AUGUSTO MIGUEL NASCIMENTO LIMA

FRAÇÕES DA MATÉRIA ORGÂNICA DO SOLO SOB POVOAMENTOS DE EUCALIPTO NO BRASIL E SIMULAÇÃO DE SUA DINÂMICA COM MODELOS PROCESSUAIS

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-graduação em Solos e Nutrição de Plantas, para obtenção do título de *Doctor Scientiae*.

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APROVADA: 18 de abril de 2008.

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A minha mãe, Maria Augusta
Ao meu padrasto, Apolônio
Aos meus irmãos, Elson, Charles, Raimundo e Cristiane
Ao meu tio, João
A minha avó Guiomar, e demais familiares....

....à quem dedico este trabalho com muito carinho!!!

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BIOGRAFIA

AUGUSTO MIGUEL NASCIMENTO LIMA, filho de José Raimundo Ribeiro Lima e Maria Augusta Nascimento da Silva, nasceu em Entre Rios-BA, em 27 de Junho de 1978. Em Entre Rios-BA, estudou no Colégio Cenecista Prof. Isabel Chaves de Almeida (CNEC), onde cursou o ensino fundamental; Em Catu-BA, cursou o ensino médio pela Escola Agrotécnica Federal de Catu-BA. Graduou em Agronomia em setembro de 2002 pela Universidade Federal de Viçosa. Realizou o Mestrado em Solos e Nutrição de Plantas pela Universidade Federal de Viçosa no período de setembro/2002 – fevereiro/2004. Nesta mesma Universidade, realizou o curso de Doutorado em Solos e Nutrição de Plantas (2004 – 2008).

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RESUMO

LIMA, Augusto Miguel Nascimento, D Sc., Universidade Federal de Viçosa, abril de 2008. **Frações da matéria orgânica do solo sob povoamentos de eucalipto no Brasil e simulação de sua dinâmica com modelos processuais**. Orientador: Ivo Ribeiro da Silva. Co-Orientadores: Eduardo de Sá Mendonça e Nairam Félix de Barros.

O seqüestro de C no solo constitui uma importante alternativa para minimizar o aumento de CO_2 da atmosfera. O reflorestamento com eucalipto em áreas anteriormente ocupadas por cultivos agrícolas e pastagens mal manejadas no Brasil é umas das estratégias recomendadas para mitigar a emissão de gases do efeito estufa para a atmosfera. Apesar de práticas de manejo adequadas para obtenção de produtividade satisfatória de madeira ser utilizadas nos plantios de eucalipto, pouco se sabe sobre o impacto dessas práticas agrícolas nos estoques de matéria orgânica do solo (MOS) nas principais regiões reflorestadas do Brasil. Assim, os objetivos deste estudo foram: i) avaliar o impacto do cultivo do eucalipto nos estoques de C e N de frações da MOS, até a profundidade de 1 m, em solos de diferentes texturas em relação aqueles sob mata nativa, pastagem e cana-de-açúcar no estado de São Paulo; ii) avaliar a dinâmica da MOS utilizando o modelo Century para simular os estoques de C orgânico do solo (COS) em duas cronosequências de plantações de eucalipto e em diferentes ordens de solos, assim como, avaliar o impacto da remoção da casca do eucalipto da área de plantio após a colheita nos estoques de COS em Minas Gerais e, iii) calibrar o modelo FullCAM para simular a dinâmica da MOS em plantações de eucalipto, pastagem e mata nativa localizadas nas principais regiões reflorestadas do Brasil (São Paulo – SP, Espírito Santo - ES, Minas Gerais - MG e Bahia - BA). Para responder ao primeiro objetivo, foram selecionadas plantações comerciais de eucalipto localizadas adjacentes à áreas de mata nativa (Floresta Atlântica e Cerrado), pastagem e cana-de-açúcar em dois grandes grupos de solos: argiloso (± 66% de argila) e arenoso (± 9% de argila). Assim, para cada solo sob distintos usos foram determinados os estoques de C orgânico total (COT) e N total (NT), C e N nas substâncias húmicas (SH), na fração leve (FL) e na biomassa microbiana (BM) nas camadas de 0-10, 10-20, 20-40, 40-60 e 60-100 cm. Os resultados indicaram que os solos argilosos, em média, apresentaram maiores estoques de C e N nas frações da MOS em relação aos solos arenosos. Os solos argilosos sob eucalipto apresentaram maiores estoques de COT (146,6 t ha^{-1}), C nas SH (139,1 t ha^{-1}) e na FL (6,9 t ha^{-1}) que o solo sob pastagem (COT = 123,4 t ha^{-1}, C nas SH = 109,9 t ha^{-1}, e na FL = 3,4 t ha^{-1}) e cana-de-açúcar (COT = 127,1 t ha^{-1}, SH = 119,9 t ha^{-1}, FL = 3,7 t ha^{-1}) até a camada de 100 cm. Não houve diferenças nos estoques de NT entre eucalipto, pastagem e cana-de-açúcar no grupo de solos argilosos e arenosos. Todos os usos do solo apresentaram menor estoque de N nas frações húmicas em relação ao solo sob mata nativa, na camada de 0-60 cm, no grupo dos solos argilosos. O solo sob eucalipto apresentou maior estoque de N na FL (0,16 t ha^{-1}) que o solo sob pastagem (0,08 t ha^{-1}) e cana-de-açúcar (0,10 t ha^{-1}) até a camada de 60 cm. Os solos arenosos sob eucalipto, pastagem e cana-de-açúcar apresentaram menores estoques de C nas SH, fração ácidos fúlvicos (FAF) e fração ácidos húmicos (FAH) em relação ao solo sob floresta nativa até a camada de 100 cm. Um comportamento similar foi observado para os estoques de C e N da FL em todas as camadas do solo estudadas. Para atingir o segundo objetivo, foram avaliados solos de duas cronosequências, formadas por áreas que têm sido cultivadas com eucalipto durante 4,0; 13,0; 22,0; 32,0 e 34,0 anos em Belo Oriente (BO) e 8,0; 19,0 e 33,0 em Virginópolis (VG). Os resultados indicaram que os estoques de C simulados pelo modelo Century decresceram após 37 anos de pastagens mal manejadas e que foram implantadas em áreas anteriormente ocupadas por mata nativa em BO e VG. O estabelecimento do eucalipto em áreas de pastagens resultou no acréscimo de 0,28 e 0,42 t ha^{-1} ano^{-1} de C em BO e VG, respectivamente. Os estoques de C nas distintas ordens de solos foram adequadamente estimados pelo modelo Century (RMSE = 20,9; EF = 0,29), apesar de resultado oposto ter sido obtido com o uso do teste de identidade de métodos analíticos proposto por Leite & Oliveira (2000)**.** A manutenção da casca do eucalipto após a colheita resulta no aumento do seqüestro de C no solo. Para atingir o terceiro objetivo, comparou-se os estoques medidos de COT do solo, C nas SH, na FL e na BM com os estoques de C nessas frações simulados pelo modelo FullCAM. Os resultados indicaram que no ES e BA os estoques de COT simulados decresceram 0,37 e 0,30 t ha^{-1} ano^{-1}, respectivamente, após o estabelecimento do eucalipto em áreas anteriormente ocupadas por pastagem bem manejada. Similar comportamento foi observado em SP, onde os estoques simulados de COT, C nas SH e na FL decresceram após substituição da floresta nativa por eucalipto. Por outro lado, após 33 anos de cultivo com eucalipto os estoques de COT aumentaram 5,6% em relação ao Cerrado no Vale do Jequitinhonha – MG. O modelo FullCAM descreveu satisfatoriamente os estoques de COT (EF=0,74) e SH (EF= 0,65). Assim, o modelo FullCAM constitui uma ferramenta apropriada para simular mudanças no C do solo após o aflorestamento com eucalipto.

ABSTRACT

LIMA, Augusto Miguel Nascimento, D Sc., Universidade Federal de Viçosa, April, 2008. **Soil organic matter fractions under eucalypt plantations in Brazil and simulation of their dynamics with mecanistic models**. Adviser: Ivo Ribeiro da Silva. Co-Advisers: Eduardo de Sá Mendonça and Nairam Félix de Barros.

Soil C sequestration is one of the most important alternatives to minimize CO_2 emissions to the atmosphere. Eucalypt afforestation of poorly managed pastures and agriculture lands in Brazil is among the most attractive strategies to mitigate greenhouse gas emissions to the atmosphere. Despite the utilization of adequate management practices to obtain high wood productivity, information on their impact on soil organic matter (SOM) stocks in areas afforested with eucalypt in Brazil is scarce. Thus, the aims of this study were: i) to evaluate the impact of short-rotation eucalypt cultivation on C and N stocks of SOM fractions, up to 1 m deep, in soils with contrasting textures in comparison to those under native forest, pasture and sugar cane in the São Paulo State, Brazil; ii) to evaluate SOM dynamics utilizing the Century model to simulate SOC stocks in two eucalypt chronosequences, and for different soils orders. It was also simulated the impact of eucalypt debarking on site during the harvest on SOC stocks in the Minas Gerais State, Brazil and, iii) to calibrate the FullCAM model to simulate the SOM dynamics in short-rotation eucalypt plantations, pasture and native forest located in four eucalypt growing states of Brazil (São Paulo – SP, Espírito Santo – ES, Minas Gerais – MG, and Bahia – BA). To accomplish the first aim, we selected commercial eucalypt plantations located nearby native forest (Atlantic forest or Cerrado), pasture and sugar cane in two soil groups: clayey (± 66% of clay) and sandy (± 9% of clay). So, for these soil it was determined the total organic C (TOC)and total N (TN) stocks, and C in the humic substances (HS), in the light fraction (LF), and in the microbial biomass (MB) in the 0-10, 10-20, 20-40, 40-60 and 60-100 cm layers. The results showed that the clayey soils, in general, have higher C and N stocks in SOM fractions than the sandy soils. The eucalypt soil has a larger TOC stock (146.6 t ha^{-1}), and stocks of C in the humic substances (HS) (139.1 t ha^{-1}), and in the LF (6.9 t ha^{-1}) than those under pasture pasture (TOC = 123.4 t ha^{-1}, HS = 109.9 t ha^{-1}, LF = 3.4 t ha^{-1}) and sugar cane soil (TOC = 127.1 t ha^{-1}, HS = 119.9 t ha^{-1}, LF = 3.7 t ha^{-1}), up to 100 cm deep, in the clayey soils group. There were no differences in the TN stocks among eucalypt, pasture and sugar cane soils in both clayey and sandy soil groups. All soil uses led to lower N stocks in humic fractions as compared to the native forest soil up to the 60 cm depth. The eucalypt soil had higher N stock in the LF (0.16 t ha^{-1}) than the pasture (0.08 t ha^{-1}) and sugar cane (0.10 t ha^{-1}) soil, up to 60 cm deep. In the sandy soils group, the eucalypt, the pasture and the sugar cane soils had lower C stocks in HS, fulvic acid fraction (FAF), and humic acid fraction (HAF) than the native forest soil up to 100 cm deep. A similar pattern was observed for the C and N stocks in the LF throughout the soil profile. To undertake our second aim, two chronosequences were constructed by selecting areas under short-rotation eucalypt cultivation for 4.0, 13.0, 22.0, 32.0 and 34.0 years in Belo Oriente (BO) and 8.0, 19.0 and 33.0 in Virginópolis (VG). The results indicated that the C stocks simulated by the Century model decreased after 37 years of poor pasture management in areas originaly covered by native forest in the BO and VG regions. The substitution of poorly managed pastures by short-rotation eucalypt in the early 70`s led to an average increase of 0.28 and 0.42 t ha^{-1} year^{-1} of C in BO and VG, respectively. The measured soil C stocks under eucalypt cultivated in distinct soil orders in independent regions with distinct edapho-climatic conditions closely resemble the values estimated by the Century model (root mean square error - RMSE = 20.9; model efficiency – EF = 0.29) despite the opposite result obtained with the statistical procedure to test the identity of analytical methods (Leite and Oliveira, 2000). Using the calibrated model it was found that the maintenance of eucalypt bark on site after harvesting resulted in an increase in C sequestration by the soil. The third aim was accomplished by comparing the observed TOC stocks, and C stocks in the HS, the LF and the MB with the C stocks in these fractions simulated by the FullCAM. The results showed that in ES and BA, the simulated TOC stocks decreased 0.37 and 0.30 t ha^{-1} year^{-1}, respectively, after the short-rotation eucalyptus establishment in formerly well managed pastures. A similar pattern was observed in SP where the simulated TOC stocks, and stocks of C in HS and in LF decreased after replacement of native forest by eucalypt. On the other hand, after 33 years of eucalypt cultivation the TOC stocks increased 5.6 % in relation to Cerrado in the Jequitinhonha Valley – MG. The FullCAM model satisfactorily described the TOC stocks (EF=0.74) and HS (EF= 0.65). So, the FullCAM model constitutes an appropriate tool to simulate the changes in soil C after eucalypt afforestation.

GENERAL INTRODUCTION

The forestry plantations in areas previously occupied by poor managed agricultural and pasture is admitted a potential tentative in order to decrease the gases emission to the atmosphere where it is inserted in the Kyoto protocol. Additionally, the Brazilian forestry sector drove just in 2005 about US$ 27.8 billion (SBS, 2007) and employed about 4.6 million of people emphasizing also its economical and social importance (CIB, 2008).

In Brasil, the majority of forestry area is constituted mostly by eucalypt where it occupies more than 3.7 million of ha (ABRAFLOR, 2007). In spite of the fact that intensive management practices applied to short-rotation eucalypt plantations may guarantee rapid growth and high economic returns, little is known about the eucalypt afforestation influence on soil organic carbon fractions dynamics and its sustainability (Ashagrie et al., 2005).

The global soil carbon pool is the second largest C pool in the earth if considered the fossil fuel reserve (Lal, 2004). This highlight importance of soil organic matter (SOM) in the C cycling, because little changes in soil C stocks may have a significant effect upon greenhouse gas emissions. In perennial cultures, such as forestry, the SOM pools are narrowly related with long term production sustainability due to soil quality (Mendham et al., 2004). Recently it was found that SOM content is the soil characteristic that better correlated with the eucalypt productivity (Menezes, 2005). The SOM is very complex constituted of some fractions (compartments) with residency time varying of days, months (microbial biomass) until millions of years (humic substances). In the majority of soils, the more recalcitrant forms are domain in quantitative term and, therefore, constituting in a compartment with important function in carbon sequester in soil (Stevenson, 1994).

Changes in soil C following afforestation are generally slow and often small compared with the initial amount (Paul et al. 2002). So, the utilization of simulation models constitutes a good device to enhance our understanding about theses factors and, hence, establishing of management more adequate practices to litter and soil organic matter maintenance (Izaurralde et al., 2006). Despite the potential application of models, however, data on SOM dynamics in many Brazilian regions under short-rotation eucalypt plantations are rare and there is no systematic study to evaluate the medium and long term soil C cycling and the C balance in these forests.

Thus, the aims of this study were: i) to evaluate the eucalypt impact on C and N stocks of SOM fractions up to 1 m deep in soils with contrasting texture in comparison to native forest, pasture and sugar cane in the São Paulo State, ii) to evaluate the SOM dynamics utilizing the Century model to simulate SOC stocks in two eucalypt chronosequences and different soils orders as well as to evaluate the impact of eucalypt bark removal from site after harvesting on SOC stocks in the 0-20 cm layer in the Minas Gerais State and, iii) to calibrate the FullCAM model to simulate the SOM dynamics in eucalypt plantations, pasture and native forest located in the main afforested regions of Brazil (São Paulo – SP, Espírito Santo – ES, Minas Gerais – MG, and Bahia – BA).

