WATER EROSION IN SOILS UNDER EUCALYPTUS FOREST AS AFFECTED BY DEVELOPMENT STAGES AND MANAGEMENT SYSTEMS

Erosão hídrica em solos sob floresta de eucalipto em diferentes estádios de desenvolvimento e sistemas de manejo

Anna Hoffmann Oliveira[1], Marx Leandro Naves Silva[1], Nilton Curi[2], Junior Cesar Avanzi[3], Gustavo Klinke Neto[4], Elias Frank Araújo[5]

ABSTRACT

The constant increasing of eucalyptus forest areas in Brazil requires an accurate monitoring of water erosion. The present study aimed to evaluate soil, nutrients and organic carbon losses occasioned by water erosion in eucalyptus planted forests (EPF) at different development stages (2, 3 and 7 years old). Soil erosion sediments were measured and sampled from standard erosion plots installed on Red Argisol-RA (Ultisol) and Haplic Cambisol-HC (Inceptisol). Soil loss decreased as the age of plants increased; at the beginning of plant development, the canopy barely covered the soil surface, exposing the soil to higher erosion at young EPF plantations. Furrow planting system was used in the Red Argisol area and caused higher soil losses (1.1 to 6.2 Mg ha^{-1} $year^{-1}$) as compared to pit planting system that was used in the Cambisol area (1.1 Mg ha^{-1} $year^{-1}$). It is known that Cambisol is less resistant to erosion than Argisol. However, using pit system in this EPF, resulted in lower erosion and, therefore, nutrients and carbon losses than the traditional furrow system used in Argisol. Concerning the soil loss, this work points to the need of improving soil conservation practices to prevent soil erosion at the earlier stages of eucalyptus plantation. The amount of calcium and potassium were higher than magnesium in the soil sediment.The relatively high amount of carbon found in the erosion sediments raises additional concerns about the environmental sustainability and deserves future research.

Index terms: Soil loss, afforestation, conservation system.

RESUMO

O aumento constante das áreas de florestas de eucalipto no Brasil impõe um monitoramento acurado da erosão hídrica. No presente estudo, objetivou-se avaliar as perdas de solo, nutrientes e carbono orgânico ocasionadas pela erosão hídrica em florestas plantadas de eucalipto em diferentes estádios de desenvolvimento (2, 3 e 7 anos). Os sedimentos de erosão foram medidos e amostrados por parcelas-padrão instaladas em Argissolo Vermelho (Ultisol) e Cambissolo Háplico (Inceptisol). As perdas de solo diminuíram com o aumento da idade das plantas; no início do desenvolvimento delas, o dossel apresentava pequena cobertura da superfície, expondo o solo das plantações jovens a maiores taxas de erosão. O sistema de plantio em sulcos utilizado no Argissolo Vermelho ocasionou maiores perdas de solo (1,1 a 6,2 Mg $ha^{-1}ano^{-1}$) quando comparado ao sistema de covas usado no Cambissolo Háplico (1,1 Mg $ha^{-1}ano^{-1}$). É conhecido que os Cambissolos (Inceptisol) é menos resistente à erosão do que os Argissolos (Ultisol). Contudo, a utilização do sistema de covas resultou em menor erosão e, consequentemente, menores perdas de nutrientes e carbono orgânico do que o tradicional sistema de sulcos utilizado no Argissolo. Quanto às perdas de solo, este trabalho salienta a necessidade de melhorar as práticas de conservação do solo para prevenir a erosão hídrica nos primeiros estágios de crescimento do eucalipto. As quantidades de cálcio e potássio no sedimento foram maiores do que as de magnésio. A quantidade relativamente maior de carbono orgânico encontrada nos sedimentos gera preocupações adicionais sobre a sustentabilidade ambiental e merece pesquisas futuras.

Termos para indexação: Perda de solo, reflorestamento, sistema conservacionista.

(Received in november 16, 2012 and approved in february 14, 2013)

INTRODUCTION

Eucalyptus wood plays an important role as a source of renewable energy and other industrial purposes. One of the greatest advantages of eucalyptus crops the possibility of subsequent harvests from the same plantation. Besides, it can grow and produce on marginal or low natural fertility soils (KENYA FOREST SERVICE, 2009). Therefore, eucalyptus crops are sustainable fuelwood sources, thus allowing to prevent deforestation of natural forests, to use higher fertility soils for food production, and to create new job opportunities (CAMPINHOS JUNIOR, 1999). In Brazil, eucalyptus is cultivated on over 4.8 million hectares; 11.2% are in the state of Rio Grande do Sul (ASSOCIAÇÃO BRASILEIRA DE PRODUTORES DE FLORESTAS

[1]Universidade Federal de Lavras/UFLA – Lavras – MG – Brasil
[2]Universidade Federal de Lavras/UFLA – Departamento de Ciência do Solo/DCS – Cx. P. 3037 – 37200-000 – Lavras – MG – Brasil – niltcuri@dcs.ufla.br
[3]Empresa Brasileira de Pesquisa Agropecuária/EMBRAPA – Centro Nacional de Pesquisa em Pesca, Aquicultura e Sistemas Agrícolas/CNPASA – Palmas – TO – Brasil
[4]Vitaramae Consultoria Ambiental Ltda – Ewbank da Câmara – MG – Brasil
[5]CMPC Celulose do Brasil Ltda. – Guaíba – RS – Brazil

PLANTADAS-ABRAF, 2012). In spite of the major advantages mentioned above, the constant increasing of plantation areas also raises concerns about the environmental impact and sustainability of this forestry activity. Site preparation practices prior to planting modify soil properties, affecting most physical, chemical and biological processes. Without an effective soil conservation system, the earlier stages of eucalyptus afforestation can expose the soil to the erosive process, leading to soil degradation and, consequently, low productivity.

Several research have been reported the influence of soil management systems and preparation methods concerning erosion rates.In general terms, the higher the aggregate soil breakdown caused by the soil preparation method or less conservation management systems, greater soil losses occur. Studies also show that better soil protection provides lower soil losses due to less soil exposure to erosive agents. This way, the more the crops develop, reduces soil areas unprotected.

