIV was not a common clay mineral for all of these soils. Unlikely, XRD analyses pointed out gibbsite for the soils from Minas Gerais (Figure 5), which also contained kaolinite, goethite, and hematite. The remarkable presence of clay minerals 1:1 and Al- and Fe-oxides suggest occurrence of more weathering in these soils, which normally have low natural fertility. According to Tardy & Nahon (1985), the occurrence of quartz, kaolinite and goethite is the typical paragenesis for permanently humid tropical red or yellow soils.

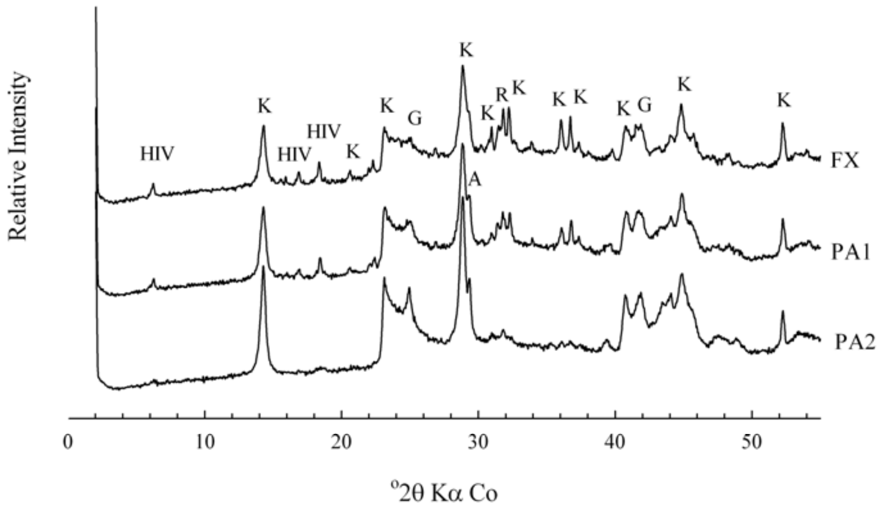

FIGURE 3 X-ray diffraction patterns of soils from Espírito Santo. FX = dystrophic Haplic Plinthosol (Phinthaquox); PA1 = dystrocohesive Yellow Argisol (Hapludult); PA2 = moderately rocky Yellow Argisol (Hapludult); HIV = hydroxy-interlayered vermiculite; K = kaolinite; G = goethite; A = anatase; and R = rutile.

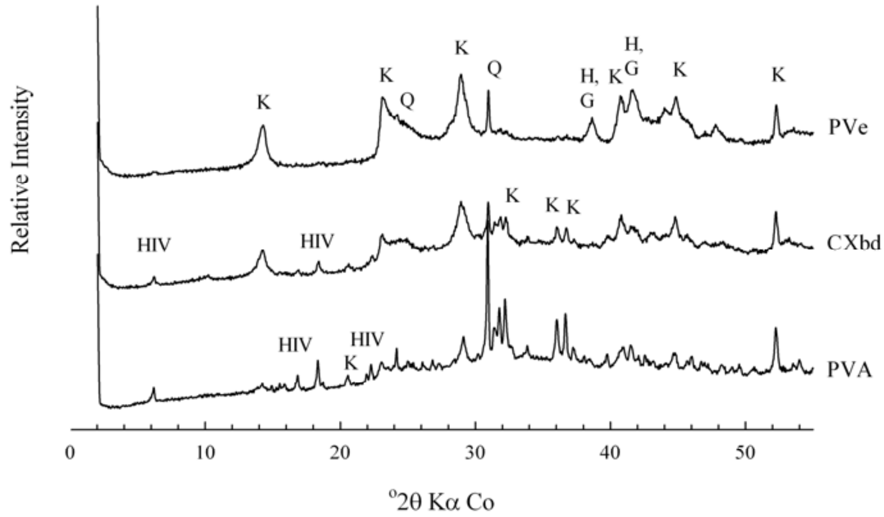

FIGURE 4 X-ray diffraction patterns of soils from Rio Grande do Sul. PVe = eutrophic Red Argisol (Rhodudalf); CXbd = dystrophic Haplic Cambisol (Dystrudept); PVA = dystrophic Red-Yellow Argisol (Hapludult); HIV = hydroxy-interlayered vermiculite; Q = quartz; K = kaolinite; G = goethite; and H = hematite.

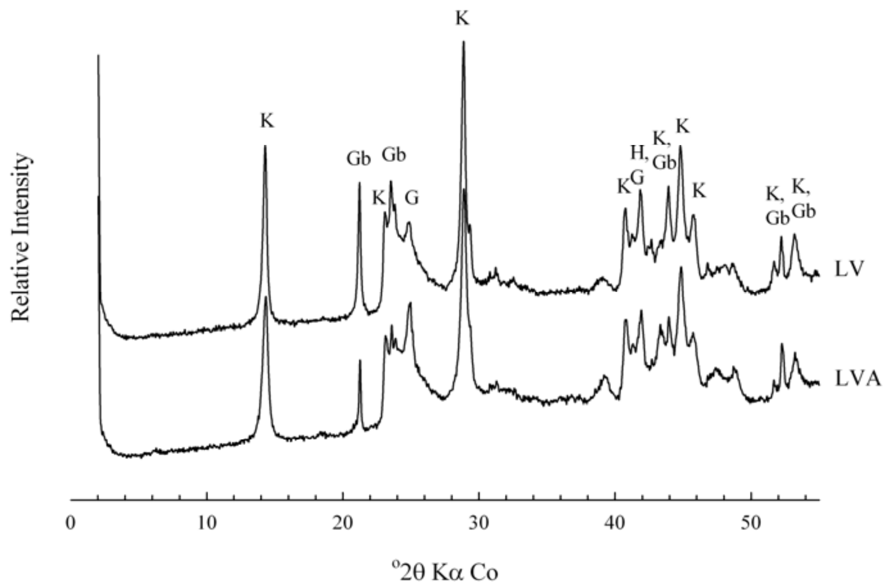

FIGURE 5 X-ray diffraction patterns of soils from Minas Gerais. LV = dystrophic Red Latosol (Haplustox); PVA = dystrophic Red-Yellow Latosol (Haplustox); Gb = gibbsite; K = kaolinite; G = goethite; and H = hematite.

Through the SiO_2/Al_2O_3 molecular ratio, it can be inferred that the soils are within advancing process of silica removal, since every soil presented molecular ratio less than 2.2 (Table 1). The gibbsite occurrence in Minas Gerais' Oxisols (Figure 5) was possibly the reason for the lowest SiO_2/Al_2O_3 molecular ratio values. These soils also showed the smallest value of $SiO_2/(Al_2O_3 + Fe_2O_3)$ molecular ratio. In such soils would be expected the lowest values for CEC, because they are very weathered. However, soils from Minas Gerais showed the highest CEC values (Table 1). This fact can be explained since the relatively high organic matter content (Table 1), which is the most important factor for negative charge development in soils with predominance of clay minerals 1:1 (Meurer, 2004). In addition, the highest clay content also was found on the soils from this region (Table 2).

The iron extraction by sulfuric attack (Fe_s) ranged from 16 g kg^{-1} to 77 g kg^{-1} (Table 1). These relatively low values of Fe_2O_3 are probably due to the parent material dominance of granitic gneisses rocks (Cenibra, 2001). The small Fe_o/Fe_d ratio (Table 1) is expected in tropical soils due to the removal of silica and oxidation of organic matter, favoring the more stable iron oxides (Fe_d) (Kämpf & Curi, 2000).

TABLE 1 Chemical and mineralogical soil properties of the A horizon from representative soils cultivated with eucalyptus.

State	Soil	CEC	OM	Fe_o	Fe_d	Fe_s	SiO_2	Al_2O_3	TiO_2	P_2O_5	Fe_o/Fe_d	Fe_d/Fe_s	Ki	Kr
		$cmol_c\ dm^{-3}$	----------------------- $g\ kg^{-1}$ -----------------------											
ES	PA1	3.9	14	1.52	13.23	34	98	87	22.4	0.11	0.115	0.389	1.77	1.41
	PA2	8.3	33	1.63	16.44	40	158	153	22.4	0.28	0.099	0.411	1.76	1.51
	FX	9.1	31	2.81	12.15	28	72	70	20.6	0.19	0.231	0.434	1.79	1.42
MG	LV	11.4	42	3.18	63.44	69	177	235	13.6	0.19	0.050	0.919	1.28	1.08
	LVA	11.6	34	1.82	44.68	77	116	173	16.6	0.50	0.041	0.580	1.14	0.89
RS	PVA	6.5	19	1.59	11.62	16	33	26	5.16	0.05	0.137	0.726	2.19	1.56
	PVe	8.4	41	2.73	49.68	53	159	140	9.9	0.34	0.055	0.937	1.92	1.59
	CXbd	10.4	36	2.91	27.52	53	103	82	17.5	0.88	0.106	0.519	2.15	1.52

PA1 = dystrocohesive Yellow Argisol (Hapludult); FX = dystrophic Haplic Plinthosol (Phinthaquox); PA2 = moderately rochy Yellow Argisol (Hapludult); LVA = dystrophic Red-Yellow Latosol (Haplustox); LV = dystrophic Red Latosol (Haplustox); PVA = dystrophic Red-Yellow Argisol (Hapludult); PVe = eutrophic Red Argisol (Rhodudalf); CXbd = dystrophic Haplic Cambisol (Dystrudept); CEC = cation-exchange capacity; OM = organic matter; Fe_o = iron extracted by ammonium oxalate; Fe_d = iron extracted by dithionite-citrate-bicarbonate; Fe_s = iron extracted by sulfuric attack; Ki = SiO_2/Al_2O_3 molecular ratio; Kr = $SiO_2/(Al_2O_3 + Fe_2O_3)$ molecular ratio.