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CHAPTER I

CHANGES IN ORGANIC CARBON AND NITROGEN POOLS AFTER EUCALYPT ESTABLISHMENT IN SOILS WITH CONTRASTING TEXTURES IN SÃO PAULO STATE, BRAZIL

ABSTRACT

Planting short-rotation eucalypt is a rapidly expanding activity in Brazil, but its impact on soil carbon (C) and nitrogen (N) pools is not well known. Thus, this study aimed at evaluating the influence of eucalypt cultivation (four rotations) on total organic C (TOC) and total N (TN) stocks and C and N stocks in humic fractions (HS), in light fraction (LF), and in microbial biomass (MB) pools down to 1 m deep in comparison to the native forest, pasture, and sugar-cane soils in a main eucalypt cultivation region of São Paulo state, Brazil. We selected commercial short-rotation eucalypt stands located adjacent to native vegetation (Atlantic forest or Cerrado/Savanna), planted pasture and sugar cane fields. The soils were divided in two great groups according to their clay content: 1. clayey (± 66% of clay) and 2. sandy (± 9% of clay). So, for each land use it was determined TOC and NT stocks of soil, the stocks of C and N in humic fractions, in LF, and in MB in the 0-10, 10-20, 20-40, 40-60 and 60-100 cm layers. The results showed that, in general, the clayey soils have higher C and N stocks in SOM fractions than the sandy soils. The eucalypt soil had higher TOC (146.6 t ha^{-1}), humic substances (HS) C (139.1 t ha^{-1}), and LF C (6.9 t ha^{-1}) stock than the pasture (TOC = 123.4 t ha^{-1}, HS = 109.9 t ha^{-1}, LF = 3.4 t ha^{-1}) and sugar cane (TOC = 127.1 t ha^{-1}, HS = 119.9 t ha^{-1}, LF = 3.7 t ha^{-1}) soil up to 100 cm deep in the clayey soils group. All other soil uses had lower TOC stocks than that under native forest in the 0-60 cm layer in the clayey and sandy soils group. There were no differences in the TN stocks among eucalypt, pasture and sugar cane soils, in both soil groups. However, their TN stocks was, respectively, 2.7, 3.4 and 4.4 t ha^{-1} lower than the native forest soil up to 100 cm deep in the clayey soils group. All soil under distinct uses also had lower N stocks in humic fractions than the native forest soil up to 60 cm depth. The soil under eucalypt had higher N stock in the LF (0.16 t ha^{-1}) than the pasture (0.08 t ha^{-1}) and sugar cane (0.10 t ha^{-1}) soil up to 60 cm deep. The eucalypt and native forest soils had lower N stock in MB than the pasture and sugar cane soils in the 0-100 cm layer**.** In the sandy soil group, the eucalypt, pasture and sugar cane cultivation resulted in lower C stocks in HS, fulvic acid fraction (FAF), and humic acid fraction (HAF) than the native forest soil (0-100 cm). A similar pattern was observed for the C and N stocks in the LF in all soil layers. The eucalypt (1.74 t ha^{-1}), native forest (1.55 t ha^{-1}) and pasture (1.48 t ha^{-1}) soil had lower C stock in MB than the sugar cane soil (2.51 t ha^{-1}) in the 0-100 cm layer. The eucalypt soil also presented lower N stock in MB than the sugar cane soil in the 0-20, 0-40, 0-60 and 0-100 cm layers. Overall, land cultivation led to lower C stocks in several organic matter fractions in comparison to the native vegetation. Short-rotation eucalypt improved C stocks in several SOM fractions in comparison to other alternative land uses (planted pastures and sugar cane) in clayey, but not in sandy soils.

Keywords: humic substances, light fraction, microbial biomass, land use changes, afforestation.

1. INTRODUCTION

The areas under tropical forests and cerrado in Brazil are being reduced very fast as a result of the growing demand for woody products and the need for new crop cultivation areas. The tropical forests contain about 40% of carbon (C) stored as terrestrial biomass (Dixon et al., 1994) and represent a substantial fraction of the world's forest net primary productivity (Melillo et al., 1993). The cerrado, the main savanna region of south hemisphere, represents about 9% of the total area of tropical savannas in the world. It occurs entirely within Brazil, mainly in the central region, and covers approximately 2 millions km^2 (23% of the territory) (Bustamante et al., 2006). Land use changes in the Brazilian cerrado include the conversion of native savanna to annual crops, planted pastures and short-rotation forest plantations. About 40 years ago the planted forests in Brazil occupied little over 400.000 ha. By 1987, Brazil had more than 6 Mha of planted forests, and more than one third was located in the southeast region. Eucalypt and pine plantations represent 80% of total planted area (Bustamante et al., 2006).

Aiming to reduce soil degradation and supply the expanding demand for timber and timber products, extensive afforestation with exotic, fast growing, tree species (e.g. eucalypt, pine) has been carried out in former pasture and agricultural land. The productivity of commercial eucalypt plantations in Brazil is very variable (3.7-20 Mg C ha^{-1} year^{-1}) and it depends on water and nutrient availability and competition factors (i.e. weeds) if we consider that solar radiation and temperature are not limiting (Barros and Comeford, 2002). Although intensive management practices applied to short-rotation eucalypt plantations may guarantee rapid growth and high economic returns, little is known about the afforestation impacts on soil organic carbon (SOC) dynamics (Ashagrie et al., 2005).

Soil organic matter (SOM) is essential for the maintenance of physical, chemical and biological properties of soils, especially those under humid tropical conditions, where soils are poor in bases, phosphorus, and nitrogen and with high exchangeable aluminum content (Novais & Smith, 1999). Additionally, the SOM plays an important role in the global carbon cycle because it is estimated to contain more than four times as much C as in the plant biomass and three times as much C as in the atmospheric pool (Lal, 2004).

Considering that the SOM is formed by different compartments with variable cycling times (Stevenson, 1994) and, that the more stable SOM pools are quantitatively dominant, the direct measurement of SOM losses or gains due to land use changes in the short-term may not be feasible (Haynes, 1999). Furthermore, several factors affect the magnitude and rates of SOM changes, including land use, soil type, climate and former vegetation (Post & Kwon, 2000; Paul et al., 2002). Consequently, the fractionation of SOM and biological analysis combined with chemical analysis can be important strategies in process-oriented SOM research (Christensen, 2001).

The clay particles play important roles in SOM dynamics (Barthès et al., 2008; Traoré et al., 2007; McLauchlan, 2006; Parton, 1987). In a study carried out in Australia with soils under eucalypt, pasture and native forest, with SOC varying from 19 to 83 g kg^{-1} (0-10 cm), Mendham et al. (2002) observed that, in general, clayey soils presented larger SOC contents and lower rates of C mineralization. Also, in a study with short-rotation eucalypt plantations in Brazil, Lima et al. (2006) observed that the clay content was one of the most important characteristics that favour the stabilization of SOM in the 0-20 cm layer of soils previously under degraded pastures. However, few studies have evaluated the effects of afforestation on SOM at deeper soil layers, which seem to be crucial in soils cultivated with deep-rooted forest species.

The aim of this study was to evaluate the influence of short-rotation eucalypt cultivation on the TOC and NT stocks of soil, and C and N stocks in humic fractions, in light fraction, and in microbial biomass down to 1 m deep in soils with contrasting textures in comparison to native forest, pasture, and sugar cane soils.

2. MATERIALS AND METHODS

2.1. Site description

This study was carried out in commercial eucalypt stands located in the Luiz Antônio county (21º33'18" S and 47º42'16" W), distant about 300 km from the São Paulo City, Brazil. This is one of the main eucalypt growing regions in São Paulo state, which has the second largest area cultivated with short-rotation eucalypt in Brazil. The mean annual precipitation is 1481 mm and most of it falls between November and March. The mean annual temperature is 23 °C. The altitude of this region is 500 m asl. According to the Köppen`s classification the climate is Cwa (humid subtropical) (Nimer, 1989). This region is dominated (~70 %) by very sandy soils (Typic Quartzipsamment) intercalated by clayey soils (Oxisol) derived from basalt.

The land use in this region is constituted mainly by sugar cane cultivation, planted pastures, citrus, and short-rotation eucalypt stands. Furthermore, other use types including, peanut, maize and soybean, generally in rotation with sugar cane, are found in this region (Pires, 1995).

In the present study the soils were divided in two great groups according to their clay content: clayey and sandy soil (Table 1). In the clayey soils group we selected adjacent areas under native vegetation (Atlantic forest), planted pasture, eucalypt and sugar cane, distant approximately 500 m from each other. The same land uses were selected in the sandy soils group. Except for the texture, the main difference among these soil groups is the native vegetation that is a dense cerrado in the sandy soils rather than the Atlantic forest of clayey ones. The pastures (*Brachiaria decumbens*) were established in areas that were under cropping for several decades and that had originally been cleared through slashing and burning of the native forest. The pastures were used for extensive cattle ranching for at least 20 years. No fertilizer or lime has ever been used. The first eucalypt rotation (*Eucalyptus grandis x Eucalyptus urophylla*) was planted manually after clearing and burning of part of Atlantic forest and Cerrado in the clayey and sandy soils group, respectively. The surface biomass was burned on site. After seven years of eucalypt planting, the trees were clear cut and the trunk removed from the area. The eucalypt residues were burned to clear the area to conduct the second rotation. Since the third rotation the burn practice was no longer used. In all rotations no bark was returned to the soil surface. In the clayey and sandy soils group, the eucalypt stands were in the fourth rotation (two year-old at time of collection) and presented a productivity of 9.5 and 11.3 Mg C ha^{-1} year^{-1}, respectively. All management practices were carried out mechanically due to favourable topography. The harvests were conducted with Feller plus Camblumck equipments.

The eucalypt stands selected for soil sampling covered approximately 10 ha, and they were located in the middle slope position. Soil samples were collected in the 0-10, 10-20, 20-40, 40-60 and 60-100 cm soil layers. There were three randomly assigned field replicates within each soil use. Each replicate was separated by more than 500 m apart from each other and it consisted of a composite of four soil samples randomly collected 20 m apart from each other. This pseudo-replication strategy was adopted due to the inexistence of native vegetation remnants near eucalypt stands, planted pasture and sugar cane fields. In each area a 120 cm deep pit was dug manually and intact soil cores were taken to determine soil density for each soil layer.

2.2. Soil analysis

After air drying, soil samples were sieved trough a 2 mm sieve for determination of C and N contents of the total, humic fractions, light fraction and microbial biomass pools. Sub-samples were also taken for texture analysis (Table 1). Soil sub-samples were grounded in an agate mortar to pass through a 100 mesh (0.149 mm) sieve for the total organic C (TOC) determination by a wet-chemical procedure (Yeomans & Bremner, 1988), and for the total N (TN) determination by the Kjeldahl method (Tedesco et al., 1985).

Table 1. Selected physical characteristics of soils under different land uses in study

Land use	Layer	Sand	Silt	Clay	Bulk Density
	(cm)	--------------(g kg^{-1})------------			(Mg m^{-3})
			Clayey soil		
Native forest	0-10	130	210	660	0.96
	10-20	110	230	660	1.11
	20-40	100	210	690	1.20
	40-60	90	210	700	1.09
	60-100	100	210	690	0.98
Pasture	0-10	130	210	660	1.23
	10-20	130	230	640	1.15
	20-40	110	220	670	1.14
	40-60	110	220	670	1.11
	60-100	110	220	670	1.02
Eucalypt	0-10	170	190	640	1.11
	10-20	170	185	645	1.16
	20-40	160	190	650	1.15
	40-60	160	190	650	1.10
	60-100	155	185	660	1.04
Sugar cane	0-10	140	210	650	1.30
	10-20	140	210	650	1.24
	20-40	120	210	670	1.17
	40-60	120	210	670	1.05
	60-100	120	210	670	1.06
			Sandy soil		
Native forest	0-10	910	20	70	1.20
	10-20	910	20	70	1.41
	20-40	920	20	60	1.35
	40-60	920	20	60	1.47
	60-100	930	10	60	1.46
Pasture	0-10	920	20	60	1.38
	10-20	920	20	60	1.44
	20-40	930	10	60	1.51
	40-60	920	20	60	1.48
	60-100	920	20	60	1.48
Eucalypt	0-10	890	20	100	1.36
	10-20	900	20	90	1.44
	20-40	900	20	90	1.45
	40-60	890	20	100	1.42
	60-100	890	10	110	1.41
Sugar cane	0-10	850	10	140	1.46
	10-20	860	0	140	1.62
	20-40	840	10	150	1.59
	40-60	840	20	140	1.54
	60-100	820	30	150	1.45

The chemical fractionation of humic substances was based on differential solubility of organic composts in acid and base solutions as suggested by the IHSS (Swift, 1996). From this separation, it was obtained the humin (HF), humic acids (HAF), and fulvic acids (FAF) fractions. The sum of HF, HAF and FAF was taken as the humic substances fractions (HS). The C content in the humic fractions was determined by a wet-chemical procedure (Yeomans & Bremner, 1988) and the N content was determined by the Kjeldahl method (Tedesco et al., 1985).

Soil sub-samples were submitted to densimetric separation of the light fraction (LF) through flotation in a NaI solution (1.8 Mg m^{-3}) (Sohi et al., 2001). The floating organic matter was thoroughly washed with deionised water, oven dried, weighed, and grounded to pass a 100 mesh (0.149 mm) sieve. The C and N content of the LF was determined by dry combustion in an elemental analyser (Perkin-Elmer, series II CHNS/O).

After incubation of soil samples during 16 days with moisture at 60% of field capacity and temperature of 20 ^{o}C to allow the microbial population reestablishment to steady-state condition, the C and N content of microbial biomass (MB) was determined by the irradiation-extraction procedure (Islam & Weil, 1998).

The C stocks in distinct SOM fractions and soil layers were calculated by multiplying the C concentration by the mass of soil in each layer of native forest to correct for management-induced compaction effects on SOM stocks (Lemma et al., 2006).

The TOC, TN stocks and the C stocks in HS, FAF, HAF, HF and MB, in each soil layer, were submitted to analysis of variance (ANOVA) to detect whether they differ in soils under native forest, planted pasture, eucalypt and sugar cane (treatments) Treatments means were compared by the protected least significant difference (LSD) test (Steel et al., 1997) ($\alpha = 0.05$) using the software SAEG 5.0 (Funarbe, 1993). We recognised that pseudo-replication is a restriction of the present study, as in many other paired-site studies (Vesterdal et al., 2002; O’Brien et al., 2003; Chen et al., 2004, Lima et al., 2006).

3. RESULTS AND DISCUSSION

The SOM levels in highly weathered soils are closely related with the eucalypt productivity (Menezes, 2005) and it favors the long-term forestry sustainability (Barros & Comerford, 2002). The SOM roles seem to depend on the most limiting factors in each site. Among several roles that the SOM has on soil, in sandy soils it is very essential to water retention and nutrient supply, whilst in clayey soils its crucial in the maintenance of physical proprieties. Thus, due to this strong link between SOM with others soil proprieties, it is important to adopt management practices that maintain or increase SOM content (Grigal & Vance, 2000). The results of the present study indicated that the clayey soils, in general, had larger C and N stocks in all SOM fractions than the sandy soils (Fig. 1, 2, 3 and 4). In general, clayey soils present larger SOM contents and lower C mineralization rates (Bird et al., 2003). In the clay fraction, C is stabilised mainly by association with soil minerals, resulting in protection against the biological degradation (Kaiser et al., 2002; Dalmolin et al., 2006). Protection of SOC by clay particles has been postulated to occur through at least two separates mechanisms: First, as SOC becomes humified, it is chemically stabilized and adsorbed onto negatively charged clay minerals with high surface area. Second, SOC is physically protected from microbial mineralization through the formation of soil aggregates. In a study evaluating the relative influences of soil texture (clay content), soil organic C and long-term management on soil properties at Rothamsted, UK, Watts et al. (2006) observed that minimum SOC values increased with increasing clay suggesting that clay offers physical protection to SOC. In soil under eucalypt, pasture and native forest in 10 Australian sites, with TOC varying from 19 to 83 g kg^{-1}, Mendham et al. (2002) observed that, in general, clayer soils presented larger SOC contents and lower C mineralization rates. Evaluating the effect of soil texture and roots on the stable carbon isotope composition of SOC in two forest soil profiles of contrasting texture from Cape York Peninsula, Queensland, Australia, Bird et al. (2003) observed that the profile on sand has comparatively low C inventory (557 mg cm^{-2} from the 0-100 cm layer) and exhibits comparatively small variation in δ^{13}C value. In contrast, the clay rich profile has a much larger inventory of soil organic C (1725 mg cm^{-2}) and larger variations in δ^{13}C value occur both with depth and between difference particle size fractions. The considerable differences in C inventories and δ^{13}C values between sites appear to be largely due to the soil texture difference. Additionally, the clay content may alter soil moisture, which affects both SOC decomposition and C inputs to soils as a result of increased plant productivity (Mclauchlan, 2006).