By increasing erosion, some soil preparation methods might reduce organic carbon (OC) in the surface layers of soils (SHUKLA; LAL, 2005). Along with organic carbon, nutrients are also lost (BERTOL et al., 2005), especially in highly weathered soils of the humid tropics where most of the cation exchange capacity (CEC) is due to the soil organic matter. Organic matter oxidation as related to soil erosion is also a real concern. Worldwide, accelerated water erosion is responsible for releasing about 1 gigaton (Gt) of carbon per year to the atmosphere (LAL et al., 2004).

Minimum cultivation and efficient plant cover are known to reduce soil and water losses by erosion. In southern China, soil losses were lower in areas where reforestation was mixed with native species (*Aphanamixis polystachya* (Wall.) R. Parker, *Cassia siamea* Lam., *Albizia odoratissima* (L. f.) Benth., *Aquilaria sinensis* (Lour.) Merr., *Santalum album* L., *Leucaena leucocephala* (Lam.) de Wit cv. Salvador and *Acacia auriculiformis* A. Cunn. ex Benth) compared to *Eucalyptus exserta* F. Muell. plantations (ZHOU et al., 2002). In Thailand, soil losses from eucalyptus plantations (19 Mg ha^{-1} year^{-1}) were intermediate between losses from pastures and cassava crops (8 and 29 Mg ha^{-1} year^{-1}, respectively) (NISKANEN, 1998).

In Brazil, some studies about water erosion in forest plantations indicated soil losses below the tolerance levels. For example, in an eucalyptus reforested watershed, soil losses were below 0.08 Mg ha^{-1} year^{-1} in an Argisol (RANZINI; LIMA, 2002). In another Argisol from the Coastal Plain region, the observed soil losses ranged from 0.68 to 0.98 Mg ha^{-1} year^{-1}, where eucalyptus was planted under minimum cultivation system (MARTINS et al., 2010). These authors registered the following nutrient concentration in the erosion sediment: Ca (0.32-0.56 g kg^{-1}), Mg (0.13-0.22 g kg^{-1}), P (0.006-0.008 g kg^{-1}) and K (0.019-0.029 g kg^{-1}). In a bare condition, an Cambisol lost 205 Mg ha^{-1} year^{-1}, and the nutrient contents in the erosion sediment were: Ca (0.22 g kg^{-1}), Mg (0.06 g kg^{-1}), P (0.003 g kg^{-1}) and K (0.002 g kg^{-1}) (SILVA et al., 2005). In southern Brazil, soil losses in crops are strongly influenced by tillage systems and time of cultivation (BERTOL et al., 2007). Thus, proper measurement of soil, organic carbon and nutrient losses is very important to support selecting and designing management systems for each condition.

Some land uses and management systems might increase soil erosion rates up to intolerable levels. The term soil loss tolerance (T) denotes the maximum rate of soil erosion that can occur and still allows crop productivity to be economically sustainable (RENARD et al., 1997). In this way, agricultural soils can tolerate a certain amount of erosion without adversely impacting on long-term productivity because new soil material is being constantly formed and compensates the losses (BAZZOFFI, 2009). Thus, soil loss tolerance data are useful to evaluate how sustainable would a given eucalyptus management system be.

Considering the current expansion of eucalyptus afforestation in southern Brazil, which occurs mostly on degraded pastures and other marginal areas, knowledge on water erosion under these forests is very important. Therefore, this study aimed to evaluate soil, nutrients and organic carbon losses caused by water erosion in eucalyptus plantations at different development stage, soils and management systems, as compared to native forest (NF) and bare soil (BS) in southern Brazil. According to the Brazilian common knowledge, it is expected that Cambisol (Inceptisol) would present greater soil loss than Argisol (Ultisol), under similar conditions; however, it depends on how the forest would be planted, since a furrow planting system, for example, can cause soil losses by erosion to be greater even in a more resistant soil.

MATERIAL AND METHODS

The studied area and soil description

The studied area is located at the Porto Alegre Metropolitan Region (Figure 1), Rio Grande do Sul state, Brazil (30º06’50" S, 51º19’30" W), at 23 m altitude. According to the Köppen classification, the regional climate is Cfa, subtropical humid, characterized by rain in all the months of the year, with temperatures of the warmest and coldest months above 22° C and 3° C, respectively (ARACRUZ CELULOSE, 2006).

The rainfall erosivity was calculated by Faculdade de Agronomia Eliseu Maciel-Faem (2008). The author used the pluviograph data from 1986 to 2005, located at Porto Alegre weather station, and calculated the EI_{30} according to Wischmeier (1959). For the 18 boundary counties, within the same physiographic zone, pluviometric data were used to calculate the modified Fournier coefficient, considering rainfall higher than 10 mm as being erosive. Thus, the modified Fournier coefficient can be described as:

$$Rc_m(mm) = (p_{>10mm})^2 / P_{>10mm} \quad (1)$$

where Rc_m (mm) is the Fournier modified coefficient; $p_{>10mm}^{\ 2}$ represents the monthly erosive precipitation (mm); and $P_{>10mm}$ is the annual erosive precipitation (mm).

Correlation between Rc_m and EI_{30} was calculated in order to estimate the rainfall erosivity factor for each county. Then, the isoerodent map for the studied region was drawn (Figure 1). All the erosion plots were situated in the same range of rainfall erosivity (4,500 to 5,000 MJ mm ha^{-1} h^{-1} year^{-1}). During the year, the lower rainfall erosivity values range from July to September and the higher ones range from November to March (FAEM, 2008).