The results of physical characterization of the soils showed different textural classes (Table 2). The soils corresponded to the following textural classes: clay (LV and PVe), sandy clay (PA2 and LVA), sandy clay loam (PA1 and CXbd), and sandy loam (FX and PVA). Silt content ranged from 28 g kg^{-1} to 206 g kg^{-1}, which can produce surface sealing in bare soils when the content is high which greatly reduces the infiltration capacity. The high content of fine sand and very fine sand can also reduce the infiltration capacity and increase runoff, consequently, increasing water and soil losses.

TABLE 2 Soil physical properties of the A horizon from representative soils cultivated with eucalyptus.

State	Soil	ρ_{bulk}	$\rho_{particle}$	Perm	Clay	Silt	Sand	Texture	VCS	CS	MS	FS	VFS
		---- Mg m^{-3} ---		mm h^{-1}	----- g kg^{-1} -----				----------- g kg^{-1} ------------				
ES	PA1	1.52	2.54	11	269	28	703	SCL	70	175	217	187	54
	PA2	1.47	2.49	17	394	72	534	SC	175	128	102	96	34
	FX	1.47	2.55	22	188	87	725	SL	69	146	211	225	75
MG	LV	1.18	2.56	54	598	71	331	C	20	74	132	86	20
	LVA	1.13	2.50	55	425	109	466	SC	83	94	144	122	22
RS	PVA	1.58	2.59	39	125	159	716	SL	71	232	232	140	42
	PVe	1.46	2.43	39	419	206	375	C	50	66	98	122	39
	CXbd	1.20	2.49	52	288	188	525	SCL	63	109	142	146	65

PA1 = dystrocohesive Yellow Argisol (Hapludult); FX = dystrophic Haplic Plinthosol (Phinthaquox); PA2 = moderately rochy Yellow Argisol (Hapludult); LVA = dystrophic Red-Yellow Latosol (Haplustox); LV = dystrophic Red Latosol (Haplustox); PVA = dystrophic Red-Yellow Argisol (Hapludult); PVe = eutrophic Red Argisol (Rhodudalf); CXbd = dystrophic Haplic Cambisol (Dystrudept); ρ_{bulk} = bulk density; $\rho_{particle}$ = particle density; PERM = soil permeability; SCL = sand clay loam; SC = sand clay; SL = sand loam; C = clay; VCS = very coarse sand; CS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sand.

Results of the different parameters obtained from the analysis of the moisture characteristic curve for fast and slow wetting are presented in Table 3. The soils demonstrated a stability ratio from 0.59 for the FX to 0.85 for the PA2. All the soils had a stability ratio higher than 50%, suggesting a high level of aggregate stability (Levy & Miller, 1997). Through statistic analysis (Table 3) soils did not show a great difference in SR, since Oxisols was statistically equal to the Inceptisols, which represent the extreme in terms of pedogenetic development. The non-plowing of the soil within eucalypt areas during seven-year production cycle, besides soil preparation only at the eucalypt planting time should provide the elevated SR values. In addition, the VDP ratio was also more than 50% for all soils (Table 3). This observation indicated that aggregate stability breakdown due to fast wetting did not result in a loss of more than 50% of the drainage pores (Levy & Miller, 1997).

TABLE 3 Results of the analysis of the moisture characteristic (MC) curves using the modified seven-parameter van Genuchten model (Pierson and Mulla, 1989), from soil samples under eucalypt cultivated forest in Brazil.

Site	Soil	Modal suction		VDP		Structural index		VDP ratio		Stability ratio	
		--- cm ---		--- g g^{-1} ---		--- g g^{-1} cm^{-1} ---					
		Fast	Slow	Fast	Slow	Fast	Slow	Mean	StDev	Mean	StDev
ES	PA1	13.3	12.3	0.133	0.193	0.010	0.016	0.69 bc	0.04	0.63 b	0.04
	PA2	13.0	12.2	0.219	0.242	0.017	0.020	0.91 a	0.19	0.85 a	0.15
	FX	13.0	12.2	0.106	0.171	0.008	0.014	0.62 c	0.13	0.59 b	0.16
MG	LV	13.6	11.6	0.286	0.320	0.021	0.028	0.89 ab	0.12	0.75 ab	0.13
	LVA	13.4	12.8	0.198	0.293	0.015	0.023	0.68 bc	0.08	0.66 ab	0.10
RS	PVA	13.3	12.5	0.125	0.187	0.009	0.015	0.67 bc	0.15	0.63 b	0.13
	PVe	13.0	12.3	0.228	0.276	0.018	0.022	0.84 abc	0.16	0.79 ab	0.09
	CXbd	13.4	12.6	0.219	0.285	0.016	0.023	0.77 abc	0.08	0.72 ab	0.07

VDP = volume of drainable pores; Means followed by the same letter are not significantly different (LSD test at $\alpha = 0.05$).

Conversely, in other studies (e.g. Levy & Miller, 1997; Levy & Mamedov, 2002; Levy et al., 2003; Norton et al., 2006; Ruiz-Vera & Wu, 2006), the soils studied did not show strong relationship between stability ratio and clay content (Table 4). Furthermore, Norton et al. (2006), Lado et al. (2004), and Mamedov et al. (2007) reported that aggregate stability increased with an increase in clay content due to high aggregation ability of clayey soils, whereas, for kaolinitic soils, which is the majority mineral in the studied soil (Figures 3, 4 and 5), the trend was less pronounced probably due to the presence of a large amount of oxides (Six et al., 2000b). For kaolinitic soils associated with iron oxides, the mineralogical effect may overshadow the long-term land use effects (Norton et al., 2006).

Espírito Santo soils showed the extreme values of aggregate stability ratio (Table 3). The lowest SR was found for the FX, which had the greatest amount of iron in non-crystalline forms (highest Fe_o/Fe_d ratio) (Table 1), and small clay content (Table 2). Moreover, the FX soil was classified according to textural class as sand loam, with high content of fine sand and very fine sand (Table 2). These combinations contributed to generate the smallest SR. In fact, the removal of the Fe-oxides played a very high disaggregation in Oxisols and Inceptisols (Pinheiro-Dick & Schwertmann, 1996). This way, iron oxides indicate their participation on soil aggregation (Lima & Anderson, 1997; Muggler et al., 1999). Aggregation in the Oxisols on Tertiary sediments in Minas Gerais state seems to be strongly influenced by iron oxides (Muggler et al., 1999). Nevertheless, the present study showed a relationship between SR and Fe_o/Fe_d ratio equal -0.56 (Table 4). However, we considered besides Oxisols, less weathered soils, as Inceptisol. Usually, Oxisols are composed predominantly of kaolinite, gibbsite, goethite and hematite, which form extremely stable aggregates (Lima & Anderson, 1997; Ajayi et al., 2009).

Studies performed under rainfall simulator showed that soils with the highest clay content produced low runoff and a low sediment concentration (Lado et al., 2004; Mamedov et al., 2002) due the large size of the entrained particle (Mamedov et al., 2002). Thus, a combination of low runoff and low sediment concentration in runoff resulted in smaller soil losses. Nevertheless, soil loss data obtained through USLE-plots under natural rainfall data compiled from Martins (2005), Oliveira (2006) and Oliveira (2008), which encompassed the studied area did not show a correlation with clay content (Table 4). However, soil loss showed a weak relationship with silt content, which can produce surface sealing in bare soils increasing runoff and then soil losses.

TABLE 4 Pearson correlation matrix of soil properties under eucalypt cultivated forest in Brazil.