3.1. Total carbon and nitrogen

In the clayey soils group, the eucalypt soil had larger TOC stocks (146.6 t ha^{-1}) than the pasture (123.4 t ha^{-1}) and sugar cane (127.1) up to 100 cm deep (Fig. 1). The great changes in soil physical, chemical and biological properties due to the frequent annual interferences for discompaction, fertilization, weed control, quality of C inputs to soil and higher SOM decomposition rates induced by the agricultural systems contribute to decrease C stock in relation to eucalypt (Murty et al., 2002). In a study evaluating the changes of SOM stocks in eucalypt chronosequences established in former degraded pastures in the Minas Gerais State, Brazil, Lima et al. (2006) also observed that the eucalypt cultivation resulted in increase of the TOC stocks (0-20 cm), where larger input of more lignified and aromatic-rich organic residues by eucalypt may have played an important role (Paul el al., 2003; Sjoberg et al., 2004). The eucalypt soil had 9.3 t ha^{-1} of TOC lower than the native forest soil up to 60 cm deep, but the C stocks in the 0-100 cm soil layer in the eucalypt soil equalled that under native forest.

A distinct effect of land use was observed on SOM of the sandy soil group (Fig. 1). The eucalypt cultivation led to larger TOC stocks (45.4 t ha^{-1}) than the pasture (34.6 t ha^{-1}) and sugar cane (35.8 t ha^{-1}) soils in the 0-40 cm layer. A similar pattern was observed when it is compared the eucalypt with the pasture soil in the 0-100 cm layer. Nonetheless, all soil uses caused a decline in TOC stocks when compared with the native forest soil in the 0-10, 0-20, 0-40, 0-60 and 0-100 cm layers, showing that the native forest presented a favourable environment for SOM maintenance. Different result was found by Lemma et al. (2006) who evaluated the soil C sequestration under different exotic species in the Southwestern highlands of Ethiopia. They observed that *E. grandis* afforestation during 20 years returned the TOC stock to nearly the native forest level after consecutive 35 years of pasture and 20 years of agriculture. Those authors worked with soils with higher clay content (clay loam texture) which could contribute for the SOM accumulation by eucalypt, as the results of our study indicated. Additionally, the lower mean annual temperature (19.4 ^{o}C) in the area studied in Ethiopia could favor the SOM maintenance after establishment of long-rotation eucalypt.

There were no differences in the TN stocks among eucalypt, pasture, and sugar cane soils in all analysed soil layers (Fig. 1). Despite eucalypt soil show higher C stocks (as described above), its N stocks did not increase, leading to a higher C:N ratio, and suggesting that qualitative aspects of inputs and structural composition are fundamental in SOM dynamics. The N is an element very important in the humification process because the N scarcity could limit the SOM stability on soil (Stevenson, 1994). So, the formation of humic fractions under eucalypt conditions may have occurred based on resistant organic residue (inherited humic fractions). In a study evaluating the influence of N fertilizer on soil C stock under *E. saligna* ($19^o50'28.1''$ N, $155^o7'28.3''$ W), Binkley et al. (2004) observed no effect of N addition on TOC of soil. On the other hand, the eucalypt soil had 2.7 t ha^{-1} of TN lower than the native forest soil up to 100 cm deep. The harvest of the eucalypt stem results in exportation of N stocked in wood and causes a decrease in N inputs to soil. Also, the pasture (6.60 t ha^{-1}) and sugar cane (5.60 t ha^{-1}) had lower NT stocks than the native forest (10.0 t ha^{-1}) soil up to 100 cm deep. The native forest soil is an environment where does not exist disturbances from management practices such as eucalypt planting and harvesting (lower N losses by volatilization and leaching), contributing for greater N stocks. Evaluating the soil physical-chemical characteristics in a tropical dry deciduous native forest, regenerated forest and eucalypt plantation close to Jharsuguda in the western part of Orissa, Behera and Sahani (2003) observed that the TOC and NT concentrations were comparatively lower in the eucalypt soil. Also, studying some physical and chemical properties of soils under different land uses in a typical watershed of Ethiopia, Bewket and Stroosnijder (2003) observed lower TN concentration in the cultivated, grazed and eucalypt soils than that under native forest. The great number of plant species in the native forest area and, additionally, the biological N_2 fixation by some leguminous trees contributes substantially to maintain or increase the N stock in soil. In the presence of N-fixer plants the SOM stabilization, especially in more stable pools, is favoured relative to stands composed exclusively of non N-fixer trees such as eucalypt (Kaye et al., 2002; Resh et al., 2002). In the sandy soil group, the pasture, eucalypt plantation and sugar cane led to lower TN stocks than the native forest in the 0-20, 0-40 and 0-60 cm layers. Also, the eucalypt (4.04 t ha^{-1}) and sugar cane (4.06 t ha^{-1}) soils had lower TN than the native forest (5.67 t ha^{-1}) soil in the 0-100 cm layer.

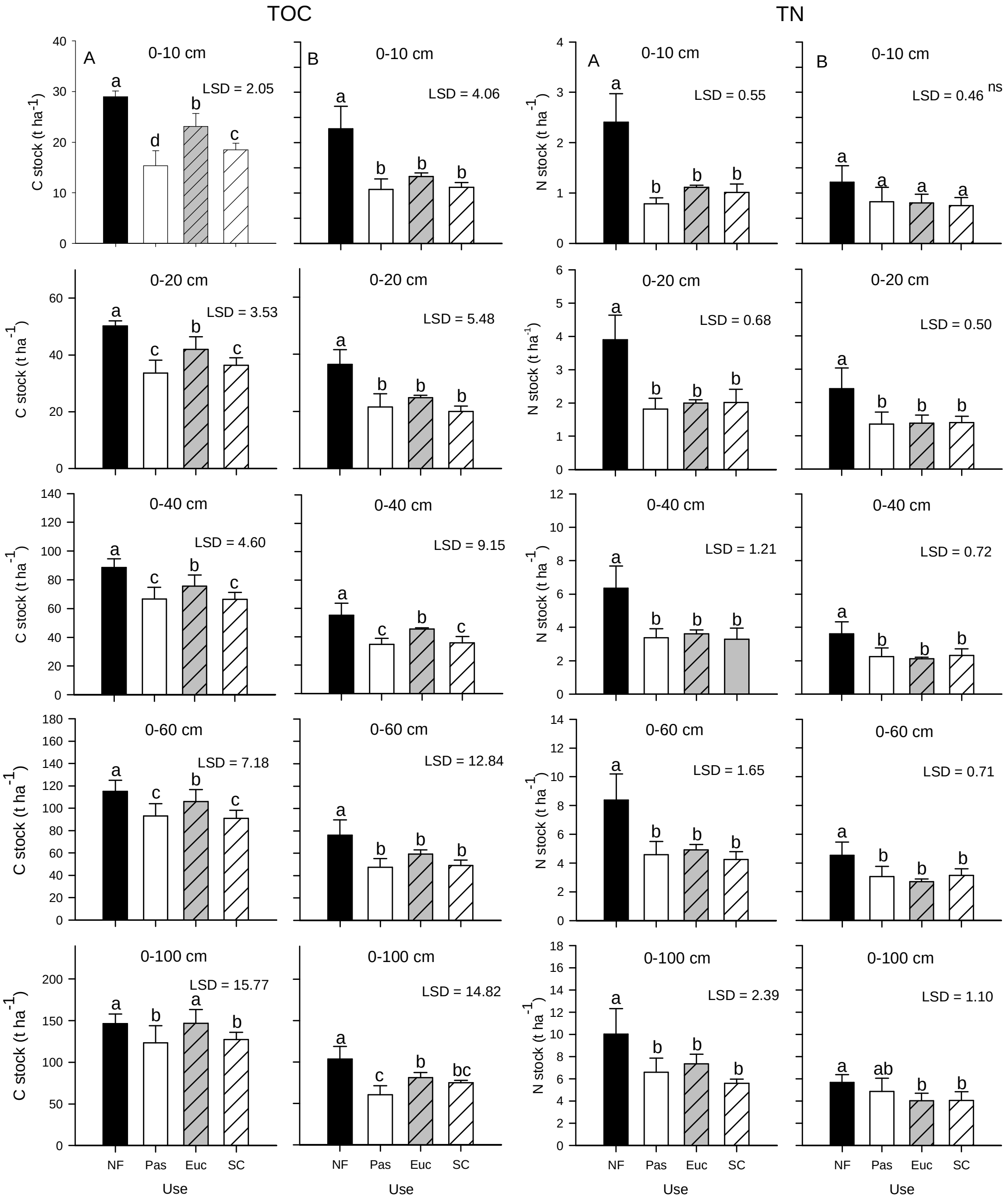

Figure 1. Total organic carbon (TOC) and total nitrogen (TN) stocks in distinct layers of the clayey (A) and sandy (B) soil groups.

3.2. *Humic substances carbon and nitrogen*

The eucalypt soil stocked 29.1 and 19.2 t ha $^{-1}$ more C in HS than the pasture and sugar cane soil, respectively, up to 100 cm deep in the clayey soil group (Fig. 2). The more recent adoption of reduced tillage and the organic residue maintenance on soil surface after harvest and the eucalypt deep root system might contribute to increase C stock in HS. Conversely, the eucalypt soil had lower C stock in HS (92.7 t ha $^{-1}$) than the native forest soil (105.8 t ha $^{-1}$) up to 60 cm layer. The fire utilization during the two first rotations of eucalypt could have contributed for C loss as CO_2 to the atmosphere, resulting in smaller C input, besides favoring soil erosion. Evaluating the soil and water losses due to hydric erosion in eucalypt plantations in Brazil, Pires et al. (2006) observed that the burning of organic residues after harvest contributed to increase soil and water loss. They suggested that the fire events increased water repellence and, consequently, decreased water infiltration rate into the soil. The eucalypt soil stored more C in the HF than the pasture soil in the 0-10 cm and 0-100 cm layer. The eucalypt soil also had larger C stock in the HAF (4.51 t ha^{-1}) than the pasture soil (2.79 t ha^{-1}) in the 0-10 cm layer. In relation to the FAF, the eucalypt soil had higher C stocks in this fraction than the pasture soil in the 0-20, 0-40, 0-60 and 0-100 cm layers. Comparatively with the sugar cane soil, the eucalypt soil stabilized more C in FAF in the 0-20 and 0-60 cm layers. Nevertheless, when compared to the native forest soil (25.2 t ha^{-1}), the eucalypt soil had lower C stock in the HAF (19.3 t ha^{-1}) up to 60 cm layer. In a study carried out in Australia, Chen et al. (2004) observed that the substitution of the native forest by *Araucaria cunninghamii* (51 year-old) resulted in decline of the C stock in FAF, while C stock in HAF was unaltered. Due to higher humification level and biochemical complexity, the HAF is more stable and less susceptible to biological decomposition (Six et al., 2002). Additionally, the interaction with fine soil particles (clay and silt) contributes to the HAF stabilization in the soil.

In the sandy soil group, the eucalypt soil had larger C stocks in HS (66.2 t ha^{-1}) than pasture (53.2 t ha $^{-1}$) and sugar cane (56.3 t ha $^{-1}$) soils in the 0-100 cm layer (Fig. 2). Differently, all soil uses had lower C stock in HS, HAF and FAF than the native forest soil up to 1 m deep. The pasture, eucalypt and sugar cane also had lower C stock in HF than the native forest soil in the 0-10 cm layer. In a study carried out in Spain, Caravaca et al. (2004) observed that the soil under native forest had larger C stock in FAF and HAF than those under agricultural use. However, they found no differences in the C stock of HF. Evaluating the land use effects on soil quality on a tropical forest of Bangladesh, Islam and Weil (2000) also found lower C concentration in FAF and HAF for cultivated soil than that under native forest. These authors concluded that soil C loss in cultivated soils may have resulted of a combination of lower C input of organic residue and greater C losses because aggregate disruption, crop residue burning, accelerated water erosion, and grazing. In a study evaluating the changes in soil C following the eucalypt establishment (30 months) in a former sugar cane area in Hawaii, Binkley and Resh (1999) found no difference on soil C stock in the upper 30 cm layer. The lack of change in soil C at the end of the first rotation resulted from the balance between the losses of older C derived from sugar cane, and gain of new soil C from eucalypt (Binkley et al., 2004).

The clayey soil under eucalypt plantation had larger N stock in HS than the pasture soil in the superficial (0-10 cm) as well as in the 0-100 cm layer (Fig. 3). On the other hand, the eucalypt soil had lower N stock in this fraction (8.2 t ha $^{-1}$) as compared to the native forest soil (10.4 t ha $^{-1}$) in all analysed layers, but the stock was similar to those in the sugar cane soil (8.1 t ha $^{-1}$). Also, all soil uses had lower N stock in all humic fractions than the native forest soil up to 60 cm deep. In a study evaluating the changes of C and N forms in soil aggregates under different uses and management systems in Brazil, Assis et al. (2006) observed that soil cropping reduced N and C concentrations in humic fractions when compared to the native forest soil due to intensive soil preparation during implantation and conduction of these agricultural crops. Probably, those soil uses have not reached the new steady state that can take more than 100 years to be reached (Dick et al., 1998). In the new steady state, the SOC stocks could be similar, higher or lower than that before soil disturb and it would depend on soil type, prior vegetation, and management practices (Swift, 2001). The eucalypt soil had larger N stock in HAF (0.80 t ha^{-1}) than the pasture soil (0.56 t ha^{-1}) in the 0-20 cm layer.

In the sandy soils group, the pasture (1.2 t ha $^{-1}$), eucalypt (1.3 t ha $^{-1}$) and sugar cane (1.4 t ha $^{-1}$) soils had lower N stock in HS than the native forest soil (1.9 t ha $^{-1}$) in the top 20 cm layer (Fig. 3). Similarly, the eucalypt and pasture soils had lower N stock in HS than the native forest soil in the 0-60 and 0-100 cm layers. All soil uses also presented lower N stocks in the HAF than the native forest soil up to 1.0 m deep. Without soil disturbation there are more favorable conditions to SOM polymerization and, consequently, to increase humic fractions stocks in soil (Assis et al., 2006). The tillage of soils by agricultural use results in break down of soil aggregates and increased C and N mineralization, resulting in C and N losses (Balesdent et al., 2000). There were no differences among pasture, eucalypt and sugar cane soils in the N stocks in HS, the HAF and the FAF up to 100 cm deep. The eucalypt soil stored less N in the HF (0.86 t ha $^{-1}$) than the sugar cane soil (1.1 t ha $^{-1}$) up to 40 cm deep.