The areas chosen for this study represent the main soils used for *Eucalyptus saligna* Sm. cultivation in the Rio Grande do Sul state. These soils were classified

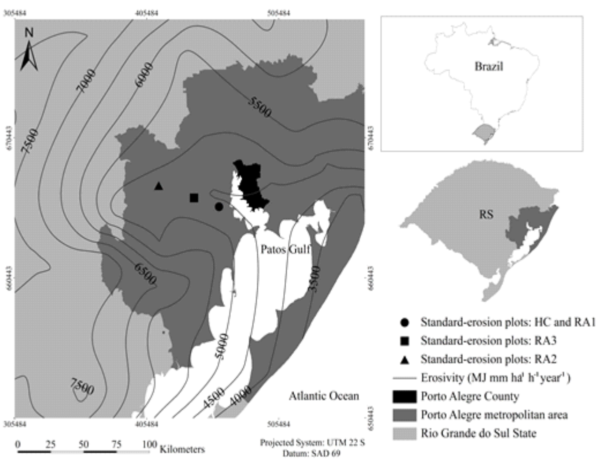

Figure 1 – Erosion plots location at Porto Alegre Metropolitan region, with isoerodent lines adapted from Faem (2008).

according to Brazilian Soil Classification (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA-EMBRAPA, 2006) and USA Soil Taxonomy (SOIL SURVEY STAFF, 1999). The studied soils were three Red Argisols (RAs) (Ultisols), represented by RA1, RA2, and RA3, which are the main soils in the studied area, and an Haplic Cambisol (HC) (Inceptisol), which is considered as a marginal soil and more likely to be affected by the erosion processes. The slope for each soil is: RA1 (8%); RA2 and RA3 (20%); and HC (45%).

Erosion measurements

The soil erosion experiments were carried out in each of the previously mentioned soil classes under *E. saligna* cultivation (EUC) at three development stages (2, 3 and 7 years old), bare soil (BS) and subtropical perennial forest – native forest (NF) (reference). This forest has medium and large size trees, forming a dense and closed canopy, with about 20 thousand species (for example, *Andira* sp., *Aspidosperma spruceanum* Benth. ex Müll.Arg., *Caesalpinia echinata* Lam., *Cariniana legalis* (Mart.) Kuntze, *Cedrela fissilis* Vell., *C. odorata* L., *Dalbergia miscolobium* Benth., *D. nigra* (Vell.) Allemão ex Benth., *D. villosa* (Benth.) Benth., *Hymenaea courbaril* L., *Machaerium* spp., *Ocotea odorifera* (Vell.) Rohwer, *Ocotea catharinensis* Mez., *Handroanthus albus* (Cham.) Mattos, *Handroanthus impetiginosus* (Mart. ex DC.) Mattos, besides Arecaceae, Bromeliaceae and Orchidaceae.

The areas chosen for this study represent the main soils used for *Eucalyptus saligna* Sm. cultivation in the Rio Grande do Sul state. These soils were classified according to Brazilian Soil Classification (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA-EMBRAPA, 2006) and USA Soil Taxonomy (SOIL SURVEY STAFF, 1999). The studied soils were three Red Argisols (RAs) (Ultisols), represented by RA1, RA2, and RA3, which are the main soils in the studied area, and an Haplic Cambisol (HC) (Inceptisol), which is considered as a marginal soil and more likely to be affected by the erosion processes. The slope for each soil is: RA1 (8%); RA2 and RA3 (20%); and HC (45%).

Erosion measurements

The soil erosion experiments were carried out in each of the previously mentioned soil classes under *E. saligna* cultivation (EUC) at three development stages (2, 3 and 7 years old), bare soil (BS) and subtropical perennial forest – native forest (NF) (reference). This forest has medium and large size trees, forming a dense and closed

canopy, with about 20 thousand species (for example, *Andira* sp., *Aspidosperma spruceanum* Benth. ex Müll.Arg., *Caesalpinia echinata* Lam., *Cariniana legalis* (Mart.) Kuntze, *Cedrela fissilis* Vell., *C. odorata* L., *Dalbergia miscolobium* Benth., *D. nigra* (Vell.) Allemão ex Benth., *D. villosa* (Benth.) Benth., *Hymenaea courbaril* L., *Machaerium* spp., *Ocotea odorifera* (Vell.) Rohwer, *Ocotea catharinensis* Mez., *Handroanthus albus* (Cham.) Mattos, *Handroanthus impetiginosus* (Mart. ex DC.) Mattos, besides Arecaceae, Bromeliaceae and Orchidaceae.

The Argisols were subsoiled at 60 cm depth, and planted in a furrow system in a 3 x 3 m spacing among plants. Planting pit system was used in the Cambisol, in order to have a minimum tillage in this area.

One soil erosion plot (4 x 12m) was built in each place, in order to quantify erosion in *E. saligna,* BS and NF conditions. The plots were monitored from November 2006 to October 2007. The plots were located at the steepest slope in each condition, so that the worst erosion scenario could be measured in each case. The boundaries of the erosion plots were 0.40 m wide steel sheets, being 0.20 m buried into the soil in order to isolate surface and subsurface water flows. A runoff collector gutter was placed at the lower end of each plot; water and sediments were driven into a collector system consisting of two sedimentation tanks. The first tank (250 L capacity) had a volumetric container inside it were the sediments were collected for low-volume runoff events, and had a Geib type splitter connected with the second tank; the second tank (500 L capacity) was used to collect the excess runoff from the first tank (GEIB, 1933). The amount of runoff in the second tank represents 1/15 of the excess runoff from the first tank.

Before crop plantation, 3 Mg ha^{-1} of dolomitic limestone was applied in the whole area. This operation is considered essential for eucalyptus cultivation in southern Brazil.

After each rainfall event, water and sediments in the tanks were vigorously and homogeneously shaken; three portions of 250 mL were sampled and transferred to the laboratory for gravimetric processing. These samples were flocculated with an aluminum sulfate saturated solution, the excess water was decanted and the solids were oven-dried at 105°C until constant weight was achieved; erosion rate (Mg ha^{-1}) was then obtained for each event.