	SR	MGD	TP	K factor	A_{USLE}	CEC	OM	Clay	Silt	Sand	Fe_d	Fe_s	Fe_o/Fe_d	Fe_d/Fe_s	SiO_2	Al_2O_3
SR	1.00															
MGD	0.20	1.00														
TP	0.03	-0.28	1.00													
K factor	-0.56	0.47	-0.67	1.00												
A_{USLE}	0.33	0.03	-0.52	0.45	1.00											
CEC	0.24	-0.15	0.81^{**}	-0.37	-0.20	1.00										
OM	0.59	0.13	0.51	-0.36	0.22	0.84^{***}	1.00									
Clay	0.63^{*}	0.39	0.56	-0.87^{*}	-0.02	0.57	0.71^{**}	1.00								
Silt	0.17	-0.61	-0.02	-0.10	0.69^{*}	0.25	0.37	-0.15	1.00							
Sand	-0.68^{*}	-0.14	-0.54	0.84^{*}	-0.26	-0.66^{*}	-0.85^{***}	-0.92^{***}	-0.26	1.00						
Fe_d	0.39	0.15	0.61	-0.73	0.19	0.66^{*}	0.77^{**}	0.88^{***}	0.20	-0.94^{***}	1.00					
Fe_s	0.35	0.02	0.82^{**}	-0.83^{*}	-0.11	0.75^{**}	0.70^{*}	0.84^{***}	0.05	-0.84^{***}	0.86^{***}	1.00				
Fe_o/Fe_d	-0.56	0.08	-0.47	0.99^{***}	-0.20	-0.34	-0.43	-0.78^{**}	-0.16	0.82^{**}	-0.77^{**}	-0.77^{**}	1.00			
Fe_d/Fe_s	0.27	0.02	0.15	-0.57	0.55	0.33	0.52	0.49	0.49	-0.67^{*}	0.77^{**}	0.35	-0.53	1.00		
SiO_2	0.80^{**}	0.51	0.31	-0.78	0.15	0.41	0.72^{**}	0.93^{***}	-0.12	-0.86^{***}	0.72^{**}	0.69^{*}	-0.67^{*}	0.37	1.00	
Al_2O_3	0.56	0.45	0.58	-0.86^{*}	-0.13	0.60	0.68^{*}	0.98^{***}	-0.26	-0.86^{***}	0.83^{**}	0.84^{***}	-0.71^{**}	0.41	0.89^{***}	1.00

SR = stability ratio; MGD = mean geometric diameter; TP = total porosity; K factor = soil erodibility; A_{USLE} = soil loss from USLE-plots; CEC = cation-exchange-capacity; OM = organic matter; Fe_d = iron extracted by dithionite-citrate bicarbonate; Fe_s = iron extracted by sulfuric attack; * = P < 0.1; ** = P < 0.05; *** = P < 0.01.

Despite not found a relationship between SR and soil losses, a negative and weak correlation between SR and soil erodibility (K factor) can be noticed. For kaolinitic soils (1:1 minerals), the trend between soil loss and SR was not as significant and soil loss was more related to clay dispersibility (Levy & Miller, 1997), whereas, the same authors reported a linear relationship for soils with 2:1 type mineralogy. A high relationship was found between soil erodibility and Fe_o/Fe_d ratio (Table 4). As the analyses were performed in the A horizon, the biocycling of silica and the relatively higher amount of organic matter help to explain the highest correlation found between these soil properties.

The soil OM did not show a relationship with SR (Table 4), corroborating Levy & Mamedov (2002), and Levy et al. (2003). Kaolinitic (1:1 clay minerals) soils have variable charges and a coexistence of both positively and negatively charged particles. If oxides, rather than soil OM, are the dominant agents in aggregation stabilization in weathered soils, the relation between soil OM and macroaggregation might not be as strong as the soils with dominant 2:1 clays (Six et al., 2000b). In addition, in tropical soils dominated by oxides and 1:1 minerals, a decrease of soil OM levels results in a smaller decrease of soil stability when compared to soils dominated by 2:1 minerals (Six et al., 2000a). Furthermore, soil OM not correlated with aggregate stability does not imply that soil OM is unimportant in clayey soil structure, but its importance is at a different level of structure (Reichert & Norton, 1994). The absence of a relation between aggregate stability and organic matter content found in our study could be ascribed to the fact that in tropical soils other soil properties may have a greater impact on aggregate stability, and hence, overshadow the effects of soil organic matter. The granular structure of tropical soils, which is associated with a more oxidic mineralogy (Ferreira et al., 1999) in comparison with the blocky structure of temperate regions soils, helps to explain such differential OM behavior.

Besides stability ratio, soil OM can affect and be influenced by several soil properties. Soil OM showed a positive relationship with clay content (Table 4). Clay particles can generate organic-mineral complex, which results in accumulation of organic matter. Thus, an increase in clay content, both soil surface area and organic matter increase (Scott et al., 1996).

In weathered soils, the mainly contribution on CEC is due to soil OM (in most cases soil OM in studied soils was more than 3%) (Table 1), which can generate a large number of negative charges. A significant relationship was found between soil OM and CEC (Table 4). This way, well management practices that protect soil OM are extremely important to keep soil fertility in these environments. The aforementioned correlation was greater than between CEC and clay content (Table 4). This fact strengthens the fact that in soils dominated by 1:1 clay content and Al- and Fe-oxides, soil OM can be more important than clay content for explaining CEC context. Levy & Miller (1997) found a direct linear relationship between stability ratio and CEC. Thus, the researchers could conclude that aggregate stability depends, not just on clay content, but also on clay type, with differences expressed in the CEC. Reichert & Norton (1994) also observed that aggregate stability was positively related to CEC for soils with 1:1 type clay minerals and oxides, and negatively related with 2:1 clay mineralogy soils, suggesting that for 2:1 clay minerals soils, increasing CEC may decrease aggregate stability due to increased amount of hydration cations and degree of swelling and dispersion. On the other hand, for these soils we did not find any relationship between CEC and SR (Table 4).

6 CONCLUSIONS

Soil samples from Brazilian eucalyptus cultivation areas were physically, chemically and mineralogically characterized and tested using HEMC aggregate stability methods.

Soil x-ray diffraction patterns showed that soils have practically the same mineralogical composition within a region; this was likely due to minor differential pedogenetic development and the same parent material.

Independent of soil classes studied, kaolinite was the predominant crystalline mineral, which resulted in soil with a low natural fertility.

Soils showed a large variation in texture; with a weak relationship with aggregate stability.

For soils with 1:1 type clay mineralogy, soils were well aggregated; being such aggregation not well correlated with clay content, soil organic matter, or Fe_o/Fe_d.

Soil external properties such as affected by management practices and long-term of eucalyptus cultivation had probably caused the high stability ratio found.

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CHAPTER 3

SPATIAL DISTRIBUTED MODEL FOR ASSESSING SOIL EROSION RISK IN A SMALL WATERSHED

1 ABSTRACT

This study was performed in an experimental forest watershed aiming to predict the potential average annual soil loss using the Universal Soil Loss Equation (USLE) and a Geographic Information System (GIS). The studied watershed is located at the Coastal Plain region of Espírito Santo state, southeastern region of Brazil. All the USLE factors were generated in a distributed approach using a GIS tool. The layers were multiplied in the GIS framework in order to predict soil erosion rates. The C factor values were 0.297 for eucalyptus and 0.017 for Atlantic Forest, the first ones obtained directly from field experiments in Brazil or even in South America. Results showed that the average soil loss was 6.2 t ha^{-1} yr^{-1}. Relative to soil loss tolerance, 86% of the area presented erosion rate smaller than the tolerable value. According to soil loss classes, 55% of the watershed had erosion less than 3 t ha^{-1} yr^{-1}. However, about 12% of the watershed had erosion rates greater than 12 t ha^{-1} yr^{-1}, thus, requiring special attention in order to include sustainable management practices for such areas. Eucalyptus cultivation showed soil loss greater than Atlantic Forest (natural ecosystem). Thus, an effort should be made to bring the erosion rates closer to the native forest. Conservation management practices should begin for the FX soil and forest roads which had the greatest soil loss. The implementation of the USLE model in GIS framework was found to be a simple and useful tool for predicting the spatial variation of soil erosion and identifying critical areas for conservation efforts.

2 RESUMO

O estudo foi conduzido em uma microbacia florestada com o objetivo de estimar o potencial médio de perdas de solo anuais através da Equação Universal de Perdas de Solo (EUPS) inserida no Sistema de Informação Geográfica (SIG). A microbacia estudada localiza-se na região dos Tabuleiros Costeiros no Espírito Santo, sudeste brasileiro. Todos os fatores da EUPS foram gerados de forma distribuída utilizando a plataforma SIG. Os mapas foram multiplicados no ambiente SIG para estimar as taxas de erosão do solo. O fator C foi 0,297 para o eucalipto e 0,017 para a Floresta Atlântica, estes são os primeiros valores obtidos diretamente de experimentos de campo no Brasil ou mesmo na América do Sul. Os resultados mostraram que a perda de solo média foi de 6,2 t ha^{-1} ano^{-1}. Em relação à tolerância de perdas de solo, 86% apresentaram taxas de erosão menores que o limite permitido. Com relação às classes de perdas de solo, 55% da microbacia tiveram perdas de solo menores que 3 t ha^{-1} ano^{-1}. Entretanto, cerca de 12% da área da microbacia apontaram taxas de erosão maiores que 12 t ha^{-1} ano^{-1}, exigindo uma atenção especial para conduzir um manejo sustentável nestas áreas. O cultivo de eucalipto mostrou perdas de solo maiores que a Mata Atlântica (ecossistema natural). Deste modo, um esforço deve ser realizado a fim de aproximar as taxas de erosão para próximo dos valores na mata nativa. As práticas conservacionistas devem se iniciar no solo FX e estradas florestais, os quais tiveram as maiores perdas de solo. A implementação do modelo EUPS no ambiente SIG mostrou ser uma ferramenta simples e útil para predição da variação espacial da erosão do solo e na identificação das áreas críticas para melhor conservação.