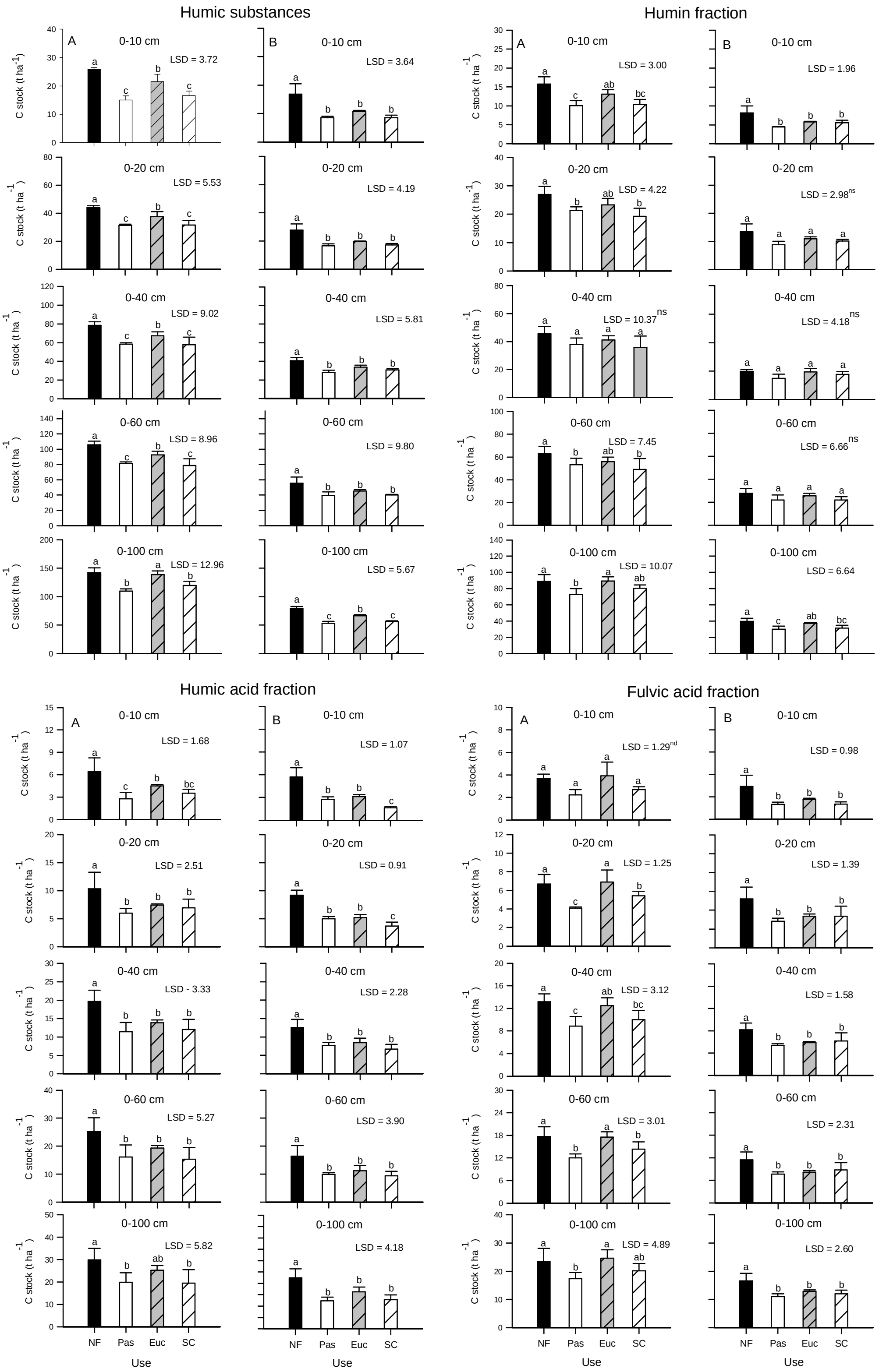

Figure 2. Carbon stocks in humic substances, humin fraction, humic acid fraction, fulvic acid fraction in distinct layers of the clayey (A) and sandy (B) soils.

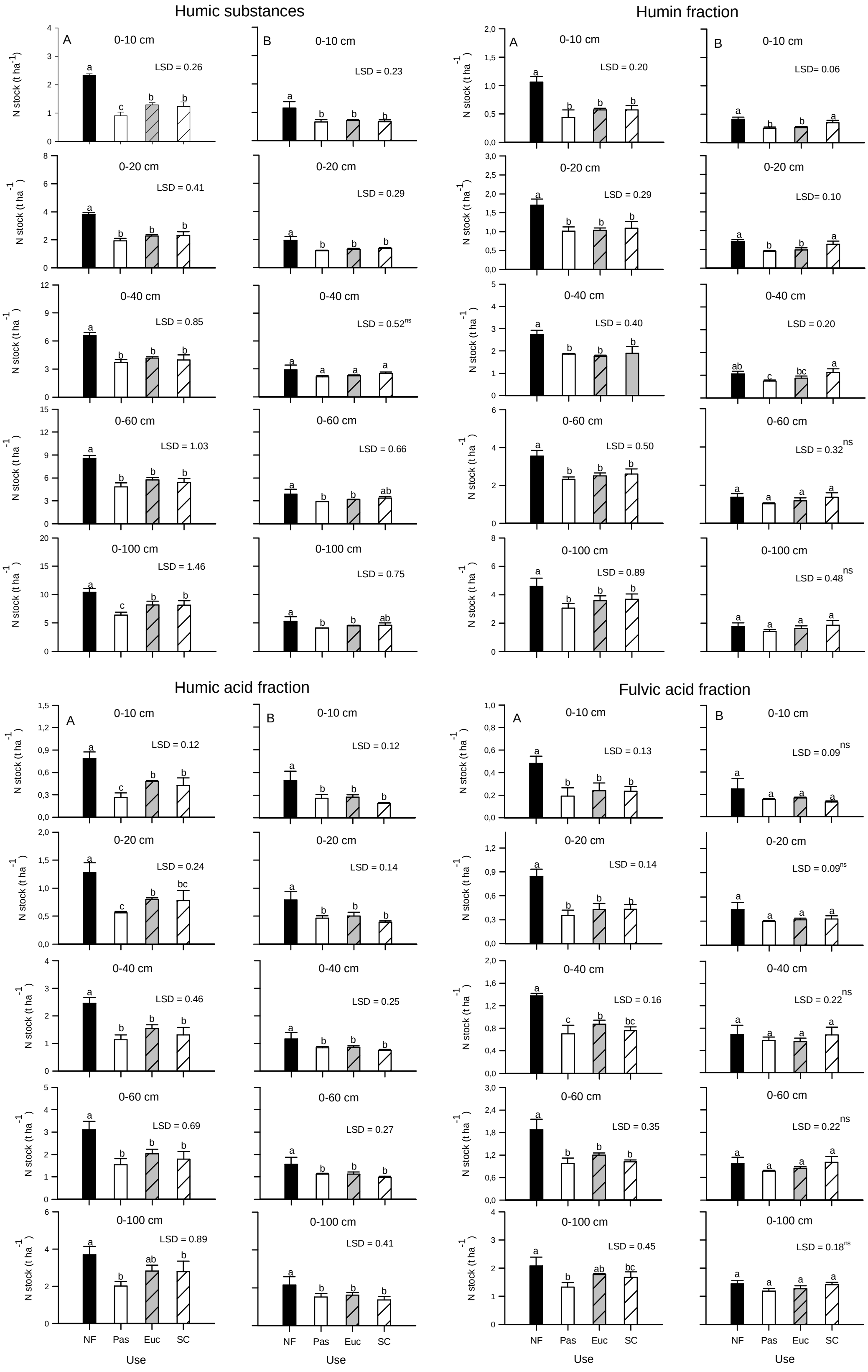

Figure 3. Nitrogen stocks in humic substances, humin fraction, humic acid fraction, fulvic acid fraction at different layers of the clayey (A) and sandy (B) soils.

3.3. Carbon and nitrogen in light fraction and microbial biomass

In the clayey soils group, the eucalypt was able to stoke more C in the LF (6.9 t ha $^{-1}$) than the pasture (3.4 t ha $^{-1}$) and sugar cane (3.7 t ha $^{-1}$) soils in all soil layers (Fig. 4). The LF is composed mainly by partially decomposed organic residues, and it is strongly influenced by the amount and quality of organic residues deposited on soil surface (Six et al., 2002). So, the increment of LF in the eucalypt soil in comparison to the pasture and sugar cane soils is reflecting the larger, continuous organic residue deposition. Lima et al. (2006) also observed a recover in C stocks in LF after approximately 34 years of short-rotation eucalypt plantation in areas previously under degraded pasture in Brazil. Oppositely, the pasture (2.7 t ha $^{-1}$), the eucalypt (5.3 t ha $^{-1}$) and the sugar cane (2.0 t ha $^{-1}$) soils stocked less C in this fraction than the native forest soil (6.7 t ha $^{-1}$) up to 60 cm deep. The eucalypt soil presented larger C stocks in MB than native forest, pasture and sugar cane in the soil layer deeper than 40 cm (Fig. 4). Similarly, the eucalypt soil had higher C stock in MB (148.5 t ha $^{-1}$) than the pasture soil (68.1 t ha $^{-1}$) in the 0-10 cm layer. Evaluating the MB size as affected by land use in South Africa (29^{o}52`S and 30$^{o}$17`E), Nsabimana et al. (2004) also found higher C concentration in BM in the eucalypt soil than the crops (maize), annual ryegrass and pine forest soils. The higher microbial stress and lower supply of C substrate under arable agricultural are likely the main cause of lower MB. Theses authors also suggested that one of possible reasons for the lower MB in the pine soil could be the high content of phenols and other biochemical substances in pine needles litter, which may inhibit microbial activity. Additionally, the land use change can result in alteration of MB quality.

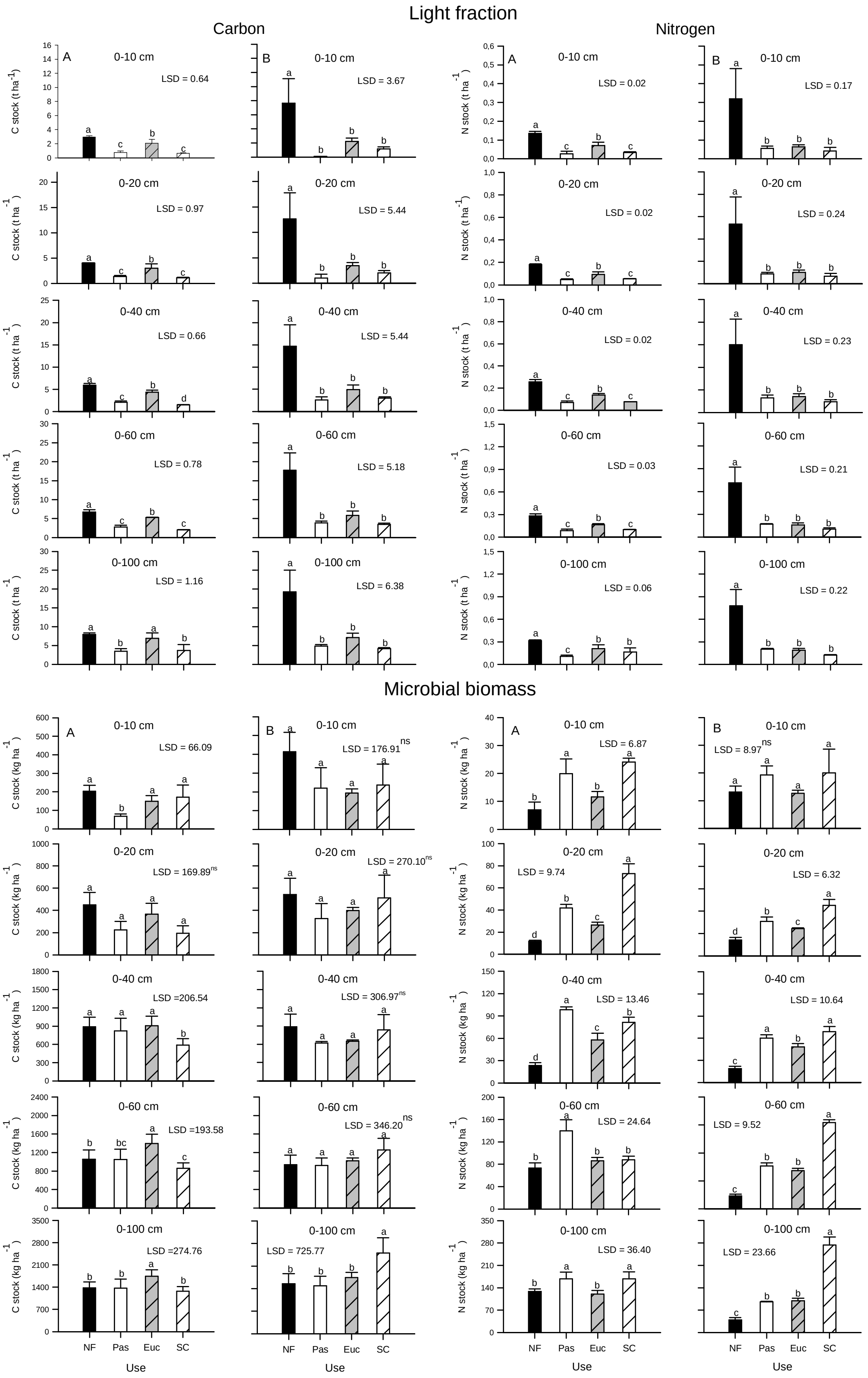

Figure 4. Carbon and nitrogen stocks in light fraction (LF) and microbial biomass (MB) in distinct layers of the clayey (A) and sandy (B) soils.

There were no differences in C stocks of the LF among pasture, eucalypt and sugar cane soils in all analysed layers in the sandy soils group (Fig. 4). Nonetheless, the pasture (4.8 t ha $^{-1}$), eucalypt (7.1 t ha $^{-1}$) and sugar cane (4.1 t ha $^{-1}$) soils stored less C in the LF than the native forest soil (19.2 t ha $^{-1}$). The utilization of management practices such as plough during agricultural use can lead to aggregate disruption and lead direct contact between particulate SOM and soil mineral fraction, which stimulates the LF/particulate OM decomposition by microorganisms. Evaluating the texture and land-use effects on SOM of Oxisols under Cerrado in central Brazil, Neufeldt et al. (2002) observed that continuous cropping and pine afforestation led to reduction of POM contents, whereas pasture and eucalypt afforestation increased both POM amount and quality in comparison to the native vegetation (Cerrado), showing once more that the higher clay content contributes for POM accumulation (physical and colloidal protection) under eucalypt plantation in relation to the sandy soils. On the other hand, the sugar cane soil (2.51 t ha $^{-1}$) had larger C stock in MB than the native forest (1.55 t ha $^{-1}$), the eucalypt (1.74 t ha $^{-1}$) and the pasture (1.48 t ha $^{-1}$) soils in the 0-100 cm layer.

The eucalypt soil had larger N stocks in LF (0.16 t ha^{-1}) than the pasture (0.09 t ha^{-1}) and sugar cane (0.10 t ha^{-1}) soil up to 60 cm deep in the clayey soils group (Fig. 4). A similar pattern was found when the eucalypt soil (0.21 t ha^{-1}) was compared to the pasture soil (0.10 t ha^{-1}) in the 0-100 cm layer. On the other hand, all soil uses had lower N stock in LF than the native forest soil up to 1 m deep. In a study evaluating the impact of conversion from native forest to eucalypt in Ethiopia, Ashagrie et al. (2005) observed lower N and C stocks in LF in the eucalypt soil than the native forest soil. In general, the LF decline due to land use change is more pronounced than that found for TOC, suggesting it as a sensitive soil quality indicator (Amado et al., 2006). The native forest and eucalypt soils had lower N stock in MB than the pasture and sugar cane soils up to 40 cm as well in the thicker soil layer (0-100 cm).

There were no differences in N stocks in LF among pasture (0.20 kg ha $^{-1}$), eucalypt (0.19 kg ha $^{-1}$) and sugar cane (0.12 kg ha $^{-1}$) in all layers of sandy soils, but their N stocks were smaller than those observed for the native forest soil (0.78 kg ha $^{-1}$) (Fig. 4). Evaluating the changes of NT and N stocks in LF down to 1 m deep after conversion from Mulga (*Acacia aneura*) to pasture and crops in Australia, Dalal et al. (2005) observed a decline of N stocks in LF in all soil depths under pasture and crops. Although the N stock in LF comprised a small percentage of soil N, larger decreases of this fraction may adversely affect SOM quality. A low N concentration in soil results in decrease of SOM humification (Stevenson, 1994) and, consequently, it may affect the plant productivity in future rotations. The native forest, the pasture and the eucalypt soils had lower N stocks in MB than the sugar cane soil in the 0-20, 0-60 and 0-100 cm layers. Also, the native forest and eucalypt soil had lower N stock in this fraction than the pasture soil in the 0-20 and 0-40 cm deep. However, except in the 0-10 cm layer, the eucalypt soil had larger N stock in MB than the native forest soil in all other soil layers. In a study aimed to assess some soil chemical and biological properties related to C and N cycles of native forest soils compared to afforested and agricultural soils in Brazil, it was observed that the N stock in MB (0-10 cm) was higher in the native and secondary forest soil than in the eucalypt soil (Nogueira et al., 2006). Although the eucalypt stand was as old as that of secondary forest, its soil biomass N did not differ from that of the fallow or the mature wheat-cropped sites, possibly due to wide C/N ratio in the eucalypt residues. These results suggest that not only the period of restoration, but also soil use and organic residue diversity have important effects on microbial biomass N.

4. CONCLUSIONS

1. The clayey soils averaged higher C and N stocks in SOM fractions than the sandy soils;

2. In clayey soils the eucalypt plantation leads to greater total organic carbon stocks and the C stocks in humic substances and light fraction than the pasture and sugar cane cultivation. A similar pattern is observed for the N stock in the light fraction. Conversely, the eucalypt cultivation leads to smaller total nitrogen stocks than the native forest soil. Also, all soil uses result in lower N stocks in humic fractions than the native forest soil;

3. A distinct effect of land use is observed on SOM in the sandy soil group. The eucalypt, pasture and sugar cane cause a decline in total organic carbon stocks when compared to native forest, and this effect is noticed in the more stable humic substances as well as in the more labile light fraction. The eucalypt soil has lower N stock in microbial biomass than the sugar cane soil.