Soil analyses

Soils under the native forest were sampled. Three replicates of disturbed and undisturbed samples from 0-10 cm depth were collected in September 2006 and individually analyzed. Undisturbed soil samples were collected using an Uhland sampler, for determining the bulk density (BD), according to Grossman and Reinsch (2002), and the total porosity (TP), according to Flint and Flint (2002a). Disturbed samples were used for chemical characterization, which was accomplished according to Embrapa (1997), including: pH in water 1:2.5), extractable cations (1M KCl extractant for Ca and Mg; 0.05M HCl + 0.05M H_2SO_4 extractant for K and P), and the organic C determinated by potassium dichromate oxidation and ferrous sulfate titration method, according to van Raij and Quaggio (1983). Particle size distribution was determined after dispersion with NaOH, measuring the clay content in suspension by the hydrometer, the sand content by sieving, and the silt content was calculated by the difference (EMBRAPA, 1997). Particle density (PD) was determined according to Flint and Flint (2002b). Soil permeability was measured in the field through a constant rate of water infiltration at 15cm depth, with two loads at 3- and 6-cm water column, using the Guelph permeameter (REYNOLDS; VIEIRA; TOPP, 1992).

Nutrients and carbon organic losses

For measuring organic C and nutrients losses, samples of the erosion sediments collected in the sedimentation tanks, after each rainfall event, were mixed to get an annual composed sample. Available P and K, exchangeable Ca^{2+} and Mg^{2+} (EMBRAPA, 1997), and organic C (van RAIJ; QUAGGIO, 1983) were determined. It was assumed that the sediment removed by erosion and measured from the erosion plots corresponded to the 0.0-0.10m depth of the soils; therefore we compared the chemical composition of the erosion sediment with that of the original soil depth. Nutrients and OC losses by runoff was not counted in the present study.

The enrichment ratio (ER) was calculated as a measure of the selectiveness of the erosion processes. The ER represents the concentration of the components in the eroded material divided by their concentrations in the soil (MASSEY; JACKSON, 1952). Such a ratio might represent an estimative of components carried by the erosion sediment.

Soil loss tolerance (T)

Based on the morphological, physical and chemical properties of the typical soil profiles, the T value was estimated for both soil classes (Cambisol and Argisol), as proposed by Lombardi Neto and Bertoni (1975), Galindo and Margolis (1989), and Bertol and Almeida (2000), which is more appropriated to the Brazilian conditions; soil effective depth for root growing, clay content ratio between the subsurface and the surface horizons, permeability and organic matter content are the parameters considered for estimating the T value. Average T values were compared to the soil losses in order to know if land use and the management systems were appropriate or if they overexposed the soil to degradation.

RESULTS AND DISCUSSION

Soil losses in reference systems

The total soil losses ranged from 0.030 to 63.795 Mg ha^{-1} year^{-1} (Table 1). These values occurred in RA1 under NF and in HC under BS treatments, respectively. Comparing NF and BS systems, the greatest soil loss was found in HC and the lowest in RA1, as a consequence of the higher resistance to erosion of RA1 due to more advanced pedological development stage, under equilibrium conditions (native forest), as opposed to HC which is more susceptible to erosion under these conditions (SILVA et al., 2005; BESKOW et al., 2009), due to the steepness of the relief, the higher silt/clay ratio, and lower soil effective depth of the latter soil (BONO et al., 1996).

For the bare soil condition, where soil exposure imposes higher erosion, soil losses in the HC soil were greater than its corresponding T value (7.3 Mg ha^{-1} year^{-1},table 1). The steepness of slope (45%), the high silt/clay ratio, and predominance of fine and very fine sand fractions in this soil (Table 2), favored the great soil loss. Soil crusting (impermeable surface layer) helped to increase soil erosion, which is peculiar for this soil. Silva et al. (2005) reported soil losses of 205 Mg ha^{-1} year^{-1} for such a soil class. Even under this bare soil condition, only one of the three studied Argisols showed soil loss value greater than its T value (Table 1). Analyzing BS conditionin the Argisols (Table 1), it can be verified that the soil loss for RA1 was more than four times lesser that the soils RA2 and RA3, most likely due to more softened slope in the RA1.

Soil losses in eucalyptus systems of different development stages

Under the eucalyptus systems, greater soil losses were observed for RA soils rather than HC soil (Table 3), even though, the rainfall erosivity for both sites was the same (Figure 1). This scenario was caused by the furrow planting system in RA soils, which is a much less conservationist system than the pitting planting used in the HC soil, discussed thereafter.

Systems with EUC had intermediate soil losses (Table 3), between the bare soil condition and the native forest (Table 1). The NF system had very low erosion rates (Table 1), as a result of the adequate protection by the canopy of the forest and the plant cover (litter) on the soil surface. The native vegetation cover has been recognized as providing high soil protection against water erosion (ROOSE, 1977; KOULI et al., 2009).

In table 3, the influence of the eucalyptus age on soil loss, comparing the same soil and slope classes, can be observed. Comparing RA2 and RA3 (same slope), the younger the plants (EUC 2 years, for both RA2 and RA3) the higher were the soil losses. The 7-year-old plantations had the lowest soil loss among the plant ages, indicating that soil protection increases with increasing the development stage of plant. Like in the NF system, the efficiency of the EUC in protecting the soil against the

Table 1 – Soil losses by water erosion for the soils and reference systems studied.

Soil	Management system	Slope %	Soil loss Mg ha^{-1} year^{-1}	Tolerance Mg ha^{-1} year^{-1}
HC	BS	45	63.795	7.3
	NF	45	0.160	
RA1	BS	8	2.228	12.9
	NF	8	0.030	
RA2	BS	20	10.243	12.9
	NF	20	0.080	
RA3	BS	20	14.637	12.9
	NF	20	0.046	

HC: Haplic Cambisol (Inceptisol); RA: Red Argisol (Ultisol); BS: bare soil (maximum soil loss); NF: native forest (equilibrium system).

Table 2 – Chemical and physical properties of soils under native forest at 0.0 to 0.10 m depth (A horizon).