3 INTRODUCTION

The process of water erosion occurs in watersheds throughout the world. It is strongly affected by anthropogenic influences. Modification of natural ecosystems can cause intense environmental degradation, mainly in soils onsite and offsite. Advanced erosion not only decreases land productivity but also can transport nutrients, organic matter and agrochemical contaminants.

Knowledge about soil erosion processes as well as how fast soil is eroded is necessary in planning of conservationist efforts. Modeling is a way to provide a quantitative and consistent approach to predict soil loss and the sediment delivery ratio under a wide range of conditions (Bhattarai & Dutta, 2007). In addition, it can be used to evaluate hypotheses and determine the appropriate soil management and land use for each site (Beven, 1989; Grayson et al., 1992; Tucci, 1998). Simple empirical methods such as the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1965; 1978), the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991, 1997) have been used for the assessment of soil erosion at the watershed scale (Jain et al., 2001; Bhattarai & Dutta, 2007; Pandey et al., 2007; Avanzi et al., 2008; Dabral et al., 2008; Bahadur, 2009; Beskow et al., 2009; Kouli et al., 2009).

The USLE is the simplest and most widely used model for erosion prediction, which estimates the long-term annual average rate of erosion with generally acceptable accuracy. Basically, the USLE estimates the soil loss per unit area based on the following factors (Wischmeier & Smith, 1978): rainfall-runoff erosivity (R), soil erodibility (K), topography (LS), cover-management (C), and support practices (P). The drawback of this model is that it is not capable of simulating deposition, sediment yield, channel erosion, or gully erosion. In addition, such an equation makes no differentiation between rill and interrill erosion, thus predicting the two processes together. Despite the above-mentioned limiting aspects, the USLE has presented consistent results when coupled with a Geographic Information System (GIS) for simulations in watersheds (Jain et al., 2001; Fistikoglu & Harmancioglu, 2002; Onyando et al., 2005; Bhattarai & Dutta, 2007; Pandey et al., 2007; Dabral et al., 2008; Ozcan et al., 2008; Bahadur, 2009; Beskow et al., 2009). The combination of USLE and a GIS has been found to be an effective and suitable approach for estimating the magnitude and spatial distribution of erosion. USLE model applications in a GIS framework allows analyzing soil erosion with much more detail since this process can account for spatial variability (Pandey et al., 2007). Soil erosion estimates using GIS techniques enable planners to identify sites which are susceptible to water erosion and also provides a quantitative measure of soil loss at different scales (Martin & Saha, 2007). The main reason for using a GIS is that the erosion process varies spatially, so that cell sizes should be used allowing spatial variation to be taken into account. In addition, the amount of data necessary for a great amount of cells is required for an accurate representation of the watershed. Since it is not practicable to input data manually, GIS can be used to gather and access databases (De Roo & Jetten, 1999).

The objective of this study is to apply the USLE model coupled with GIS framework for assessing soil loss in a small watershed located in the Coastal Plain region (100 million hectares) of Brazil. It is expected that this methodology will provide a useful tool to identify high risk areas for soil erosion, thus allowing the targeting of conservation and better management practices in the studied and similar watersheds of the Brazilian Coastal Plain region.

4 MATERIAL AND METHODS

4.1 The Study Area and Soil Description

The experimental watershed (EAW) is located in the Aracruz Celulose S.A. area, in the Espírito Santo state, southeastern region of Brazil, between parallels 19°51'S and 19°53'S and, meridians 40°11'W and 40°14'W (Figure 1). According to Köppen classification, the climate of this region is Aw (tropical with rainy summer and dry winter), with annual rainfall equal to 1,400 mm (Embrapa, 2000). The watershed has a drainage area of about 286 ha, containing eucalyptus plantations and native forest (Atlantic Forest), with advanced regeneration.

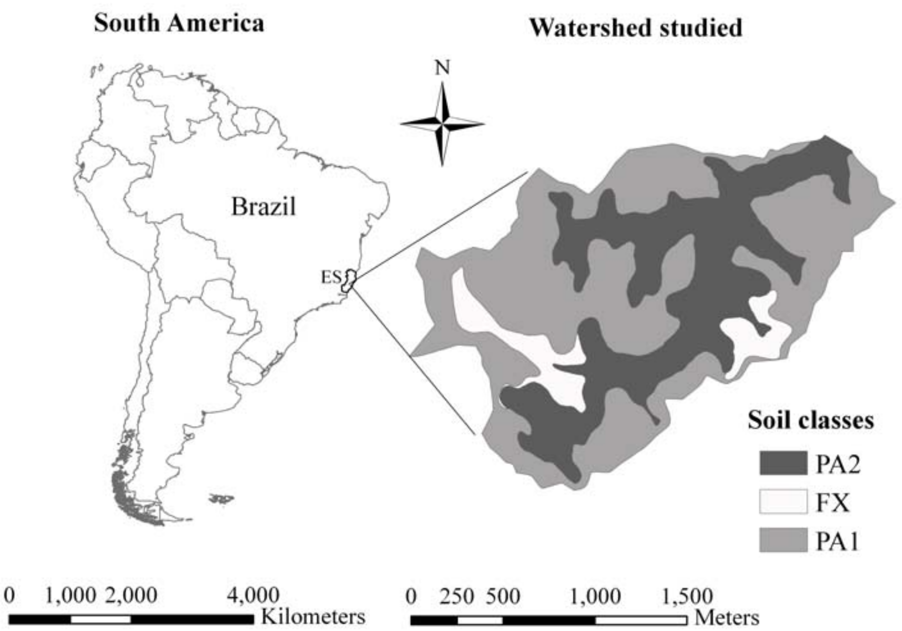

FIGURE 1 Location of the studied area and soil map for the experimental watershed.

The soil classification in the EAW was performed in accordance with soil classification by Embrapa (2006), and by Soil Survey Staff (1999), the latter appearing between parentheses. The EAW includes the following most representative soils of the Brazilian Coastal Plain (100 Million hectares): a) dystrocohesive Yellow Argisol – PA1 (Hapludult), b) moderately rocky Yellow Argisol – PA2 (Hapludult), and c) dystrophic Haplic Plinthosol – FX (Phinthaquox).

4.2 The Universal Soil Loss Equation (USLE)

The USLE allows an estimate of the long-term annual average soil loss for specific conditions. This model was applied in a GIS environment to evaluate potential soil loss and its distribution in a forest watershed at the Brazilian Coastal Plain. The USLE computes soil loss as the product of six factors (Wischmeier & Smith, 1978):

$$A = R \times K \times L \times S \times C \times P \qquad \text{Eq. 1}$$

where A is the average annual soil loss per unit of area (t ha^{-1} yr^{-1}), R represents the average annual rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), L corresponds to the slope length factor (dimensionless), S is the slope-steepness factor (dimensionless), C represents the cover management factor (dimensionless), and P is the support practice factor (dimensionless).

A Geographic Information System (GIS) was used in order to obtain spatially distributed results from USLE predictions. The details of all factors in Equation 1, which were represented in a 10-meter-resolution map, are described below.

a) Rainfall-runoff erosivity factor (R)

Erosivity is defined as the potential of a given rainfall event to cause soil erosion due to the raindrop impact and runoff. This factor depends primarily on the intensity and the amount of rainfall (Lal, 1994).

In order to estimate the rainfall-runoff erosivity factor, the rainfall data were recorded every 5 minutes from January 1998 to July 2004. Suggestions described by De Maria (1994) were followed, including only rainfall events with the following characteristics: (a) amount greater than 10 mm; (b) maximum intensity greater than 24 mm h^{-1} within 15 minutes; (c) kinetic energy greater than 3.6 MJ. The kinetic energy was computed for all the rainfall events by using the equation suggested by Wischmeier & Smith (1958):

$$E = 0.119 + 0.0873 \times \text{Log}(I) \qquad \text{Eq. 2}$$

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

The EI index for a specific event was calculated as the product of the total kinetic energy (E) by the maximum 30 minutes intensity (I_{30}), according to Wischmeier & Smith (1958). Both annual and monthly values were computed as the sum of all the EI_{30} (MJ mm ha^{-1} h^{-1}) values during the respective period of time with the given conditions described as above.