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Appendix A

Table 2. C stocks in all analyzed soil organic matter fractions at different soil layers of the clayey soils group

	Layer	Use			
	cm	Native forest	Pasture	Eucalypt	Sugar cane
		------------------t ha^{-1}------------------			
TOC $^{(1)}$	0-10	28.95±0.65	15.35±1.71	23.10±1.47	18.50±0.72
	10-20	21.23±0.42	18.19±1.87	18.86±1.10	17.77±1.18
	20-40	38.38±2.42	33.10±2.19	33.73±2.59	30.25±1.28
	40-60	26.57±2.49	26.36±2.32	30.12±1.88	24.44±1.31
	60-100	31.27±2.56	30.39±5.58	40.85±3.58	36.18±1.01
HS $^{(2)}$	0-10	25.87±0.33	15.05±0.84	21.53±1.45	16.55±0.91
	10-20	18.03±0.55	16.31±0.80	16.06±0.61	14.96±1.08
	20-40	34.51±1.56	26.83±1.48	29.86±1.02	26.23±3.25
	40-60	27.36±0.57	23.26±1.57	25.23±1.59	20.91±0.57
	60-100	36.68±2.73	28.50±1.23	46.40±1.76	41.21±6.19
HF $^{(3)}$	0-10	15.73±1.10	10.04±0.77	13.10±0.67	10.31±0.80
	10-20	11.15±0.72	11.25±0.76	10.18±0.74	8.87±1.03
	20-40	18.67±1.31	16.63±2.75	17.83±0.95	16.52±3.22
	40-60	17.37±0.84	15.38±1.31	14.78±1.15	13.31±0.88
	60-100	26.15±1.68	19.46±0.89	33.37±1.06	31.26±5.76
HAF $^{(4)}$	0-10	6.41±1.06	2.79±0.49	4.51±0.09	3.51±0.31
	10-20	3.92±0.81	3.19±0.45	2.92±0.15	3.39±0.61
	20-40	9.33±0.38	5.42±1.28	6.41±0.33	5.15±0.77
	40-60	5.51±1.12	4.76±0.95	5.44±0.41	3.24±0.89
	60-100	4.73±0.19	3.65±0.19	5.88±0.74	4.17±0.97
FAF $^{(5)}$	0-10	3.72±0.20	2.22±0.28	3.93±0.70	2.72±0.14
	10-20	2.96±0.40	1.86±0.34	2.96±0.09	2.71±0.17
	20-40	6.51±0.24	4.78±0.97	5.62±0.39	4.56±0.77
	40-60	4.48±0.75	3.12±0.63	5.00±0.19	4.37±0.29
	60-100	5.81±1.20	5.39±0.67	7.15±0.98	5.79±0.43
LF $^{(6)}$	0-10	2.96±0.10	0.73±0.14	2.05±0.33	0.63±0.04
	10-20	1.03±0.10	0.61±0.14	0.91±0.21	0.45±0.05
	20-40	1.92±0.22	0.76±0.07	1.38±0.43	0.44±0.07
	40-60	0.79±0.12	0.64±0.15	0.95±0.31	0.47±0.08
	60-100	1.20±0.29	0.71±0.11	1.59±0.82	1.70±0.86
MB (kg ha^{-1}) $^{(7)}$	0-10	202.85±18.36	68.11±7.22	148.49±17.46	170.52±38.29
	10-20	246.01±63.21	155.13±37.88	218.76±38.85	23.03±0.26
	20-40	438.25±110.7	598.02±131.7	539.83±34.76	391.70±55.77
	40-60	169.65±43.75	229.07±65.16	487.25±58.04	275.10±63.90
	60-100	321.27±71.83	319.61±46.18	346.96±9.07	412.59±29.18

$^{(1)}$ = Total organic carbon, $^{(2)}$ = humic substances, $^{(3)}$ humin fraction, $^{(4)}$ humic acid fraction, $^{(5)}$ fulvic acid fraction, $^{(6)}$ light fraction, and $^{(7)}$ microbial biomass.

Table 3. N stocks in all analyzed soil organic matter fractions at different soil layers of the clayey soils group

	Layer	Use			
	cm	Native forest	Pasture	Eucalypt	Sugar cane
		------------------------------------t ha^{-1}------------------------------------			
TOC [(1)]	0-10	2.41±0.33	0.78±0.07	1.11±0.03	1.01±0.09
	10-20	1.49±0.11	1.03±0.19	0.89±0.04	1.00±0.14
	20-40	2.46±0.34	1.55±0.13	1.61±0.13	1.27±0.16
	40-60	2.03±0.30	1.22±0.21	1.31±0.08	0.95±0.11
	60-100	1.65±0.28	2.02±0.22	2.42±0.32	1.36±0.26
HS [(2)]	0-10	2.33±0.03	0.90±0.08	1.29±0.04	1.23±0.09
	10-20	1.48±0.10	1.03±0.08	0.97±0.03	1.07±0.10
	20-40	2.75±0.14	1.77±0.16	1.92±0.10	1.67±0.17
	40-60	1.97±0.03	1.15±0.10	1.56±0.11	1.44±0.06
	60-100	1.84±0.23	1.56±0.13	2.45±0.19	2.74±0.31
HF [(3)]	0-10	1.06±0.06	0.44±0.07	0.57±0.01	0.57±0.04
	10-20	0.63±0.06	0.57±0.09	0.46±0.03	0.52±0.06
	20-40	1.05±0.08	0.84±0.05	0.73±0.04	0.81±0.08
	40-60	0.82±0.06	0.47±0.07	0.75±0.06	0.70±0.01
	60-100	1.03±0.17	0.74±0.14	1.08±0.11	1.09±0.06
HAF [(4)]	0-10	0.78±0.05	0.27±0.04	0.48±0.01	0.43±0.06
	10-20	0.49±0.07	0.29±0.03	0.32±0.02	0.36±0.06
	20-40	1.17±0.08	0.58±0.11	0.74±0.06	0.53±0.07
	40-60	0.65±0.09	0.40±0.08	0.49±0.04	0.48±0.06
	60-100	0.60±0.09	0.47±0.02	0.80±0.06	1.00±0.18
FAF [(5)]	0-10	0.48±0.04	0.19±0.04	0.24±0.04	0.23±0.03
	10-20	0.36±0.02	0.16±0.01	0.19±0.01	0.19±0.04
	20-40	0.53±0.03	0.35±0.05	0.45±0.03	0.33±0.03
	40-60	0.50±0.14	0.27±0.01	0.33±0.01	0.26±0.01
	60-100	0.21±0.02	0.36±0.01	0.57±0.04	0.66±0.11
LF [(6)]	0-10	0.14±0.01	0.03±0.01	0.07±0.01	0.03±0.00
	10-20	0.04±0.01	0.02±0.01	0.02±0.00	0.02±0.00
	20-40	0.08±0.01	0.02±0.00	0.04±0.02	0.02±0.00
	40-60	0.02±0.01	0.02±0.00	0.03±0.01	0.02±0.00
	60-100	0.03±0.01	0.02±0.00	0.04±0.02	0.07±0.03
MB (kg ha^{-1}) [(7)]	0-10	7.05±1.58	19.91±3.07	11.57±1.15	24.06±0.80
	10-20	4.66±1.32	21.99±1.27	14.74±0.65	48.80±5.20
	20-40	11.96±2.09	56.40±3.55	31.73±5.69	8.49±1.14
	40-60	49.65±5.08	41.25±12.48	28.30±3.75	6.83±0.52
	60-100	55.19±6.93	28.36±2.68	33.81±4.31	79.70±16.35

(1) = Total organic carbon, (2) = humic substances, (3) humin fraction, (4) humic acid fraction, (5) fulvic acid fraction, (6) light fraction, and (7) microbial biomass.

Table 4. C stocks in all analyzed soil organic matter fractions at different soil layers of the sandy soils group

	Layer	Use			
	cm	Native forest	Pasture	Eucalypt	Sugar cane
		------------------------------------t ha^{-1}------------------------------------			
TOC $^{(1)}$	0-10	22.77±2.56	10.72±1.20	13.26±0.43	11.13±0.55
	10-20	13.74±0.96	10.82±1.62	11.52±0.32	8.83±0.57
	20-40	18.72±2.01	13.05±0.48	20.62±0.80	15.84±1.48
	40-60	21.01±3.13	12.84±1.90	13.95±1.59	13.11±0.74
	60-100	27.26±1.22	12.97±2.28	21.82±1.90	26.08±4.25
HS $^{(2)}$	0-10	16.79±2.12	8.53±0.32	10.70±0.24	8.57±0.48
	10-20	10.97±0.98	8.17±0.82	8.84±0.39	8.67±0.31
	20-40	12.77±1.19	11.24±1.12	14.19±1.04	13.30±0.50
	40-60	15.17±2.54	11.64±1.57	11.51±0.64	9.68±0.39
	60-100	23.12±3.31	13.66±0.99	20.98±0.72	16.05±1.12
HF $^{(3)}$	0-10	8.15±1.05	4.45±0.04	5.80±0.08	5.61±0.36
	10-20	5.26±0.71	4.44±0.68	5.16±0.45	4.60±0.64
	20-40	6.38±0.83	5.98±1.13	8.49±0.96	7.51±0.92
	40-60	8.04±1.66	7.08±1.40	6.38±0.19	4.29±0.76
	60-100	11.94±2.99	7.92±0.66	11.26±0.45	9.50±0.38
HAF $^{(4)}$	0-10	5.71±0.70	2.77±0.19	3.14±0.14	1.63±0.11
	10-20	3.46±0.18	2.23±0.03	2.08±0.19	2.04±0.30
	20-40	3.40±0.75	2.68±0.38	3.23±0.43	2.98±0.37
	40-60	3.83±0.95	2.29±0.17	2.79±0.38	2.73±0.17
	60-100	6.11±0.23	2.42±0.54	5.05±0.30	3.40±0.35
FAF $^{(5)}$	0-10	2.93±0.57	1.31±0.12	1.77±0.06	1.34±0.12
	10-20	2.25±0.28	1.50±0.14	1.60±0.08	2.03±0.52
	20-40	2.99±0.03	2.59±0.24	2.48±0.09	2.81±0.31
	40-60	3.30±0.54	2.27±0.21	2.33±0.18	2.65±0.26
	60-100	5.07±0.59	3.32±0.20	4.67±0.15	3.15±0.92
LF $^{(6)}$	0-10	7.65±2.00	0.08±0.01	2.22±0.28	1.16±0.17
	10-20	5.00±2.51	0.91±0.43	1.22±0.20	0.85±0.12
	20-40	2.04±0.29	1.60±0.11	1.46±0.36	0.99±0.12
	40-60	3.03±0.19	1.22±0.13	0.93±0.13	0.49±0.10
	60-100	1.53±0.71	0.98±0.06	1.25±0.04	0.64±0.04
MB (kg ha^{-1}) $^{(7)}$	0-10	414.28±59.12	219.41±63.39	193.27±13.05	236.39±63.94
	10-20	129.38±24.86	106.87±16.46	204.18±4.46	276.39±63.55
	20-40	345.51±68.85	296.88±80.72	253.33±19.23	324.64±45.68
	40-60	51.48±0.37	296.75±81.81	373.95±22.54	418.53±0.74
	60-100	611.27±157.0	561.98±108.7	719.71±68.88	1251.71±243.45

$^{(1)}$ = Total organic carbon, $^{(2)}$ = humic substances, $^{(3)}$ humin fraction, $^{(4)}$ humic acid fraction, $^{(5)}$ fulvic acid fraction, $^{(6)}$ light fraction, and $^{(7)}$ microbial biomass.

Table 5. N stocks in all analyzed soil organic matter fractions at different soil layers of the sandy soils group

	Layer	Use			
	cm	Native forest	Pasture	Eucalypt	Sugar cane
		------------------------------------t ha^{-1}------------------------------------			
TOC (1)	0-10	1.22±0.19	0.83±0.16	0.80±0.10	0.75±0.09
	10-20	1.19±0.18	0.52±0.08	0.57±0.04	0.64±0.07
	20-40	1.20±0.19	0.90±0.18	0.75±0.09	0.93±0.16
	40-60	0.92±0.12	0.80±0.14	0.57±0.07	0.80±0.20
	60-100	1.14±0.23	1.82±0.34	1.35±0.27	0.93±0.18
HS (2)	0-10	1.15±0.13	0.66±0.04	0.70±0.02	0.67±0.04
	10-20	0.79±0.03	0.55±0.03	0.60±0.02	0.69±0.02
	20-40	0.95±0.15	0.94±0.08	0.96±0.01	1.18±0.06
	40-60	1.01±0.11	0.76±0.08	0.88±0.03	0.81±0.09
	60-100	1.43±0.13	1.20±0.01	1.36±0.01	1.28±0.21
HF (3)	0-10	0.41±0.02	0.25±0.01	0.26±0.01	0.34±0.03
	10-20	0.30±0.01	0.20±0.01	0.22±0.02	0.29±0.03
	20-40	0.34±0.04	0.29±0.02	0.38±0.02	0.48±0.05
	40-60	0.32±0.05	0.29±0.01	0.32±0.03	0.24±0.05
	60-100	0.38±0.07	0.38±0.06	0.43±0.03	0.48±0.08
HAF (4)	0-10	0.49±0.07	0.26±0.03	0.27±0.02	0.19±0.01
	10-20	0.30±0.01	0.21±0.03	0.23±0.02	0.20±0.02
	20-40	0.37±0.06	0.38±0.04	0.35±0.02	0.35±0.02
	40-60	0.41±0.06	0.28±0.05	0.27±0.02	0.24±0.03
	60-100	0.59±0.08	0.40±0.09	0.50±0.02	0.39±0.07
FAF (5)	0-10	0.25±0.05	0.15±0.01	0.17±0.00	0.13±0.01
	10-20	0.19±0.00	0.14±0.01	0.15±0.01	0.20±0.03
	20-40	0.24±0.05	0.28±0.03	0.24±0.03	0.35±0.06
	40-60	0.29±0.00	0.19±0.04	0.29±0.02	0.33±0.01
	60-100	0.47±0.03	0.42±0.04	0.43±0.03	0.41±0.08
LF (6)	0-10	0.32±0.09	0.06±0.01	0.06±0.01	0.04±0.01
	10-20	0.21±0.12	0.03±0.00	0.04±0.01	0.03±0.00
	20-40	0.07±0.01	0.04±0.01	0.04±0.00	0.03±0.00
	40-60	0.11±0.01	0.04±0.01	0.02±0.00	0.01±0.00
	60-100	0.06±0.01	0.03±0.00	0.03±0.00	0.02±0.00
MB (kg ha^{-1}) (7)	0-10	13.11±1.24	19.29±1.87	12.66±0.61	20.00±4.98
	10-20	1.09±0.22	11.55±0.43	11.69±0.41	25.15±4.19
	20-40	4.47±0.45	29.27±1.68	23.99±2.99	23.55±3.69
	40-60	4.58±1.22	16.88±0.45	20.12±0.77	85.54±1.30
	60-100	16.44±4.55	18.93±2.50	30.62±2.45	119.35±12.59

(1) = Total organic carbon, (2) = humic substances, (3) humin fraction, (4) humic acid fraction, (5) fulvic acid fraction, (6) light fraction, and (7) microbial biomass.