Soil	pH	P	K	Ca	Mg	OC
	(H_2O)	g kg^{-1}				
HC	4.3	0.0049	0.0987	0.28	0.072	21.0
RA1	5.5	0.0015	0.0437	0.42	0.144	11.0
RA2	5.9	0.0041	0.0617	0.84	0.132	24.0
RA3	5.1	0.0025	0.0620	0.20	0.060	9.0

Soil	BD	PD	TP	Clay	Silt	TS	VCS	CS	MS	FS	VFS	Perm.
	-- kg dm^{-3} --		%	g kg^{-1}								mm h^{-1}
HC	1.20	2.49	52	177	243	580	37	83	93	230	137	10 (s)
RA1	1.58	2.59	39	133	130	737	57	273	217	150	40	21 (s/m)
RA2	1.46	2.43	39	227	213	560	57	183	147	133	40	3 (vs)
RA3	1.73	2.50	31	240	140	620	60	130	200	180	50	50 (s/m)

HC: Haplic Cambisol (Inceptisol); RA: Red Argisol (Ultisol); OC: organic carbon; BD: bulk density; PD: particle density; TP: total porosity; TS: total sand; VCS: very coarse sand; CS: coarse sand; MS: medium sand; FS: fine sand; VFS: very fine sand; Perm: soil permeability (s: slow; s/m: slow/moderate; vs: very slow).

Table 3 – Soil losses under eucalyptus plantations for different soil classes, planting ages and methods.

Soil	Management system	Slope %	Planting method	Soil loss Mg ha^{-1} $year^{-1}$
HC	EUC(3)	45	Planting-hole	1.064
RA1	EUC(3)	8	Opening-row	2.147
RA2	EUC(2)	20	Opening-row	6.249
RA3	EUC(2)	20	Opening-row	2.858
	EUC(7)	20	Opening-row	1.108

HC: Haplic Cambisol (Inceptisol); RA: Red Argisol (Ultisol); EUC (3): three-year-old eucalyptus; EUC (2): two-year-old eucalyptus; EUC (7): seven-year-old eucalyptus.

direct impact of raindrops is a result of the relatively long crop cycle (7 years), with increasing accumulation of stable plant material on the ground, forming the litter. Likewise, the maintenance of crop residues on the soil surface after harvesting the eucalyptus plants increases the protection against erosion.

On the other hand, mechanized harvesting can degrade soil structure; this is considered the main disturbance in planted forests (AJAYI et al., 2009). Harvesting activities are responsible for increasing erosion rates by up to four times (SOUZA; SEIXAS, 2001). In native eucalyptus forests of Australia, the maximum impact on the production of runoff and sediments occurs immediately after road construction and timber harvesting, significantly decreasing after five years (CROKE; HAIRSINE; FOGARTY, 2001). In the present study, the soil loss in the system with EUC (7 years) was about six times lower than that observed for the EUC (2 years) in RA2 soil (Table 3). The largest soil loss observed for EUC (2 years) (Table 3), and also for BS treatment (Table 1) in RA2, compared to RA3 soil is due to the much lower permeability and greater silt/clay ratio of RA2 compared to RA3 soil (Table 2). Thus, plantings implanted right after the harvesting operations will increase erosion as the plants are younger. As the plants grow up, there is a reduction of soil loss and the values tend to approach those observed at the equilibrium condition (NF) (Table 1).

In regard to the different development stages of eucalyptus, there is a difference between the EUC (2 years) and both EUC (3 years) and EUC (7 years), showing a significant decrease of soil loss after the first two years of the crop development (Table 3).

The soil loss in EUC (3 years) for RA1 was lower than EUC (2 years) for RA2 and RA3, which is due to a combination of factors, which are the eucalyptus plantation being slightly old (more developed) in RA1, and also situated in a more gentle relief (Table 2).

The lowest soil loss for EUC observed in HC (Table 3) is due to the lower impact of the pit planting system as compared to the furrow system used in RA. In the same region, Baptista and Levien (2010) found similar results, with soil losses up to 1.57 Mg ha^{-1} year^{-1} in pit-planted eucalyptus in HC area.

This planting system was so effective in preventing higher erosion that even in the Cambisol, which is known as being naturally more susceptible to erosion, the soil losses were relatively close to that found in RA3 for the 7-year-old EUC. These findings are in agreement with practical field observations, where, due to the steeper relief of HC, the harvest operations leave much more residues on its soil surface than in RA, providing additional protection against erosion.

For both soil and eucalyptus ages (Table 3), the soil losses were below the tolerance values (Table 1), indicating that the crop management performed had been adequate regarding the erosion point of view.

Nutrients and organic carbon (OC) losses

Losses of nutrients and OC are proportional to soil losses. The soil under NF (Table 2) was used as a reference for natural fertility in the discussion of the nutrient contents in the erosion sediment. The contents of OC and nutrients in the erosion sediments for each system are shown in table 4. Generally, the sediments are richer in nutrients than the original soils (Table 2), as also noted by some authors (SEGANFREDO; ELTZ; BRUM, 1997; BERTOL et al., 2004; MARTINS et al., 2010). Phosphorus was the nutrient presented in greater contents in sediments as compared to the original soil. Phosphate has strong interaction with clay particles, which are the main size fraction removed by the water erosion. This increased P content in the sediments, as compared to the original soil, can be due to redox reactions (SILVA et al., 2005) and increased pH (Table 2 versus table 4) in the runoff collecting tanks, that can increase P solubility and can also release P from water soluble organic carbon.

For all the situations in this study, there was more Ca than Mg in the sediments, due to the higher Ca concentration in the original soils (Table 2), as also shown by Silva et al. (2005). There was also more K than P in the sediments, because K is effectively more mobile in the soil and less concentrated in the upper layer than P, under the conservationist system, as indicated by Schick et al. (2000) and Bertol et al. (2004).

Organic carbon is one of the first components of the soil to be carried away, and bound to it may be K and P (SEGANFREDO; ELTZ; BRUM, 1997). For eucalyptus systems, the highest contents of Ca, Mg and OC in the erosion sediment were registered for EUC (3 years) in RA1 (Table 4).