The sum of EI values for a given period is a numerical measure of the erosive potential of the rainfall within that period (Renard et al., 1997). It is worthwhile to point out that the annual EI value in a particular locality corresponds to the rainfall-runoff erosivity index (R) for that location. The R factor for the studied watershed was determined by previous study and presented by Martins (2005).

b) Soil erodibility factor (K)

The soil erodibility is considered as the soil susceptibility to be detached by splash during rainfall and/or shallow surface flow (Renard et al., 1997). It is generally considered as an intrinsic soil property with a constant value. The K factor of the USLE is represented by the mean ratio of soil loss from a standard plot divided by the rainfall-runoff erosivity index:

$$K = A/R \qquad \text{Eq. 3}$$

where A is the soil loss (t ha^{-1} yr^{-1}) and R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}). Therefore, K factor is expressed in t h MJ^{-1} mm^{-1} units. The standard plot has the characteristics as follows (Renard et al., 1997): (a) it is 22.1 m long and 1.83 m wide; (b) uniform slope of 9%; and (c) continuous clean-tilled fallow with tillage up and downslope. The K factor for each soil type in the studied watershed was determined by previous study and presented by Martins (2005). The K values used were 0.007, 0.017, and 0.0004 t h MJ^{-1} mm^{-1} for the PA1, FX, and PA2, respectively. The K factor map was created with GIS tools and derived from the soil map of the area.

c) Topographic factor (LS)

Both the slope length (L) and the slope steepness (S) have substantial influence on water erosion ratio (Wischmeier & Smith, 1978). The effects of these factors have been evaluated separately in studies which use uniform-gradient plots. However, in erosion prediction, the factors L and S typically have been evaluated together (Renard et al., 1997).

In this study, a large number of elevation points were surveyed throughout the watershed, which allowed the generation of a 10-m-resolution Digital Elevation Model (DEM) (Figure 2). The database inputs for the model taking into account homogeneous cells as small as possible are necessary, thus allowing soil loss to be characterized with a good resolution. Bhattarai & Dutta (2007) verified that DEM resolution influences the LS factors, where 30 m DEM resolution showed better when compared to 90 m resolution using USLE method. The researchers emphasized the fact that better results can be expected for the resolution which is closer to the slope length used in the derivation of USLE relationship.

The DEM was imported to the GIS in order to develop a slope map; thereafter, the latter map was classified into four classes according to Yuksel et al. (2008): (i) very gentle to flat (<5%); (ii) gentle (5-15%); (iii) steep (15-30%); and (iv) very steep (>30%) (Figure 3). The slope length factor (L) and the slope steepness factor (S) were also generated on a grid cell basis.

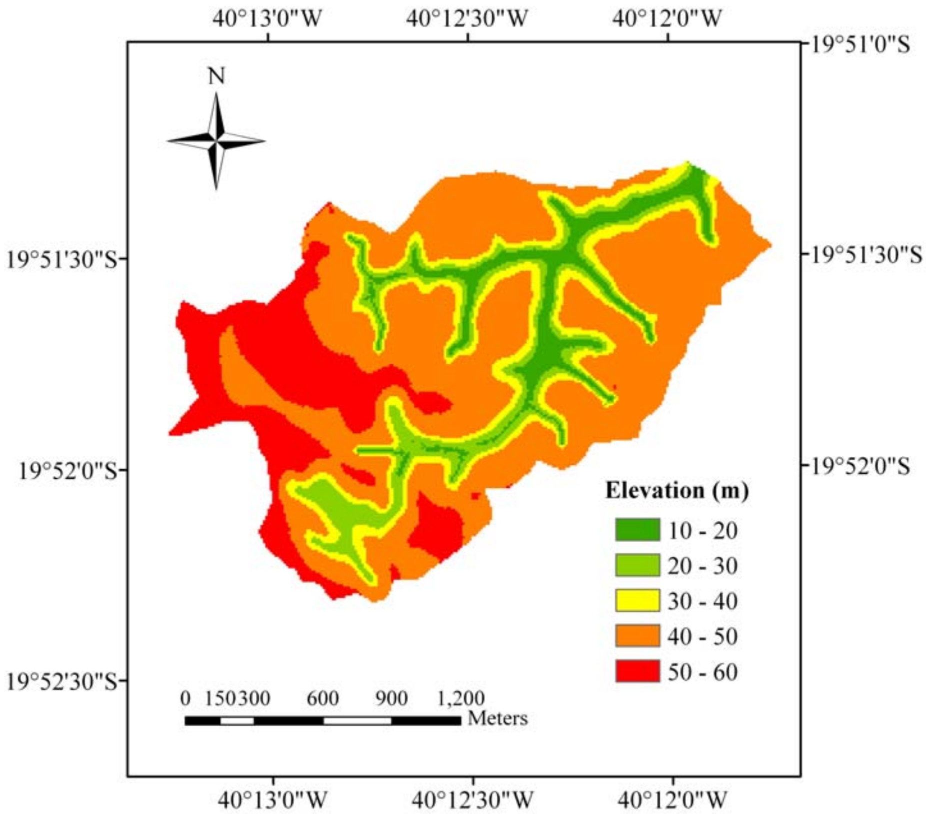

FIGURE 2 The Digital Elevation Model (DEM) of the experimental watershed.

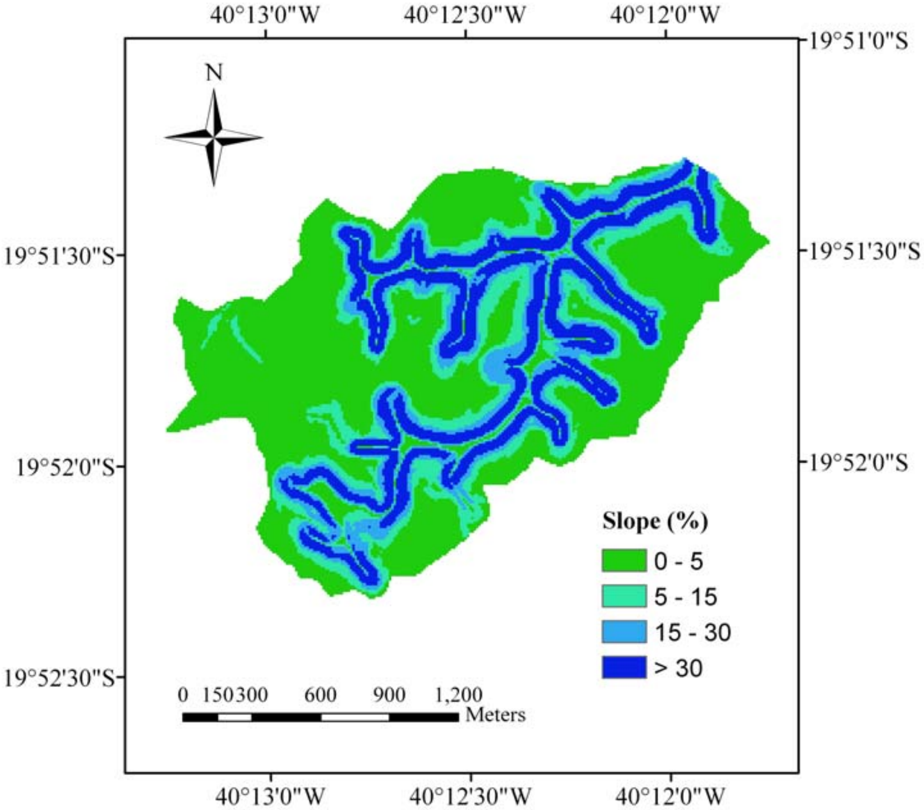

FIGURE 3 Map of slope categories according to Yuksel et al. (2008) for the experimental watershed.

The slope length factor (L) is expressed by (Renard et al., 1997):

$$L = (\lambda/22.13)^m \quad \text{Eq. 4}$$

where λ is the field slope length (m), and *m* is the slope-length exponent (Wischmeier & Smith, 1978). A grid size of 10 m was used as field slope length (λ). Similar procedure was adopted by several researchers (Liu et al., 2000; Jain et al., 2001; Fistikoglu & Harmancioglu, 2002; Bhattarai & Dutta, 2007; Pandey et al., 2007; Dabral et al., 2008; and Beskow et al., 2009).

The slope-length exponent m is related to the ratio (β) of rill to interrill erosion by the following equation (Foster et al., 1977):

$$m = \beta/(1+\beta) \qquad \text{Eq. 5}$$

Values for the ratio β of rill to interrill erosion were computed according to the equation proposed by McCool et al. (1989):

$$\beta = (\sin\theta/0.0896)\Big/\left[3.0 \cdot (\sin\theta)^{0.8} + 0.56\right] \qquad \text{Eq. 6}$$

where θ is the slope angle (degree).

The slope-steepness factor (S) was evaluated according to equations presented in McCool et al. (1987) for slopes greater than 4 m, which were applied in several studies like Bhattarai & Dutta (2007), Pandey et al. (2007), Dabral et al. (2008) and Beskow et al. (2009):

$$S = 10.8 \cdot \sin\theta + 0.03 \quad \text{for slope} < 9\% \qquad \text{Eq. 7}$$

$$S = 16.8 \cdot \sin\theta - 0.50 \quad \text{for slope} \geq 9\% \qquad \text{Eq. 8}$$

where S is the slope-steepness factor, and θ corresponds to the slope angle (degree). The combined LS factor was calculated by multiplying L and S factor maps and the final map was generated through GIS software.

d) Cover-management factor (C)

The cover-management factor (C) reflects the effect of cropping and management practices on erosion rates, indicating how the conservation measures used can affect the average annual soil loss. It varies with activities, such as crop rotations, or other management practices (Renard et al., 1997). The concept of the C factor is the ratio of soil loss from an area with specific cover and management to soil loss from an identical area in a clean-tilled continuous fallow condition (Wischmeier & Smith, 1978). The soil loss ratio (SLR) is then estimated by the ratio between soil loss under actual conditions and soil loss experienced under the reference conditions:

$$SLR = SL_c / SL_r \quad \text{Eq. 9}$$

where SL_c is the soil loss from a specific cropping/management, and SL_r is the soil loss from reference conditions (bare-soil).