CHAPTER II

SOIL ORGANIC CARBON MODELLING AFTER FOUR EUCALYPT HARVESTING CYCLES IN FORMER PASTURE LAND IN SOUTHEASTERN BRAZIL WITH THE CENTURY MODEL

ABSTRACT

The soil organic matter (SOM) has important roles on the carbon (C) cycle and soil quality. Considering the complexity of factors which control the SOM cycling and the long time that it usually takes to SOM stocks changes to be observed, the modelling constitutes a very important tool to understand the SOM cycling in forest soils. So, the aims of the current study were: (i) to evaluate the SOM dynamics using the Century model to simulate the changes of C stocks for two eucalypt plantation chronosequences in the Rio Doce Valley, Minas Gerais State, Brazil; (ii) to compare the C stocks simulated by Century with the C stocks measured in soils belonging to different orders at distinct regions in the Rio Doce Valley cultivated with eucalypt, and (iii) to evaluate the impact of removal of the eucalypt bark from the site during harvest operation in the C stocks. In the Belo Oriente (BO), a lower elevation and warmer region, short-rotation eucalypt plantations has been cultivated for 4.0; 13.0, 22.0, 32.0 and 34.0 years, while in the Virginópolis (VG), a higher elevation and milder climate region, those time periods were 8.0, 19.0 and 33.0 years. Thus, it was determined soil C stock in the 0-20 cm layer. The results indicate that the C stocks simulated by the Century model decreased after 37 years of poorly managed pastures in areas previously covered by native forest in the BO and VG regions. The substitution of poorly managed pastures by eucalypt in the early 70`s led, on average, to increases of 0.28 and 0.42 t ha^{-1} year^{-1} of C in BO and VG, respectively. The measured C stocks under eucalypt cultivated in distinct soil orders and independent regions with variable edapho-climate conditions were slightly close to estimated values by the Century model (root mean square error - RMSE = 20.9; model efficiency – EF = 0.29) despite the opposite result obtained with the statistical procedure to test the identity of analytical methods (Leite and Oliveira, 2000). Under conditions of lower soil C stocks the model over-estimated the C stock in the 0-20 cm layer. Model simulation results indicate that the maintenance of the eucalypt bark on site after harvest resulted in greater C sequestration in soil. Thus, the Century model has a great potential to detect changes in the C stocks in distinct soil orders under eucalypt,

as well as to indicate the impact of harvest residue management on SOM in future rotations.

Index terms: soil organic matter, land use change, afforestation, bark removal.

1. INTRODUCTION

Carbon (C) sequestration in soil constitutes an important alternative to decrease CO_2 emissions to the atmosphere and thus to minimise environmental problems (Izaurralde et al., 2006). Several studies have shown the potential of soil organic carbon (SOC) to sequester C in more stable forms (Lal, 2002; Leite et al., 2004; Bayer et al., 2006).

The global SOC contains four times as much C as in the living pool and about thee times as much as in the atmospheric pool (Lal, 2004). Besides acting as a C storage, the SOM contributes to improve the soil quality, suppling nutrients for plants and controlling water and gases fluxes (Woomer et al., 1994; Leite et al., 2004; Gama-Rodrigues et al., 2005). In perennial cultures, such as forestry, the SOM pools are closely related with long-term production sustainability due to the beneficial effect on the soil quality (Morris et al., 1997; Mendham et al., 2004). In fact, it has recently been found that SOM content is the soil characteristic that better correlates with the eucalypt productivity in highly weathered soils in the Rio Doce Valley in Brazil (Menezes, 2005).

Land use changes have the potential to cause either release or sequester C. Consequently, changes in SOC associated with land use have received considerable attention recently due to the need to limit CO_2 emissions (Lemma et al., 2006). One of recommended strategies to mitigate C emissions to atmosphere is to increase afforestation in former agriculture and pasture areas, as has occurred with short-rotation eucalypt in Brazil. However, in a study carried out in Australia, Mendham et al. (2004) observed no difference in the SOC stock when compared *E. globulus* (11-14 years) with pasture in the 0-10 cm layer. On other hand, O'Brien et al. (2003) observed that *Eucalyptus regnans* (10 - > 250 years) contributed to increase the C content in areas previously occupied by pasture in Australia. Also, Lima et al. (2006) observed a increase in soil C stocks (0-20 cm) after four eucalypt rotations in two areas previously occupied by degraded pasture in the Minas Gerais State, Brazil. However, Turner & Lambert (2000) observed a decrease in the C stock in the 0-10 cm layer of soil after five years of *Eucalyptus grandis* cultivation in area previously with pasture in Australia. These authors estimated that only after 20 years of eucalypt cultivation the SOM stock would return to the original level. This lack of consistency in experimental results seems that indicated that the direction of SOM changes is highly dependent on previous use and the time since land use change had occurred.

Considering the complexity of factors that control the SOM dynamics and the long time that takes to SOM changes be observed and quantified, researchers have looked for alternatives to better understand SOM. These complex relations can be better understood by combining modelling with datasets from experimental areas (Diels et al., 2004; Izaurralde et al., 2006). The Century model simulates the SOM decomposition, C, N, P, and S fluxes into and among several soil compartments (Parton et al., 1987, 1988, 2004). It has been utilized with success in several temperate ecosystems (Kelly et al., 1987; Del Grosso et al., 2001) and, in a few cases, under tropical conditions (Motavalli et al., 1994; Parton et al., 2004; Leite et al., 2004). This lack of information is particularly true for short-rotation eucalypt in Brazil. Additionally, there are no studies where model simulations for short-rotation eucalypt has been carried out for planting regions with distinct soil and climate conditions. So, the effects of eucalypt establishment on SOM dynamics are virtually unknown. Therefore, the aims of this study were: (i) to evaluate the SOM dynamics after pasture substitution by plantations using the Century model for two eucalypt chronosequences; (ii) to compare the C stocks simulated by Century with the C stocks in different soil orders in eight regions of the Rio Doce Valley that have been cultivated with eucalypt for about 28 years (four rotations), and (iii) to evaluate the impact of eucalypt debarking on site during harvest on the C stocks.

2. MATERIALS AND METHODS

The present study involved the utilization of the Century model for simulating the dynamics of C stocks after the eucalypt establishment on pasture land. Since there are no long-term records for the calibration of the Century model to evaluate the SOM dynamics in short-rotation eucalypt plantations, this study evaluated the performance of the Century model in simulating the temporal changes pattern for two eucalypt chronosequences. Also, it was simulated the SOC stocks for independent eucalypt stands located in eight regions with distinct soil order and climate. Because eucalypt bark is removed from site to energy production, we also simulated the effect of removal of the eucalypt bark from the site in the long-term SOM stocks.

2.1 The Century model

The Century model is a plant-soil ecosystem model that simulates plant production, soil C turnover, soil nutrients cycling, and temperature and soil water (Parton et al., 1987, 1988, 1993). Initially, this model was used to simulate the biomass production and the SOM dynamics in the prairie ecosystem of the United States (Parton et al., 1987), and modified to be used also in forest ecosystems (Motavalli et al., 1994; Kirschbaum & Paul, 2002). However, the utilization of Century in the tropical soils without adequate calibration has been questioned (Gijsman et al., 1996; Leite, 2002). The SOM and nutrient sub-models represent the flow of C, N, P and S in plant litter and different organic and inorganic soil pools, with mineralization of soil nutrients primarily resulting from turnover of SOM pools. The plant production sub-model calculates plant production and allocation of nutrients to live aboveground and belowground compartments as a function of climatic factors and available soil nutrients. Key variables are monthly precipitation and monthly average minimum and maximum temperatures. Soil texture, litter N, lignin content and tillage disturbance are also important rate-controlling factors. In the Century model, the SOM is shared in tree compartments: active, slow and passive. The active pool includes soil microbes and microbial products with short turnover time (1-3 months). The slow SOM pool includes resistant plant material derived from structural plant material and stabilized soil microbial products that have turnover times ranging from 10 to 50 years, depending on the climate. The passive pool includes physically and chemically stabilized SOM that is very resistant to decomposition (cycling time from 400 to 4000 years), usually represented by the humic substances pool. The complete description of the Century model structure and the equations used to describe the C and nutrients fluxes are showed by Parton et al. (1987, 1988, 1993).

2.2 The eucalypt plantations chronosequences

The chronosequences of the eucalypt plantations are located in the Belo Oriente (BO) and Virginopolis (VG) regions. The BO region has an elevation of 250 m above sea level (masl), annual mean temperature of 25 °C, and eucalypt stem (without bark) productivity at seven years of 26 m^3 ha^{-1} $year^{-1}$. The soil is a clayey Yellow Latosol

(Oxisol). The VG region has an elevation of 850 masl, annual mean temperature of 22 °C, and eucalypt stem productivity at seven years of 42 m^3 ha^{-1} $year^{-1}$. The soil is a clayey Red Latosol (Oxisol). The distance between those two regions is approximately 100 km, and since they have very similar rainfall rate and distribution over the year, they offer a good opportunity to evaluate the C addition and the different edaphic-climate conditions (mainly altitude and clay content) on the SOM dynamics after the substitution of the poorly managed pastures by short-rotation eucalypt. The length of the harvesting cycle in all regions is around 7 years.

In the BO region, eucalypt stands have been cultivated for 4.0; 13.0, 22.0, 32.0 and 34.0 years, while in the VG region those time periods were 8.0, 19.0 and 33.0 years (Table 1). In each region, areas under Atlantic forest and pastures located near the eucalypt stands were also selected for sampling. Currently, the total area with eucalypt in each region covers approximately 30,000 ha. The eucalypt sites selected for soil sampling are representative of each region and they covered approximately 10 ha and were located in the middle slope position. Soil samples were collected between tree rows, in the 0–20 cm layer, after digging a pit about 40 cm deep. Also, intact soil samples were taken to determine soil density. Three replicates were randomly assigned to each stand. Each replicate was set apart by more than 500 m and consisted of a composite of four soil samples randomly collected 20 m apart from each other. Soil sampling was carried out during the rainy season, in stands as close as possible to harvest age. The same procedure was used to sample soils in adjacent native forest and pasture.

In each region, the tropical forest (Atlantic forest) (IBGE, 1993) is constituted by trees that average more than 12 m of height. This forest is the dominant in the Rio Doce Valley and covers approximately 30.56% of the total region area (Drumond, 1996). Among of main tree species found in the native forest are: *Newtonia contorta, Pouteria sp.*, *Sloaneae sp.*, *Endlicheria paniculata*, *Carpotroche brasiliensis*, *Ocotea odorífera* and *Sorocea bonplandii*, *Brosimum*. The pastures (*Melinis minutiflora*) were established in 1930s after slashing and burning the native forest. In that period, the areas under pasture were not fertilized and, additionally, they were overgrazed. So, there was laminate erosion due to the practice of annual burn during the dry winter, leading to soil surface exposure to erosion by direct rain impact, which resulted in degraded pastures. In 1969, the eucalypt plantation replaced the pasture (Fig. 1). The first eucalypt stand (*Eucalyptus urophylla*) was planted manually after burning the pasture. After a seven year (harvesting cycle) the trees were harvested (clear cut) and removed from the area. Then, the tree residues were burnt to clear the area for the second cycle. Until the third eucalypt harvesting cycle, the harvest operation involved the cutting and removal of the wood from the area and burning the tree residues. The burn of the forest residues was gradually discontinued since the fourth harvesting cycle. In all rotations debarking was performed off site, with no bark returned to the site. Except to the harvest, the management practices were carried out manually due to the steep relief.

Table 1. Soil use, age and physical characteristics for the 0-20 cm layer soils of two chronosequences of eucalypt plantations in the Belo Oriente (BO) and Virginópolis (VG) regions

Soil use	Age	Sand	Silt	Clay	S.D.
	(years)	--------------(g kg^{-1})	-------------		(Mg m^{-3})
Belo Oriente					
Native forest	-	370	60	570	1.09
Pasture	-	460	70	470	1.37
Eucalypt	4.0	290	90	620	1.22
Eucalypt	13.0	360	50	590	1.14
Eucalypt	22.0	240	70	690	1.15
Eucalypt	32.0	310	40	650	1.40
Eucalypt	34.0	370	50	580	1.41
Virginópolis					
Native forest	-	320	40	640	0.87
Pasture	-	300	50	650	0.91
Eucalypt	8.0	450	30	520	1.13
Eucalypt	19.0	240	70	690	0.96
Eucalypt	33.0	250	50	700	0.93

S.D. –Soil density

Figure 1. Overview of land use changes that occurred in the study site.

2.3 The eight distinct regions in the Rio Doce Valley

The eight distinct regions in the Rio Doce Valley where the eucalypt plantations were established are: 1. Belo Oriente (BO), 2. Nova Era (NE), 3. Santa Bárbara (SB), 4. Virginópolis (VG), 5. Sabinópolis (SAB), 6. Correntinho (COR), 7. Ipaba (IP) and 8. Cocais (CO) (Fig. 2). The climate according to the Köppen classification of the BO and IP regions is Aw (humid subtropical), while for other regions is Cwa (tropical wet-dry) (Nimer, 1989) (Table 2).

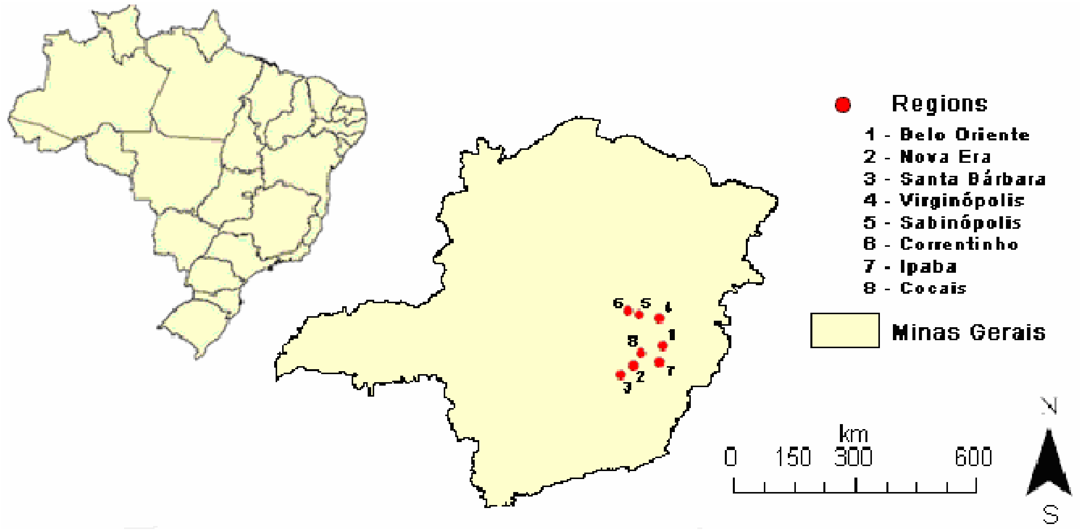

Figure 2. Geographic localization of the eight regions being studied in the Rio Doce Valley, Minas Gerais State, Brazil.

Table 2. Climate characteristics and elevation of the studied areas (sites)

Climate characteristic	PPT	$\overline{T}_{anual}$	$\overline{T}_{max}$	$\overline{T}_{min}$	Elevation
	mm		°C		masl
Belo Oriente	1,163	25.0	31.2	18.9	250
Nova Era	1,444	18.5	21.9	15.6	837
Santa Bárbara	1,450	22.3	27.2	17.3	838
Virginópolis	1,153	22.0	22.8	15.3	850
Sabinópolis	1,183	21.7	26.7	15.9	899
Correntinho	1,342	20.0	24.3	16.6	843
Ipaba	1,204	24.8	31.2	18.9	276
Cocais	1,281	20.7	25.2	15.1	1016

PPT = Average annual precipitation, $\overline{T}_{anual}$ = Average annual temperature, $\overline{T}_{max}$ = Average maximum temperature, $\overline{T}_{min}$ = Average minimum temperature

Sites in the eight distinct regions that had been under short-rotation eucalypt plantations for 28 years (four rotations) were selected in order to cover main different soil orders (Table 3). Furthermore, we also selected areas under native forest (Atlantic forest) that were near the eucalypt plantation as references.

Table 3. Soil order, use, texture and soil density (0-20 cm) of soils under native forest and eucalypt plantations and eucalypt productivity (mean annual increment) for the eight regions in study.