The highest concentration of OC in the upper layer of the soils, and the consequent low density of the soil material in this layer, account for the higher contents of OC in the sediment as compared to the topsoil from where it was removed, as noted by Schick et al. (2000). Generally, the lowest concentration of OC in the sediments collected

Table 4 – Contents of nutrients and organic carbon (OC) in the erosion sediment.

Soil	Management system	pH	P	K	Ca	Mg	OC
			------------------------- g kg^{-1} -------------------------				
HC	BS	6.1	0.0120	0.0423	0.3000	0.0700	15.0
	EUC (3)	5.8	0.0087	0.0958	0.5667	0.1200	36.5
RA1	BS	6.3	0.0046	0.0158	0.1519	0.0304	9.0
	EUC (3)	6.3	0.0049	0.0601	1.1392	0.2051	53.3
RA2	BS	6.2	0.0074	0.0573	0.5753	0.1151	18.0
	EUC (2)	6.2	0.0049	0.0666	0.5205	0.1151	23.0
RA3	BS	6.2	0.0447	0.0247	0.2312	0.0555	9.0
	EUC (2)	6.4	0.0062	0.0384	0.2081	0.0486	10.0
	EUC (7)	6.5	0.0043	0.0272	0.1387	0.0139	4.6

HC: Haplic Cambisol (Inceptisol); RA: Red Argisol (Ultisol); EUC (2): two-year-old eucalyptus; EUC (3): three-year-old eucalyptus; EUC (7): seven-year-old eucalyptus; BS: bare soil.

from erosion plots of BS (Table 4) is due to the absence of vegetation (primary source of organic carbon in the soil); the very low OC concentration in RA3 under EUC (7 years) is unexpected and deserves further investigation. Concentrations of Ca, Mg and P in the sediments are above those observed in other studies for eucalyptus systems in Brazil (OLIVEIRA et al., 2010; MARTINS et al., 2010), but they are in agreement with the higher contents of these elements in the upper layer of these soils compared to those from the literature. The Red Latosols (Oxisols) (between 6 and 10 g kg^{-1}se observed for Red-Yellow Latosols and Red Latosols (Oxisols) (Ultisol), with values around 37 g kg^{-1}IRA et al., 2010), and similar to those found for Yellow Argisol (Ultisol), with values around 37 g kg^{-1} (MARTINS et al., 2010).

The highest sediment enrichment rate (ER) was observed for P in RA3 under the BS treatment (Table 5), in agreement with the data from the literature, where such behavior is explained by the erosion selective nature that takes more of the clay fraction where P is adsorbed (SEGANFREDO; ELTZ; BRUM, 1997). Among the soil classes, the highest values of ER were observed in RA1 under EUC (3 years), except for P. In general, systems with 2–3-year-old plantations had ER values greater than 1.0. The ER for EUC (7 years) decreased, when compared to younger eucalyptus systems, again except for P.

The EUC (7 years) system had the lowest nutrient contents in sediment, while the greatest contents were found in the sediments of HC under BS treatment. Nutrient contents tend to be greater in the sediments of eucalyptus systems than in the BS (Table 6), due to the lack of nutrients bio-cycling and the occurrence of crusting observed in the latter condition in the field (RESENDE; CURI; LANI, 1999).

Table 5 – Sediment enrichment rate (ER)* in relation to organic carbon (OC) and nutrients for the studied soils and treatments.

Soil	Management system	P	K	Ca	Mg	OC
HC	BS	2.4	0.4	1.1	1.0	0.7
	EUC (3)	1.8	1.0	2.0	1.7	1.7
RA1	BS	3.1	0.4	0.4	0.2	0.8
	EUC (3)	3.3	1.4	2.7	1.4	4.8
RA2	BS	1.8	0.9	0.7	0.9	0.8
	EUC (2)	1.2	1.1	0.6	0.9	1.0
RA3	BS	17.9	0.4	1.2	0.9	1.0
	EUC (2)	2.5	0.6	1.0	0.8	1.1
	EUC (7)	1.7	0.4	0.7	0.2	0.5

HC: Haplic Cambisol (Inceptisol); RA: Red Argisol (Ultisol); EUC (2): two-year-old eucalyptus; EUC (3): three-year-old eucalyptus; EUC (7): seven-year-old eucalyptus; BS: bare soil; OC: organic carbon.* ER = values in Table 4 / values in Table 2.

Table 6 – Soil losses and nutrients and organic carbon (OC) contents in the erosion sediment.

Soil	Management system	Soil loss Mg ha^{-1} year^{-1}	pH	P	K	Ca	Mg	OC
				-------------------- g ha^{-1} year^{-1} --------------------------				
HC	BS	63.795	6.1	765	2,695	19,138	4,466	956,925
	EUC (3)	1.064	5.8	9	102	603	128	38,836
RA1	BS	2.228	6.3	10	35	338	68	20,052
	EUC (3)	2.147	6.3	10	125	2,446	440	114,435
RA2	BS	10.243	6.2	75	587	5,893	1,179	184,374
	EUC (2)	6.249	6.2	30	416	3,253	719	143,727
RA3	BS	14.637	6.2	654	361	3,384	812	131,733
	EUC (2)	2.858	6.4	18	110	595	139	28,580
	EUC (7)	1.108	6.5	5	30	154	15	5,097

HC: Haplic Cambisol (Inceptisol); RA: Red Argisol (Ultisol); EUC (2): two-year-old eucalyptus; EUC (3): three-year-old eucalyptus; EUC (7): seven-year-old eucalyptus; BS: bare soil; OC: organic carbon.

Calcium was the nutrient that showed the greatest values in the sediment in all studied systems, ranging from 153 to 3,252 g ha^{-1} for eucalyptus systems (Table 6). The highest Ca contents in sediment were due to the higher concentration of this nutrient in the previously limed soil (3 Mg ha^{-1} of dolomitic limestone) which was applied in the whole area prior to crop plantation; this operation is fundamental for eucalyptus nutrition in subtropical Brazilian conditions.