The C factor was calculated by multiplying the SLR for each time interval by its corresponding EI value (Wischmeier & Smith, 1978), using the following equation:

$$C = (SLR_1 \cdot EI_1 + SLR_2 \cdot EI_2 + ... + SLR_n \cdot EI_n) / EI_t \quad \text{Eq. 10}$$

where C is the cover-management factor, SLR_i is the soil loss ratio for the time step i, EI_i is the EI occurring during that time step, n is the number of time steps used, and EI_t is the sum of EIs for the entire period of time.

e) Support practice factor (P)

The P factor is the ratio of soil loss with a specific support practice, such as terracing, strip cropping, or contouring, to the corresponding soil loss with up and downslope tillage (Renard et al., 1997). For this study, no support practices were considered, so the P factor was set equal to 1.0 for the entire area. A similar assumption was also adopted by Gaffer et al. (2008), Ozcan et al. (2008), Beskow et al. (2009), and Kouli et al. (2009).

4.3 Soil Loss Tolerance (T)

The soil loss tolerance (T) is closely related to soil formation. In other words, the tolerable value can be considered equal to soil formation rate. Thus, the term soil loss tolerance denotes the maximum rate of soil erosion that can occur and still allows crop productivity to be economically sustainable (Renard et al., 1997). This way, agricultural soils can ''tolerate'' a certain amount of erosion without adversely impacting on long-term productivity because new soil is constantly being formed to compensate losses (Bazzoffi, 2008). Within tolerance context, the erosion value can be considered as the weathering-limited process (Stallard, 1995), where the transport processes remove weathered material from an area more rapidly than the weathering can generate soil material (Bazzoffi, 2008). The tolerable value depends on soil depth, on soil organic matter amount, on soil permeability, on clay ratio between A and B horizon, and on clay amount (Galindo & Margolis, 1989). For such soils, the clay amount and soil permeability might be the main properties to consider because they showed high clay amount and low permeability, mainly in the B horizon.

The tolerance values used in this study were generated by Martins (2005) who applied the methodologies suggested by Smith & Stamey (1964), Lombardi Neto & Bertoni (1975), and Galindo & Margolis (1989). Martins (2005) presented a T value for each soil class as the average value obtained through the aforementioned methods. Thus, the T values were 10, 13 and 11 t ha^{-1} yr^{-1} for the PA1, FX and PA2, respectively. These values were compared to USLE predictions using GIS tools to identify areas where land-use and management were appropriate, and to identify areas that need more attention in order to reduce and to prevent long-term soil degradation.

4.4 Geographic Information System (GIS)

GIS is a tool for making and using spatial information. It can be defined as a computer-based system to aid in the collection, maintenance, storage, analysis, output, and distribution of spatial data and information (Bolstad, 2005). Within the GIS environment a raster data model describe the area as a regular set of cells in a grid pattern. Thus, for EAW the cell dimension was defined as 10 meters on each side. The integration of USLE model and GIS framework can be established by converting all parameters of USLE into a raster-based format and by evaluating these digital parameter layers. Thus, a map illustrating the water erosion potential for the watershed was created. To do this, the USLE model

(Equation 1) was applied by multiplying different layers with GIS software: K, R, LS, C and P factors.

5 RESULTS AND DISCUSSION

5.1 USLE Parameters

Annual rainfall-runoff erosivity ranged from 4,536 MJ mm ha^{-1} h^{-1} yr^{-1} to 17,056 MJ mm ha^{-1} h^{-1} yr^{-1} (Figure 4). The large variation shows that the assessment of the rainfall-runoff erosivity for this particular watershed was very important to achieve a reliable estimate of the R factor. The R factor calculation based on rainfall amount and/or geographic location can be useful for regions of Brazil where intensity values have not been recorded. However, when such information is available, the rainfall-runoff erosivity factor can be estimated with more accuracy.

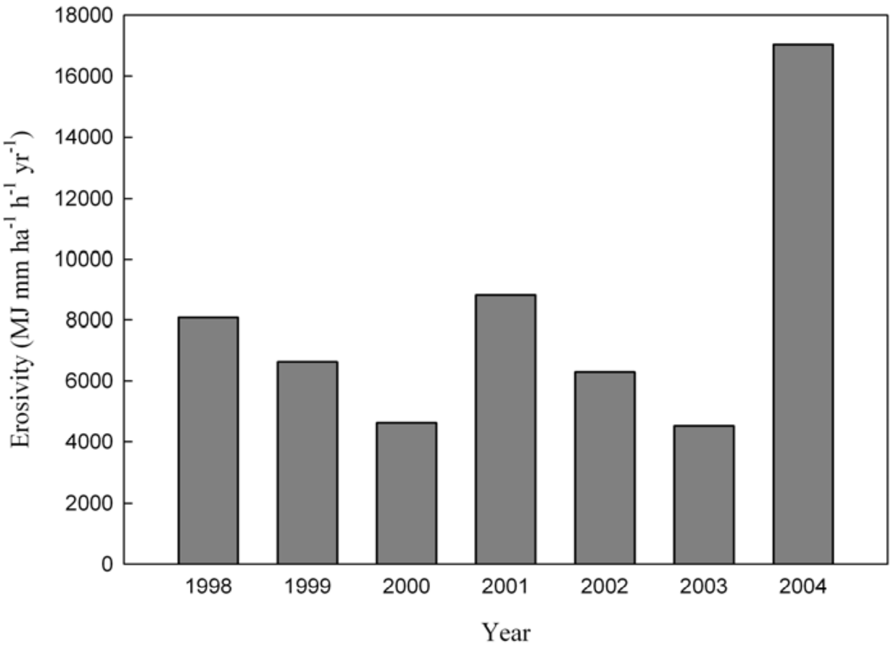

FIGURE 4 Rainfall-runoff erosivity index for the studied watershed. For 2004 it was showed a partial value from events between January and July (modified from Martins, 2005).

The greatest R value (17,056 MJ mm ha^{-1} h^{-1} yr^{-1}) was observed in 2004. It is important to mention that the R value for March/2004 corresponded to 12,540 MJ mm ha^{-1} h^{-1}. This monthly value was greater than the annual values for previous six years (Figure 4). A gap in the data did not allow the determination of the total erosivity factor in 2004; nevertheless, it can be inferred that it would be high since higher erosivity values have been observed during December months. In this study, the spatial distribution of the R factor was assumed to be constant in the entire watershed. The EAW area is about only 286 ha, where small rainfall spatial variability is expected, consequently a small variation in rainfall-runoff erosivity. This procedure was also adopted by Dabral et al. (2008) for a much larger watershed with 127,878 ha in Northeastern India.

The soil erodibility map (Figure 5) was generated using results from field plots which were measured by Martins (2005). It is worthwhile to point out that the greater the erodibility value, the lesser resistance of the soil to water erosion. Analyzing the K factor map, it can be noticed that the major part of the watershed (92%) can be considered as having low soil erodibility, with values less than 0.010 t h MJ^{-1} mm^{-1}, while the remaining part has moderate soil erodibility (Foster et al., 1981).

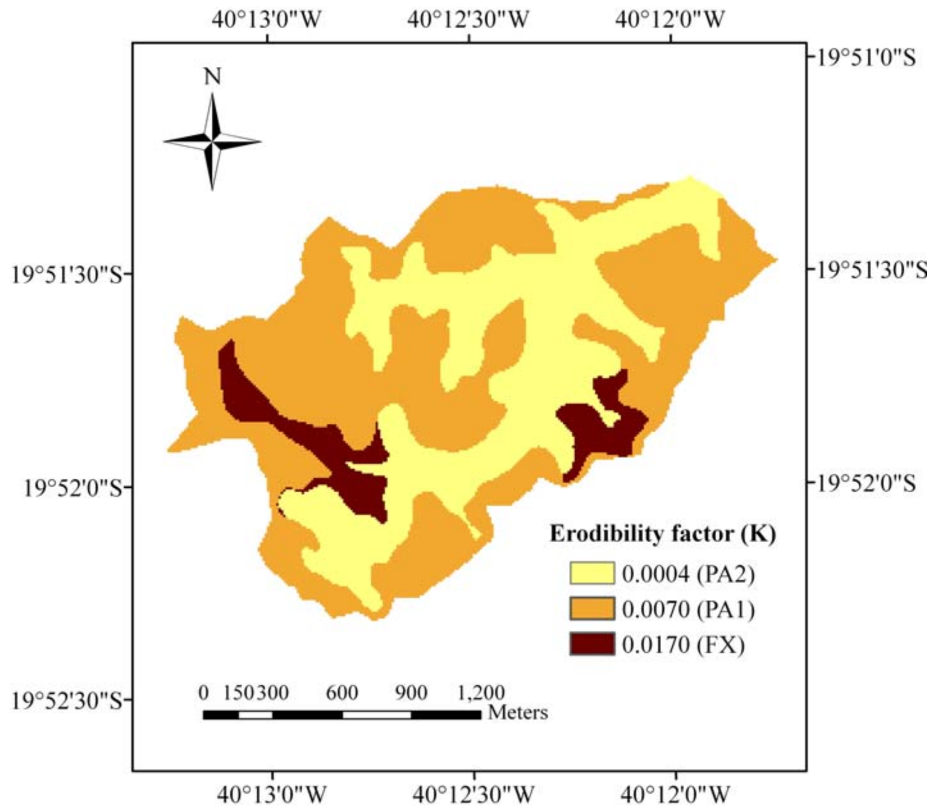

FIGURE 5 Erodibility factor (K) for the experimental watershed.