Soil order ⁽¹⁾	Soil use	Sand	Silt	Clay	S.D.	Eucal. stem produc. ⁽¹⁾
		--------------($g\ kg^{-1}$)		--------------	($Mg\ m^{-3}$)	($Mg\ C\ ha^{-1}yr^{-1}$)
Belo Oriente (BO)						
Oxisol	Native forest	280	50	670	1.14	
Oxisol	Eucalypt	250	60	690	1.41	7.1
Inceptisol	Eucalypt	280	70	650	1.42	6.8
Entisol	Eucalypt	480	190	330	1.46	7.3
Nova Era (NE)						
Inceptisol	Native forest	420	90	490	1.10	
Oxisol	Eucalypt	530	30	440	1.27	8.6
Inceptisol	Eucalypt	370	80	550	1.17	6.9
Santa Bárbara (SB)						
Oxisol	Native forest	420	90	490	1.24	
Oxisol	Eucalypt	390	110	500	1.26	8.6
Inceptisol	Eucalypt	430	100	470	1.45	7.5
Virginópolis (VG)						
Inceptisol	Native forest	520	120	360	1.22	
Oxisol	Eucalypt	220	60	720	1.07	10.9
Inceptisol	Eucalypt	370	100	530	0.85	8.8
Sabinópolis (SAB)						
Oxisol	Native forest	390	60	550	1.15	
Oxisol	Eucalypt	340	50	610	1.26	7.7
Inceptisol	Eucalypt	220	100	680	1.22	8.3
Correntinho (COR)						
Oxisol	Native forest	60	130	810	0.84	
Oxisol	Eucalypt	60	100	840	0.97	8.8
Inceptisol	Eucalypt	220	100	680	1.22	8.8
Ipaba (IP)						
Inceptisol	Native forest	320	80	600	1.26	
Oxisol	Eucalypt	310	60	630	1.55	7.3
Entisol	Eucalypt	640	120	240	1.65	7.3
Cocais (CO)						
Inceptisol	Native forest	500	100	400	1.07	
Oxisol	Eucalypt	340	50	610	1.13	8.6
Inceptisol	Eucalypt	440	110	450	1.18	9.6

S.D.: Soil density; ⁽¹⁾ at seven year-old.

Unfortunately, the extensive forest clearing for pasture introduction in the past century left only a few forest remnants in the region, thus sampling the same soil order under all uses was no possible. The management practices since the substitution of the native forest by pastures, and more recently by eucalypt, were similar as described above.

2.4 Soil analysis

Soil samples were air-dried and passed through a 2 mm sieve. Sub-samples were taken form texture analysis (Tables 1 and 3). Soil samples were also ground in an agate mortar to pass in a 100 mesh (0.149 mm) sieve for organic C determination by a wet – chemical procedure (Yeomans & Bremner, 1988). The C stocks in each land use were calculated by multiplicating the SOC concentration by the soil mass of the native forest, to avoid the effect of soil compaction. We are sure that pseudo-replication is a limitation of the present study, as in many other paired-site studies (Vesterdal et al., 2002; O’Brien et al., 2003; Chen et al., 2004, Lima et al., 2006). This was necessary in order to set a “time series” and to restrict soil variability to the site level.

2.5 Calibration of the Century model

The century 4.0 parameterisation and calibration was carried out for the BO chronosequence. The monthly climate parameters were obtained from climatologic stations located near the study sites, and for the 1985-2005 period (Table 2). Other properties as soil texture (sand, silt and clay), soil density and soil C stocks were measured in each site (Table 1 and Fig. 2). The productivity and quality (C/N, lignin/N, etc) data of biomass material of eucalypt were obtained from the literature, and whenever possible from studies carried out in the local conditions (Leite, 1995; Ladeira (1999); Faria (2000)) (Table 4). Once adequately calibrated for the BO region, we evaluated the performance of the Century model to simulate the SOM dynamics for the other eucalypt chronosequence, as well as for the eight independent regions (see below).

The equilibrium simulation of soil C stock using the native forest as reference was performed for a period of 7,000 years before starting the simulations of soil use changes. The Atlantic forest productivity simulated at equilibrium was 115.7 t ha^{-1}, while the actual measured productivity was 112.0 t ha^{-1} (Drumond, 1996). The equilibrium simulation values were utilised as input data for simulating the impact of land use changes on SOM.

Table 4. General inputs of eucalypt used for calibration of the Century model

Input	Leaf	Fine root	Fine branch	Trunk	Coarse root
C/N	20 (1)	182 (2)	160 (3)	400 (1)	178 (3)
C/P	400 (1)	267 (2)	1000 (1)	8000 (1)	102 (2)
Lignin (%)	41.1	28.2	21.7	22.1 (4)	28.2
Assumed C allocation (%)	1.05	2.7	2.7	84.8	8.8

(1) Leite (1995); (2) Ladeira (1999); (3) Faria (2000); (4) Paul et al., (2004). We assumed same lignin percentage for fine e coarse root. The C allocation of fine roots refers to the sum of C allocation to the medium and fine roots.

2.6 Evaluation of the previously calibrated Century model

It was evaluated the performance of Century model calibrated for the BO region in simulating the SOM dynamics in the VG chronosequence. It was also run independent simulation of SOM stocks for eucalypt under different soil orders at the eight regions in study. Local conditions included climate data (temperature, precipitation), soil texture, soil C stocks, soil density, soil use and management practices (historic use, burn, harvest type). The soil C stocks were estimated by the Century model 4.0, and the estimated values were compared with measured values for each region. Additionally, the effect of eucalypt debarking on site during harvest on the soil C stocks was simulated for the BO region for a period of approximately 100 years, starting in 2003. For that simulation it was considered a mass of eucalypt bark of 7.8 t ha^{-1}.

It was computed the relative difference (%) between simulated values and measured values for each soil order and region in study. After calibration, it was determined how well the Century model predicted the SOC stocks by calculating the model efficiency (EF), a statistic analogous to R^2, as defined by Soares et al., (1995):

$$EF = 1 - \left(\frac{\sum (yi - \hat{y}i)^2}{\sum (yi - \overline{y})^2} \right)$$

where y_i are the measured/observed values, $\hat{y}i$ are the predicted values, $\overline{y}$ is the mean of the measured data. The EF values may be negative or positive with a maximum value of 1. A negative value indicates that the simulated values describe the trend in the measured data less well than a mean of the observations. A positive value indicates that the simulated values describe the data much better than the mean of observations, with a value of 1 indicating a perfect fit. Also, all results were compared by root mean square error (RMSE) (Cerri et al., 2007; Kamoni et al., 2007). Methodological details may be found in Smith et al. (1997).

$$RMSE = \frac{100}{\overline{y}}\sqrt{\left(\frac{\sum_{i=1}^{n}(\hat{y}i - yi)^2}{n}\right)}$$

Where $\hat{y}i$ are the predicted values, $\overline{y}$ are the mean measured data, y_i are measured values, and n is the number of paired values. An statistical procedure to test the identity of analytical methods ($\alpha = 0.05$) was also applied according to Leite and Oliveira (2000). The proposed procedure results from the combination of the F test modified from Graybill (1976), t test for the medium error, and analysis of the linear correlation coefficient to check if the simulated values by the Century model differ from the measured values. Based on these informations, it is proposed a decision rule to test the hypothesis of identity between two analytical methods or any two vectors, that is, groups of quantitative data.

3. RESULTS

3.1. Measured SOC stocks

The BO region

Under the equilibrium condition, the SOC stock for the native forest was 53.0 t ha^{-1} (Fig. 3). The results indicated substantial variations in the SOC stock when the native forest was replaced by pasture, which in turn was substituted by short-rotation eucalypt. As expected for a system at the steady-state, the native forest presented stable SOC stock up to 1931, but it was observed a 40.5% reduction of SOC due to the establishment of pasture (31.5 t ha^{-1}). On the other hand, four rotations of eucalypt plantation in soils previously under poorly managed pasture favoured the recover of the SOC stock. After 34 years of eucalypt cultivation the observed SOC stock was 41.5 t ha^{-1} (31.7% greater than in the soil previously under pasture).

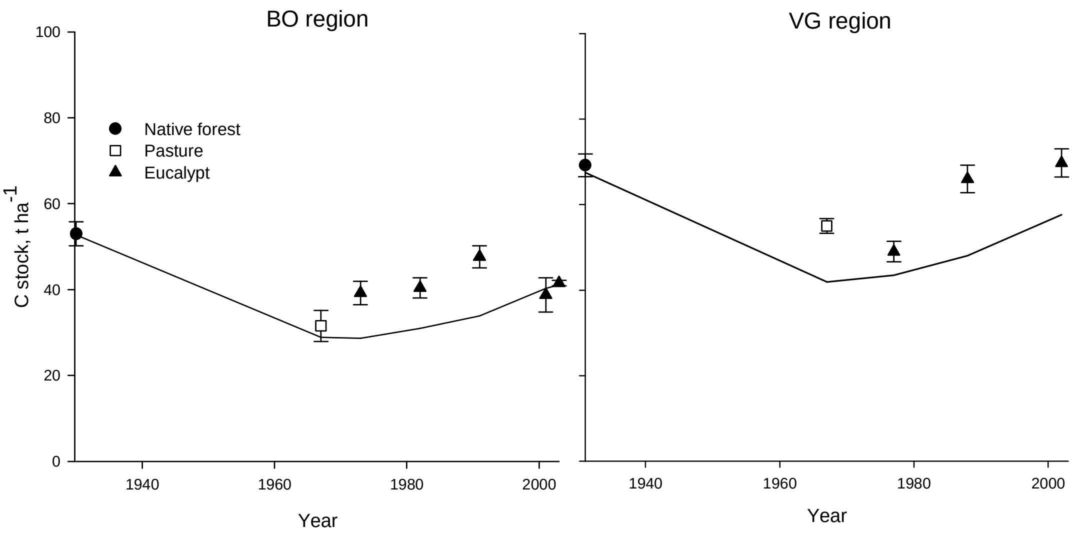

Figure 3. Observed (symbols) and simulated (solid line) SOC stocks by Century for the 0-20 cm layer of soils of the eucalypt cultivation chronosequences in the Belo Oriente (BO) and Virginópolis (VG) regions.

The VG region

The observed SOC stock for the soil under native forest was 69.2 t ha^{-1} in the VG region (Fig. 3). For pasture, it was observed a SOC stock of 55.0 t ha^{-1}, indicating a reduction of 20.5% of SOC in comparison with that under native forest. After four rotations, eucalypt planted on pasture soil led to an increase of 26.8% (69.7 t ha^{-1}) in the SOC stock.

3.2. Simulated SOC stocks

The BO region

In the BO region, the simulated SOC stock for the native forest was 52.7 t ha^{-1}, while 37 years of pasture cultivation after forest removal resulted in a reduction of 45.2% (28.9 t ha^{-1}) (Fig. 3). Contrastingly, four eucalypt rotations resulted in a SOC stock of 41.1 t ha^{-1}, an increase of 42.2% of the SOC stock in relation to the pasture soil.

The VG region

Following the calibration for the BO region, independent simulations with the Century model estimated a SOC stock of 67.5 t ha^{-1} for the native forest in the VG region (Fig. 3). For the pasture soil was estimated to have 37.9% lower SOC stock (41.9 t ha^{-1}) than that under previous vegetation (native forest). The Century model indicates that 33 years of eucalypt (57.6 t ha^{-1}) cultivation resulted in a 37.5% increase of the SOC stock in relation to the previous pasture use.

3.3. Observed and simulated SOC stocks for different soil orders and regions

For the BO region, the simulated SOC stock for the Oxisol under native forest was 11.6% higher than the measured SOC stock, while the difference was only -3.5% in the Santa Barbara (SB) region (Fig. 4). In the BO and SB regions, the simulated SOC stocks for the Oxisol under eucalypt differed 8.2 and -8.2% from the observed values, respectively. For the BO region, the simulated SOC stocks for the Inceptisol and Entisol under eucalypt differed -9.6 and -9.1% from the measured values, respectively. In the SB region, the simulated SOC stock for the Inceptisol under eucalypt was 17.5% lower than the measured SOC stock.

For the Nova Era (NE) region, the simulated SOC stock for the Inceptisol under native forest was 15.0% less than the measured SOC stock. Conversely, in the VG region the difference was only -5.8%. In the NE and VG regions, the simulated SOC stocks for the Oxisols under eucalypt were 27.5% and 17.8% lower than the observed SOC stocks, respectively. In NE, the simulated SOC stock differed only -4.9% from the observed SOC stock for the Inceptisol under eucalypt, while that for the VG region the difference was -32.6%.

For the Sabinópolis (SAB) and Correntinho (COR) regions, the estimated SOC stocks for the Oxisol under native forest differed -18.6% and +17.7% in comparison to the observed SOC stocks, respectively. For the Oxisol under eucalypt the difference was -18.6% in SAB and +7.3% in COR. In the Inceptisol under eucalypt the estimated SOC stock was only 0.6% lower than the observed SOC stock in the SAB region and only 0.1% less than the observed SOC stock in the COR region.

In the Ipaba (IP) region, the estimated SOC stock for the Inceptisol under native forest was 33.8% lower than the observed SOC stock, while the difference was only -3.6% in the Cocais (CO) region. For the Oxisol under eucalypt the difference of the simulated SOC stock in comparison to the observed SOC stock was -1.05% in the IP region and -38.7% in the CO region. In the IP region, the estimated SOC stock by Century was 16.4% smaller than the observed SOC stock for the Entisol under eucalypt. However, for the Inceptisol under eucalypt in the CO region the difference was -22.3%.

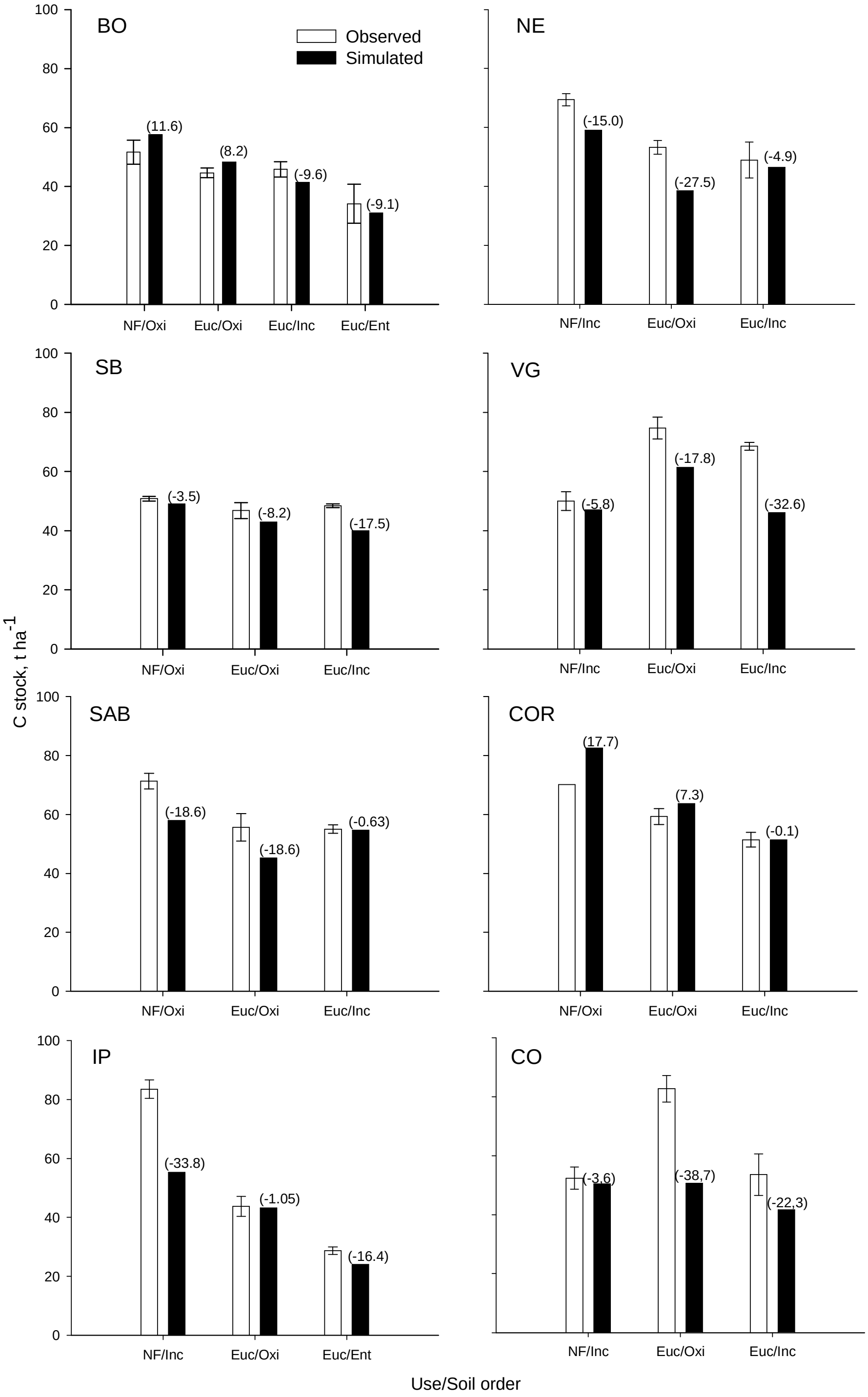

Figure 4. Observed and simulated SOC Stocks for the 0-20 cm layer of soils of the Belo Oriente (BO), Nova Era (NE), Santa Bárbara (SB), Virginópolis (VG), Sabinópolis (SAB), Correntinho (COR), Ipaba (IP) and Cocais (CO) regions. The values between parentheses refer to the difference (%) between simulated and observed values. NF – Native forest, Euc – Eucalypt, Oxi – Oxisol, Inc – Inceptisol, Ent – Entisol.