Organic carbon was highly found in the sediments, especially for HC under BS tratment (957 kg ha^{-1}). In the 2–3-year-old plantations, the OC values ranged from 29 to 144kg ha^{-1} (Table 6). These values are greater than those observed in the literature for eucalyptus plantations in Brazil (OLIVEIRA et al., 2010; MARTINS et al., 2010), which confirms the need for improving conservation practices that reduce erosion, maintaining and/or increasing this organic fraction in the soil, since it is important in enhancing soil structure, moisture retention and CEC, among other important soil properties. In the RA2, the EUC (2 years) was the system with greater amounts of nutrients, especially Ca, which was the nutrient mostly lost in all the eucalyptus systems (Table 6). The amounts of nutrients observed for EUC (7 years) were the lowest among the eucalyptus systems, which are due to the most protective condition of the crop at this age.

CONCLUSIONS

The Cambisol was more susceptible to erosion, either under the bare soil or the native forest. However, the pit planting system used in this soil area prevented higher losses of soil, nutrients and organic carbon. There is a reduction in soil losses as the development stage of eucalyptus forest increases after the first two years, with soil loss rates close to those observed for native forest, indicating a tendency to achieve sustainability in terms of water erosion. The plantings installed after the harvest operations will favor erosion as the eucalyptus trees are younger.

This paper also showed that soil losses in eucalyptus systems were much lower than the tolerable values, indicating the adequacy of the adopted minimum cultivation regarding water erosion. The results suggest the need for additional care in the management system for the Argisol, mainly related to soil preparation for planting.

There were higher losses of K as compared to P in the erosion sediment; Ca was the nutrient that showed the greatest values in the erosion sediment in all the management systems. The highest concentration of OC in the original soil upper layer, along with its low density, accounted for the greater losses of OC in these management systems.

ACKNOWLEDGEMENTS

We thank the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) for the scholarship given to the first author.

REFERENCES

AJAYI, A.E. et al. Strength attributes and compaction susceptibility of Brazilian Latosols. **Soil and Tillage Research**, Amsterdam, v.105, n.1, p.122-127, set, 2009.

ARACRUZ CELULOSE. **Resumo público do plano de manejo florestal da Aracruz Celulose**: unidade Guaíba. Aracruz Celulose, Guaíba, 2006, 25p.

ASSOCIAÇÃO BRASILEIRA DE PRODUTORES DE FLORESTAS PLANTADAS-ABRAF. **Anuário estatístico ABRAF**: ano base 2011. ABRAF, Brasília, 2012, 150p.

BAPTISTA, J.; LEVIEN, R. Métodos de preparo de solo e sua influência na erosão hídrica e no acúmulo de biomassa da parte aérea de *Eucaliptus saligna* em um Cambissolo Háplico da Depressão Central do RS. **Revista Árvore**, Viçosa, v.34, n.4, p.567-575, jul./ago, 2010.

BAZZOFFI, P. Soil erosion tolerance and water runoff control: minimum environmental standards. **Regional Environmental Change**, Berlim, v.9, n.3, p.169-179, set, 2009.

BERTOL, I. et al. Aspectos financeiros relacionados às perdas de nutrientes por erosão hídrica em diferentes sistemas de manejo do solo. **Revista Brasileira de Ciência do Solo,** Viçosa, v.31, n.1, p.133-142, jan./fev, 2007.

BERTOL, I. et al. Soil tillage, water erosion, and calcium, magnesium, and organic carbon losses. **Scientia Agricola,** Piracicaba, v.62, n.6, p.578-584, nov./dec, 2005.

BERTOL, I. et al. Erosão hídrica em um Nitossolo Háplico submetido a diferentes sistemas de manejo sob chuva simulada: II – perdas de nutrientes e carbono orgânico. **Revista Brasileira de Ciência do Solo,** Viçosa, v.28, n.6, p.1045-1054, nov./dez, 2004.

BERTOL, I; ALMEIDA, J.A. Tolerância de perda de solo por erosão para os principais solos do estado de Santa Catarina. **Revista Brasileira de Ciência do Solo**, Viçosa, v.24, n.3, p. 657-668, jul./set, 2000.

BESKOW, S. et al. Soil erosion prediction in the Grande River Basin, Brazil, using distributed modeling. **Catena,** Amsterdam,v.79, n.1, p.49-59, oct, 2009.

BONO, J.A.M. et al. Cobertura vegetal e perdas de solo por erosão em diversos sistemas de melhoramento de pastagens nativas. **Pasturas Tropicales,** Cali, v.18, n.2, p.2-8, ago, 1996.

CAMPINHOS JUNIOR, E. Sustainable plantations of high-yield shape eucalyptus trees for production of fiber: the Aracruz case. **New Forests,** Amsterdam, v.17, n.1-3, p.129-143, jan, 1999.

CROKE, J.; HAIRSINE, P.; FOGARTY, P. Soil recovery from track construction and harvesting changes in surface infiltration, erosion and delivery rates with time. **Forest Ecology and Management**, Amsterdam,v.143, n.1-3, p.3-12, apr, 2001.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. **Manual de métodos de análises de solos.** 2. ed. Rio de Janeiro: Ministério da Agricultura, 1997, 212p.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. **Sistema Brasileiro de classificação de solos.** 2. ed. Rio de Janeiro: Embrapa Solos, 2006, 306p.

FACULDADE DE AGRONOMIA ELISEU MACIEL-FAEM-UFPEL. **El Niño, La Niña e a erosividade das chuvas no Estado do Rio Grande do Sul.** Pelotas, Brazil, 2008. Available in: <http://faem.ufpel.edu.br/erosividade> Accessed on Mar. 07, 2013.

FLINT, A.F.; FLINT, L.E. Particle density. In: DANE, J.H.; TOPP, G.C. (eds). **Methods of soil analysis:** physical methods**,** v. 4. Madison: American Society of Agronomy, 2002b, p.229-240.