The LS factor was calculated by Equations 4, and 7 or 8 taking into account its spatial variation which ranged from 0.03 to 6.88 (Figure 6). The spatial analysis of the LS factor indicated that 65% of the EAW had a topographic factor less than 1.0. It means that in only a small part of the watershed the LS factor resulted in a water erosion risk. In addition, through slope categories (Figure 3), it is also found that a considerable area (52%) had gradients less than 5%, indicating a low risk for soil losses. On the other hand, the steeper slopes may cause more runoff and result in greater soil erosion.

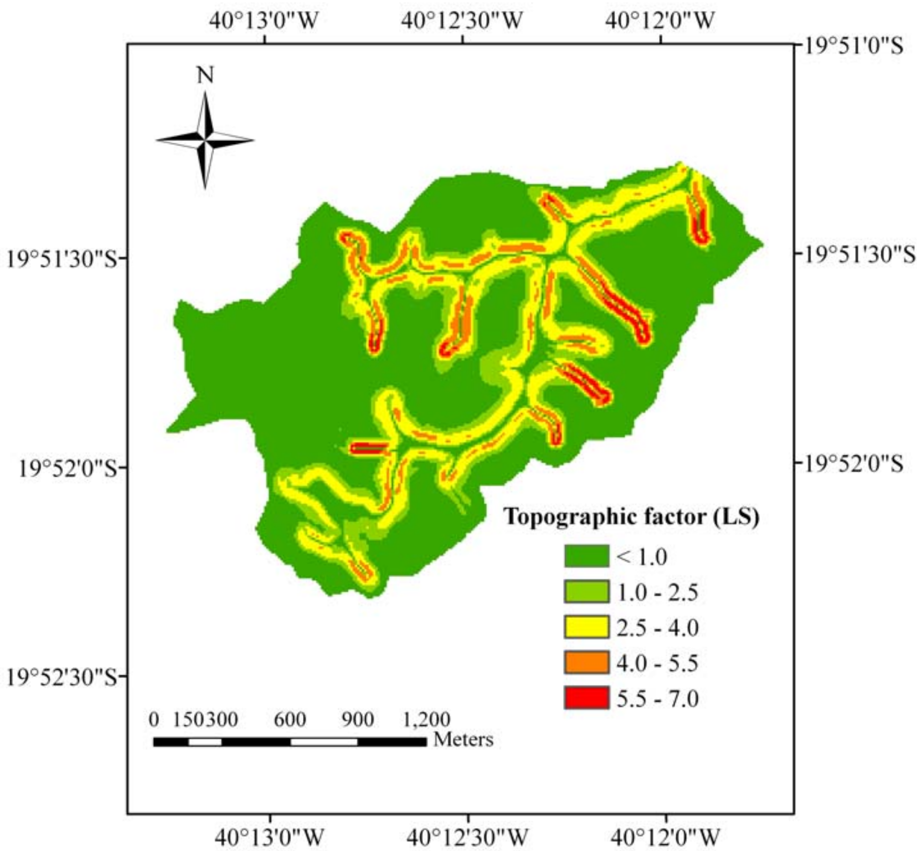

FIGURE 6 Topographic factor (LS) of the studied area.

The watershed is composed of only three types of land-use, namely native forest (30%), planted eucalyptus forest (59%) and forest roads (11%). Figure 7 shows the C factor map which was generated according to Equation 10. From such equation, the C factors calculated were 0.297 and 0.017 for the eucalyptus plantation and the Atlantic Forest (native forest), respectively. The C value for the forest roads was assumed to be equal to 1.0. To our knowledge, these cover-management factor values for eucalyptus and Atlantic Forest are the first ones obtained directly from field experiments in Brazil or even in South America. Researchers have come up with a certain variation of the cover-management factor for forest areas. Roose (1977) recommended a value of 0.001 for dense tropical forest in Africa. The C factor estimated for broad-leaved forest in Greece was 0.130 (Kouli et al., 2009) based on satellite image analysis. Among the USLE factors the cover-management is the easiest one that can be modified in order to substantially reduce the erosion risks. In this context, keeping native forest may reduce soil erosion risk by hundreds of times compared to forest roads.

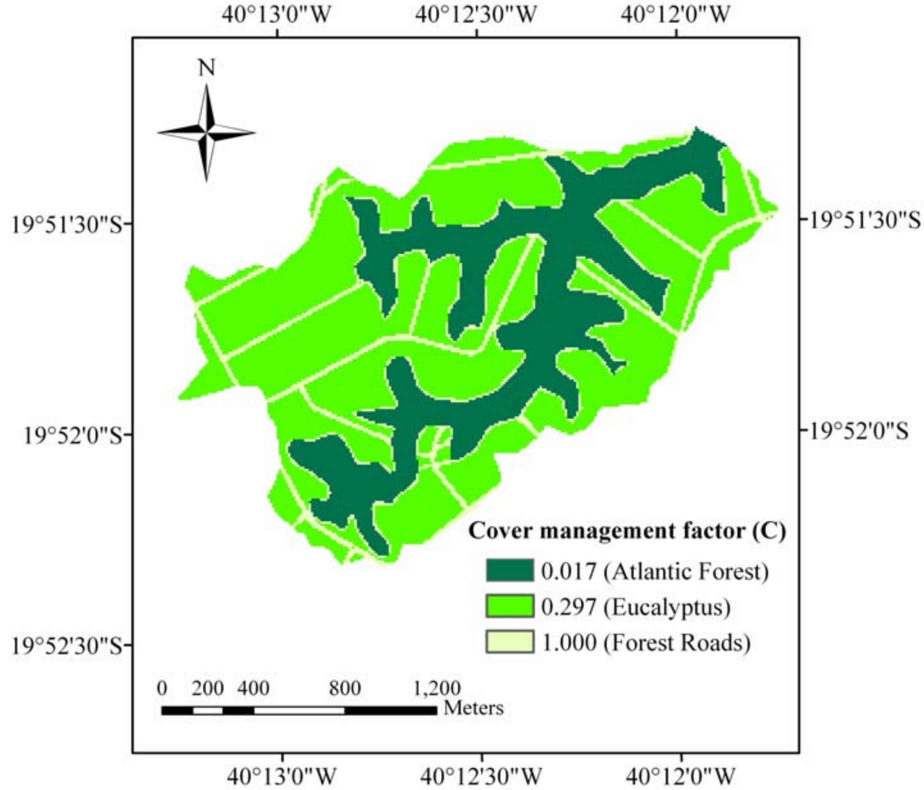

FIGURE 7 Cover-management factor (C) for the studied area.

5.2 Spatial Distribution of Soil Loss

The map of long-term annual average soil loss (Figure 8) was generated using Equation 1. This calculation was done multiplying the USLE factors using GIS. The soil loss values calculated ranged from $2x10^{-3}$ to 983 t ha^{-1} yr^{-1}, with a weighted average value equal to 6.2 t ha^{-1} yr^{-1}. The annual soil loss values were reclassified (Table 1) according to the classes suggested by Bahadur (2009). In Table 1 we can observe that 72.7% of the watershed area had an erosion rate under "very slight" category, with annual soil loss less than 6 t ha^{-1} yr^{-1}. This behavior can be explained due to the predominant low slope gradient (Figure 3) and the soil mineralogy in the watershed, which has a high kaolinite content with very low gibbsite and iron-oxide (Duarte et al., 2000), favoring blocky structure and increasing cohesion and, consequently, decreasing soil erosion. In addition, the greatest part of the watershed (65%) has LS factor less than 1.0 (Figure 6) and an adequate cover management (Figure 7). We can conclude that such factors contributed to the low erosion rate, although the erosivity factor was considered high according to Foster et al. (1981). The results indicated that "severe" to "very extremely severe" erosion risk occurs in 11.5% of the area (Table 1). The greatest soil erosion values were found in sites occupied by forest roads (Figure 7) and with high LS values (Figure 6). This kind of information is extremely valuable since it can be used to plan a conservation management with focusing on sites with a high potential for water erosion. Sediment delivery control practices like sediment basins, barriers, containment structures, and vegetable drainage ditches should be constructed in order to keep the sediments from moving, thus reducing the process of sediment transport. According to Antonangelo & Fenner (2005), forest roads have been one of the main reasons for soil erosion and siltation of rivers in forest areas. The construction of forest roads removes natural protection and makes soil movement easier, thus making these roads more vulnerable to the effect of rainfall-runoff erosivity.