FLINT, L.E.; FLINT, A.F. Porosity. In: DANE, J.H.; TOPP, G.C. (eds). **Methods of soil analysis: physical methods,** v.4. Madison: American Society of Agronomy, 2002a, p.241-254.

GALINDO, I.C.; MARGOLIS, E. Tolerância de perdas por erosão para os solos do Estado de Pernambuco. **Revista Brasileira de Ciência do Solo,** Campinas, v.13, p.95-100, jan./abr, 1989.

GEIB, H.V. A new type of installation for measuring soil and water losses from control plots. **Journal of the American Society of Agronomy,** Washington, v.25, n.7, p.429-440, jul, 1933.

GROSSMAN, R.B.; REINSCH, T.G. Bulk density and linear extensibility. In: DANE, J.H.; TOPP, G.C. (eds). **Methods of soil analysis: physical methods,** v.4. Madison: American Society of Agronomy, 2002, p.201–228.

KENYA FOREST SERVICE. **A Guide to On-Farm Eucalyptus Growing in Kenya**: A mature Eucalyptus plantation in Kericho District, Kenya. Kenya Forest Service, 2009, 36p.

KOULI, M.; SOUPIOS, P.; VALLIANATOS, F. Soil erosion prediction using the Revised Universal Soil Loss Equation (RUSLE) in a GIS framework, Chania, Northwestern Crete, Greece. **Environmental Geology,** Berlin, v.57, n.3, p.483-497, ago, 2009.

LAL, R. et al. Managing soil carbon. **Science**, Washington, v.304, n.5669, p.393, apr, 2004.

LOMBARDI NETO, F.; BERTONI, J. **Tolerância de perdas de terra para solos do estado de São Paulo.** Campinas: IAC, Boletim Técnico n.28, 1975, 12p.

MARTINS, S.G. et al. Perdas de solo, água, nutrientes e carbono orgânico em cultivo de eucalipto nos Tabuleiros Costeiros, ES. **Scientia Forestalis,** Piracicaba, v.38, n.87, p.517-526, set, 2010.

MASSEY, H.F.; JACKSON, M.L. Selective erosion of soil fertility constituents. **Soil Science Society of America Journal,** Madison, v.16, n.4, p.353-356, oct, 1952.

NISKANEN, A. Value of external environmental impacts of reforestation in Thailand. **Ecological Economics,** Amsterdam, v.26, n.3, p.287-297, set, 1998.

OLIVEIRA, F.P. et al. Avaliação de perdas de solo em estradas florestais não pavimentadas no Vale do Rio Doce, Minas Gerais. **Scientia Forestalis**, Piracicaba, v.38, p.331-339, set, 2010.

RANZINI, M.; LIMA, W.P. Comportamento hidrológico, balanço de nutrientes e perdas de solo em duas microbacias reflorestadas com *Eucalyptus* no Valei do Paraíba, SP. **Scientia Forestalis**, Piracicaba, v.61, n.144-159, jun, 2002.

RENARD, K.G. et al. **Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).** U.S. Department of Agriculture, Oxford, 1997, 404p.

RESENDE, M.; CURI, N.; LANI, J.L. Tropical soils: implications on sustainable development. In: FORMOSO, M.L.L. (org). **Workshop on Tropical soils**. Rio de Janeiro: Academia Brasileira de Ciências, p.157-170, 1999.

REYNOLDS, W.D.; VIEIRA, S.R.; TOPP, G.C. An assessment of the single-head analyses for the constant head well permeameter. **Canadian Journal of Soil Science,** Ottawa, v.72, n.4, p.489-501, nov, 1992.

ROOSE, E.I. Application of the universal soil loss equation of Wischmeier and Smith in West Africa. In: GREENLAND, D.J.; LAL, R. **Soil conservation and management in the humid tropics.** Chichester: John Wiley and Sons, p.177-187, 1977.

SCHICK, J. et al. Erosão hídrica em Cambissolo Húmico alumínico submetido a diferentes sistemas de preparo e cultivo do solo: II – perdas de nutrientes e carbono orgânico. **Revista Brasileira de Ciência do Solo,** Campinas, v.24, n2. p.437-447,abr./jun, 2000.

SEGANFREDO, M.L.; ELTZ, F.L.F.; BRUM, A.L.R. Perdas de solo, água e nutrientes por erosão em diferentes sistemas de culturas em plantio direto. **Revista Brasileira de Ciência do Solo,** Campinas, v.21, n.2, p.287-291, abr./jun, 1997.

SHUKLA, M.K.; LAL, R. Erosional effects on soil organic carbon stock in an on-farm study on Alfisols in west central Ohio. **Soil and Tillage Research,** Amsterdam, v.81, n.2, p.173-181, apr, 2005.

SILVA, A.M. et al. Perdas de solo, água, nutrientes e carbono orgânico em Cambissolo e Latossolo sob chuva natural. **Pesquisa Agropecuária Brasileira,** Brasília, v.40, n.12, p.1223-1230, dez, 2005.

SOIL SURVEY STAFF. **Soil Taxonomy: a basic system of soil classification for making and interpreting soil surveys.** 2. ed. Washington: U.S. Department of Agriculture, 1999, 169p.

SOUZA, C.R.; SEIXAS, F. Avaliação de diferentes coberturas do solo no controle da erosão em taludes de estradas florestais. **Scientia Forestalis,** Piracicaba, v.60, p.45-51, dez, 2001.

VAN RAIJ, B.; QUAGGIO, J.A. **Métodos de análise de solo para fins de fertilidade**. Campinas: IAC, Boletim Técnico n.81, 1983, 31p.

WISCHMEIER, W.H. A rainfall erosion index for a universal soil-loss equation. **Soil Science Society of America Proceedings**, Madison, v.23, p.246-249, 1959.

ZHOU, G.Y. et al. Hydrological impacts of reafforestation with eucalyptus and indigenous species: a case study in southern China. **Forest Ecology and Management,** Amsterdam, v.167, n.1/3, p.209-222, aug, 2002.