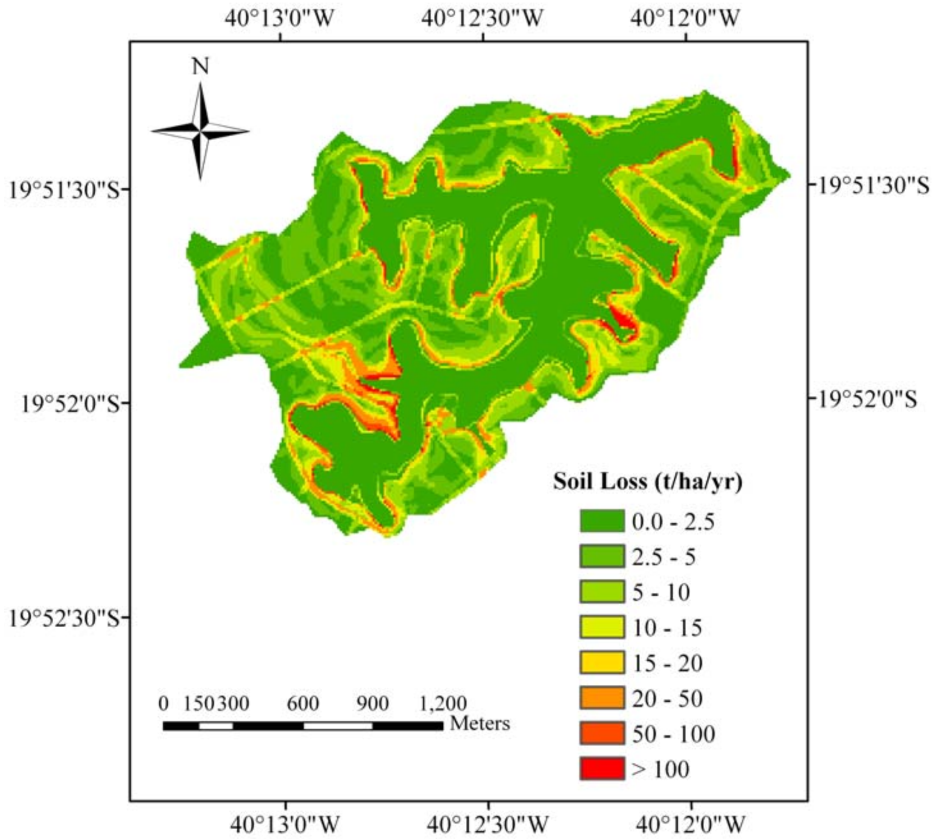

FIGURE 8 Map of soil loss for the studied area.

The FX soil (Figure 1), mainly that located on the western part of the watershed, presented the most soil loss (Figure 8). In the field, we observed that this soil occurs on slightly concave slopes, which can concentrate the runoff flow leading to greater erosion rate. Thus, the erosion control practices should concentrate on protecting these soils.

TABLE 1 Classes of soil loss according to Bahadur (2009) for the studied watershed.

Soil loss rate $t\ ha^{-1}\ yr^{-1}$	Area %	Soil loss class
0.0 – 1.0	32.0	Nil to very extremely slight
1.0 – 3.0	22.9	Extremely slight
3.0 – 6.0	17.8	Very slight
6.0 – 9.0	9.7	Slight
9.0 – 12	6.1	Moderate
12 – 25	7.1	Severe
25 – 50	2.6	Moderate Severe
50 – 100	1.1	Very severe
100 – 400	0.6	Extremely severe
> 400	0.1	Very extremely severe

Comparing the soil loss estimates for different land-uses for the watershed (Table 2) it was possible to verify that the natural system (Atlantic Forest) had lower values of mean and median than the other uses. Additionally, a substantial difference for soil loss was found between Atlantic Forest and forest roads. The eucalyptus land-use showed soil loss values for mean and median lesser than tolerable values for soil loss, in the order of 10, 13 and 11 $t\ ha^{-1}\ yr^{-1}$ for the PA1, FX and PA2, respectively (Martins, 2005). However, these soil losses were greater than for the native forest. Better management practices should be considered for the eucalyptus area in order to bring the erosion rate much closer to the native forest to make it more sustainable.

TABLE 2 Soil loss for different uses for the studied watershed.

Soil use	Soil loss ($t\ ha^{-1}\ yr^{-1}$)	
	Mean	Median
Atlantic Forest	0.94	0.19
Eucalyptus	6.97	3.53
Forest roads	21.79	7.13

Most of the area in the studied watershed (86%) had soil loss rate less than soil loss tolerance (Figure 9). However, 14% of the watershed area where erosion was greater than soil loss tolerance needs special attention for the implementation of soil erosion controls.

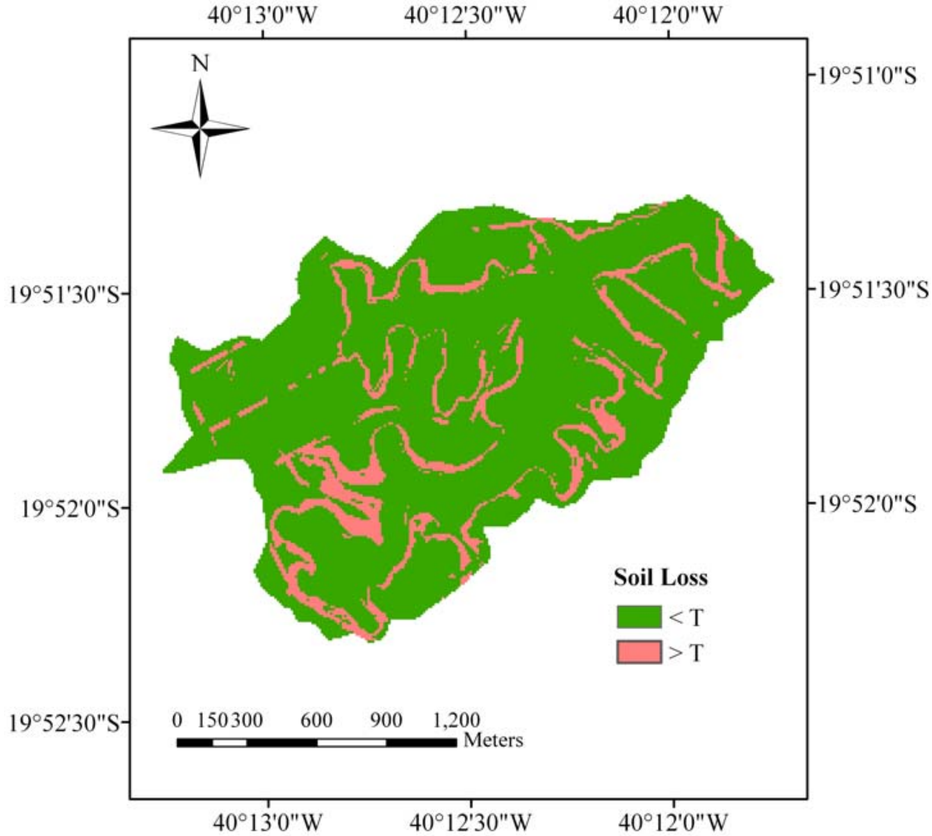

FIGURE 9 Spatial distribution map of soil loss greater and smaller than tolerable rate for the studied watershed.

6 CONCLUSIONS

Implementation of the USLE model in GIS environment was found to be a simple and useful tool for predicting the spatial distribution of soil erosion and identifying critical areas for the studied watershed in the Coastal Plain of Espírito Santo state, Brazil.

The C factor values calculated were 0.297 for eucalyptus and 0.017 for Atlantic Forest, strengthening that these are the first ones obtained directly from field data for Brazil or even South America.

The long-term average annual soil loss for the studied watershed was 6.2 t ha^{-1} yr^{-1}. About 86% of the watershed area presented soil erosion rate less than the tolerable value, indicating generally adequate management for such areas.

In terms of soil loss classes, 55% of the area is classified as extremely slight, with values smaller than 3 t ha^{-1} yr^{-1}. However, about 12% of the watershed area had soil erosion greater than 12 t ha^{-1} yr^{-1} (severe), where conservation practices need to be implemented to control soil erosion.

Although the long-term average annual soil loss for eucalyptus was less than the tolerable value, conservation practices should be employed in order to decrease erosion rate much closer to the Atlantic Forest to reduce offsite effects and degradation. In addition, erosion control practices should be concentrated on the FX soils and roads.

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