3.4. Effect of eucalypt debarking during harvest on SOC stocks

Thinking in the long-term sustainability of the eucalypt productivity, we used the calibrate Century model to simulate SOC changes as influenced by adoption or not of on-site eucalypt debarking for the next 13 rotations (100 years, starting in 2003). The simulation results indicated that the SOC stocks would increase by 18.3 t ha^{-1} (0.2 t ha^{-1} yr^{-1}) in the BO region (Fig. 5). The maintenance of the eucalypt bark on soil surface after harvest would result in an increase of 5.4% in the SOC stock as compared to its removal. So, the maintenance of bark would result in a SOC stock of 62.6 t ha^{-1} in comparison to the SOC stock of 59.3 t ha^{-1} if bark were to be removed from the site.

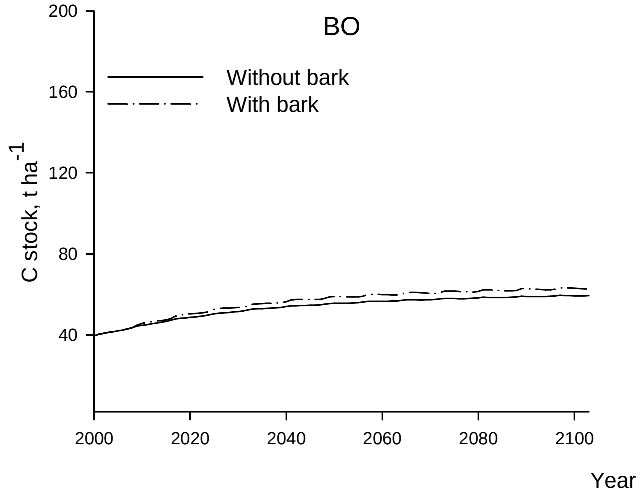

Figure 5. Long-term simulated organic C stocks in the 0-20 cm layer of soils in the Belo Oriente (BO) managed with or without removal of the eucalypt bark (starting 2003) during harvest.

4. DISCUSSION

The efficiency of a model can be assessed by calculating the root mean square error (RMSE) (Cerri et al., 2007; Smith et al., 1997). The RMSE value of 20.9% found in the present study indicates that the values simulated by the Century model were, in general, close to the measured values. This RMSE value is comparable to (or in some cases greater than) those found by Cerri et al. (2007) who evaluated the performance of the Century model to simulate data from 11 land use change chronosequences in the

Brazilian Amazon and found RMSE values around 20%, showing accurate results and supporting the idea that the utilization of Century constitutes a good alternative to study the SOM dynamics in different edapho-climatic conditions and soil uses (Diels et al., 2004; Parton et al. 2004; Izaurralde et al., 2006). RMSE can also be used directly to compare errors in simulations made by different models, in which a lower value of RMSE indicates a more accurate simulation (Smith et al., 1996). Given the limitations of using chronosequences based on farmers practice compared to well-designed long-term experiments, this degree of agreement between soil C measurements and models values is considered satisfactory (Cerri et al., 2007). Also, the coincidence between measured and simulated values by the Century model was verified by calculating the model efficiency (EF) according to Soares et al. (1995). The model efficiency was positive (EF = 0.29) meaning that the Century's simulations explained the SOC dynamic better than an arithmetic mean, despite the fact that in soils with lower C stocks the model over-estimated the C stocks in the 0-20 cm layer (Fig. 6). In a study evaluating C and N stocks in soils under different uses and managements and their modelling by Century in Minas Gerais State, Brazil, Wendling (2007) showed that the Century model satisfactorily simulated the soil C and N stocks, which was supported by the similarity between simulated and measured stocks. According to the statistical procedure suggested by Leite and Oliveira (2000), in general, the values simulated by Century differ from the measured values (significant F test, $\alpha = 0.05$), based on which it was concluded that, simultaneously, β_0 and β_1 are different from 0 and 1, respectively (despite β_1 = 1 by test t, equation slope is equal to 1). Additionally, the t test for the mean error ($t\bar{e}$) indicates that the differences between the simulated and measured values are caused by random factors. This test is very conservative because it takes into account a series of statistical restrictions. Although the linear correlation coefficient between simulated and measured values was relatively high (r = 0.75), the use of this coefficient, separately, is not enough to decide about the identity of two methods (simulated and observed values in the present case) due to the possibility of the intercept and of the regression coefficient to be quite different from 0 and 1, respectively (Leite & Oliveira, 2000).

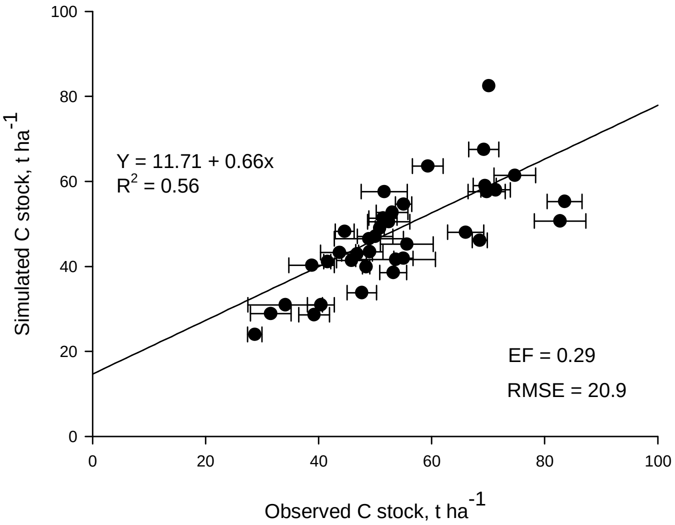

Figure 6. Relationship between the observed and simulated SOC stocks by the Century model for all regions in study. EF = Model efficiency, RMSE = root mean square error.

The Century model was parameterized and calibrated to simulate the equilibrium of SOC stocks for the BO region. Under the equilibrium conditions, the simulated SOC stock in the native forest was very similar to the observed SOC stock, with a difference of only -0.57 %. Leite et al. (2004) and Cerri et al., (2004) also found such close agreement between the observed TOC and simulated TOC stocks by Century for native forests in Brazil.

Soil use changes have great regional and local implications in the C cycle. The observed and simulated SOC stocks showed a reduction after substitution of native forest by pasture in the BO and VG regions (Fig. 3). That decrease can be attributed to the poor management of the pasture, employing extensive grazing with low inputs and annual burn, combined with soil erosion due to the steep relief, resulting in large CO_2 emission to the atmosphere. Utilizing the Century model, Polyakov & Lal (2004) observed that the erosion has a preponderant role on SOM loss and on CO_2 emission. The importance of adequate pasture management was evidenced in a study where simulations of SOC changes in 11 land use chronosequences from the Brazilian Amazon with the RothC and Century models, where it was predicted that forest clearance and conversion to well managed pastures would cause an initial decline in soil

C stock (0-20 cm depth), followed by a slow recover to levels that could even exceed those under native forest in the majority of cases (Cerri et al., 2007).

The establishment of the eucalypt plantation in the BO and VG regions resulted in an increase of the SOC stock in comparison to the pasture use (Fig. 3). In the BO region the increment was 0.28 t ha^{-1} year^{-1}, while for the VG region it was 0.42 t ha^{-1} year^{-1}. Successive eucalypt rotations with average productivities increasing from 3.8 Mg C ha^{-1}year^{-1} in the 60s to 8.8 Mg C ha^{-1} year^{-1} in current years (Barros & Comerford, 2002) contributed substantially for higher deposition of organic residues and, consequently, increase on SOM. Furthermore, the adoption of the minimum tillage without biomass burning and reduced erosion during the establishment of the eucalypt plantation surely contributed for such gains. In a recent review, the mean rate of C sequestration in the 0–20 cm layer of no-tillage soils located in the subtropical Southern region of Brazil was estimated to be 0.48 Mg ha^{-1} year^{-1} and it is higher than 0.35 Mg ha^{-1} year^{-1} observed for the tropical region of Brazil (Bayer et al., 2006). Thus, for the eucalypt rotations the rates of C sequestration in the BO region paralleled those found for soils cultivated with annual crops in the warmer tropical region of Brazil, whereas the potential for C sequestration of the VG region is somewhat similar to that found for the milder subtropical region of Brazil.

These results highlight the great potential that short-rotation eucalypt has to increase C sequestration in soils previously occupied by pastures. One question that remains, however, is whether the C build up will continue and for how long. The net change will probably depend on previous land use (Silver et al., 2000). In a study conducted in an area under regenerated native forest (*Eucalyptus regnans*) after wild fire in Australia, O'Brien et al. (2003) observed that the *Eucalyptus regnans* cultivation (10 to >250 years) resulted in increases of the SOC content, but the decrease in soil density permitted no gains in the SOC stocks. Evaluating the soil C sequestration under different exotic species in the Southwestern highlands of Ethiopia, Lemma et al. (2006) observed that the afforestation with *E. grandis* for 20 years returned the SOC to nearly the level of the native forest following 35 consecutive years of pasture and 20 years of agriculture. The data reviewed by Guo and Gifford (2002) indicated that conifer planting in soil previously occupied by pasture decreased the SOC in 12 %, while the implantation of broad leaf species (*Eucalyptus* and *Populus*) caused no changes in SOC. Turner & Lambert (2000) observed decrease of SOC in the 0-10 cm layer in soil with five years under E. *grandis* plantation in area previously occupied by pasture in

Australia. Theses authors estimated that the return of C to initial level would occur with approximately 20 years of eucalypt cultivation.

The sensibility of the Century model for variations in soil use under different soil and climate conditions, presented in this work, showed the great potential that this model has to detect SOM changes in the long-term. So, it can be utilized as a tool to help the adoption of management practices that favour the increase of soil C. The SOC stocks simulated by the Century model for native forest, pasture and eucalypt plantations in the VG chronosequence were higher than the SOC stocks in the BO chronosequence (Fig. 3). The higher clay content plus lower average annual temperature (Tables 1 and 2) in the VG region can have contributed for this. On clay particles, the C is stabilised mainly by association with soil minerals, resulting in protection against the biologic degradation (Schulten & Leinweber, 2000; Kaiser et al., 2002; Dalmolin et al., 2006). In soils under eucalypt, pasture and native forest in 10 Australian sites, with SOC varying from 19 to 83 g kg^{-1} (0-10 cm), Mendham et al. (2002) observed that, in general, clayeyer soil presented larger SOC contents and lower C mineralization rates. Studying Ferralsol profiles along a climosequence in Southern Brazil, Dalmolin et al. (2006) observed that the organic matter content increased from the lowest to the highest sites (440-950 m altitude) as result of an increase in rainfall and a decrease in temperature. This influence was more pronounced in the clayey Ferralsols, suggesting that the organic matter accumulation was enhanced by soil organic matter-mineral interactions. In addition, the eucalyptus stem productivity in the VG region (10.5 Mg C ha^{-1} yr^{-1}) was higher than in the BO region (6.5 Mg C ha^{-1} yr^{-1}), which contributes substantially to increase the organic residue deposition and, consequently, SOC stocks (Leite, 2001). Integrating informations on use history, climate and soil characteristics with the Century model, Ardö & Olsson (2003) obtained good approximation of SOM cycling in relation to climate and management for soils under annual crops of the semi-arid region in Sudan. Also, utilizing the Century model in a study carried out in the Brazilian Amazon, Cerri et al. (2004) found encouraging results for the TOC, total N, microbial biomass C pools and ^{13}C as a function of management in a pasture cultivation chronosequence established in areas previously occupied by the native Amazon forest.

The C stocks simulated by Century in different soil orders were mostly in close agreement with the observed values (Fig. 4). Also, simulating the SOC stocks for different management systems in Brazil, Leite et al., (2004) found small differences between simulated and observed values (0.4-7.0 %). However, in another study carried out for soils under plough in Hungary, Falloon & Smith (2002) observed that the simulated SOC values were higher than the observed values. In the present study, for some soil orders such as the Inceptisols under eucalypt and native forest in the VG and IP regions, respectively, and the Oxisol under eucalypt in the CO region, the simulated SOC stocks showed larger discrepancies from the observed values (-32.6% in the Inceptisol under eucalypt in VG, -33.8% in the Inceptisol under native forest in IP and -38.7% in the Oxisol under eucalypt in CO, respectively). We have no specific reason for such variation, but in tropical soils the formation of Al-MOS complex has an important role preventing SOM mineralization, and the higher acidity and aluminium contents are responsible for SOM stabilization (Mendonça, 1995; Meda et al., 2001). So, it is evident the necessity of more detailed studies focusing on the effects of soil mineralogy, pH and aluminium content in formation and stabilization of SOM under tropical conditions. All inputs and assumptions made in our study have uncertainty in their values, thus uncertainty analysis may show how expected variations in the value of important parameters influence the soil C stock.

The following 100 years of the eucalypt cultivation (starting 2003) simulated by Century resulted in a 44.4 % increase in the soil C stock in the BO region (Fig. 5). Considering the possibility of utilization of eucalypt afforestation for C sequestration, it is imperative the adoption of adequate management practices that maximize the profits and at the same time guarantee the soil C maintenance and sustain forest growth. The maintenance of bark, branch and foliages on soil after harvesting constitutes a good alternative with such purpose. Due to the increasing adoption of biomass removal (especially the bark) after harvest for several industrial and energetic purposes, it is important to know what the long-term impact of residue removal on SOC stock is. The Century simulations indicated that the maintenance of the eucalypt bark on soil surface after harvest resulted in an increase of the C stock of 3.2 t ha^{-1} in the BO region (Fig. 6). Evaluating the response of soil quality by residue removal under subarctic conditions (Alaska), Sparrow et al. (2006) found that the retention of crop residues on soil surface conserved about 650 g m^{-2} of C higher than the removal of all residues each year. The harvest residues (foliages, branches and bark) left on the area after harvest are very important source of nutrients such as N, P, K, Ca and Mg (Gama-Rodrigues & Barros, 2002).

Additionally, the maintenance of harvest residues will reduce the leaching of N, improve water content and enhance nutrients supply through mineralization in the long-term (O’Connell et al., 2000). Analysing data from several studies, Johnson & Curtis (2001) found that, in general, the fertilization (e.g. nitrogen) and presence of N_2-fixing plants results in an increase of SOC stocks due to improved plant productivity and humification processes. Several authors have found that the quality of eucalypt residues (high lignin content, and C/N ratio) contribute to accumulation of C in the soil following eucalypt cultivation (Gama-Rodrigues & Barros, 2002; Costa et al., 2005). Similarly, the litter decomposition rate in area under *Pinus elliottii*, *Eucalyptus sp*. and native forest in Santa Maria, Rio Grande do Sul State, observed indicated larger litter accumulation under *Pinus elliottii* followed by *Eucalyptus sp*. and native forest (Kleinpaul et al., 2005). Among the possible explanations it was postulated by the authors that the higher lignin content of pinus foliage contributed substantially to increase the litter layer, which in turn could affect the SOM dynamics in time. Conversely, organic residues may induce greater N immobilization due to deposition of soluble extractives leached from leaf material to soil mainly in N-deficient conditions (Aggangan et al., 1999). This could result in short-term limitations in N supply for new seedlings in some sites, where additional inputs of fertilizers for maintenance of early tree growth may be necessary (O`Connell et al., 2003).

5. CONCLUSIONS

1. The eucalypt plantations lead to an average increase of 0.28-0.42 t ha^{-1} $year^{-1}$ of C in soils previously under poorly managed pastures;

2. The simulated C stocks by the Century model are, in general, close to the measured values (root mean square error - RMSE = 20.9; model efficiency – EF = 0.29), but there are indications that the simulated and observed values differ base on the identity models test;

3. Simulations indicate that the maintenance of the eucalypt bark on soil surface after harvest will increase the C sequestration in soil in the long-term.

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CHAPTER III

CALIBRATION OF THE FULLCAM MODEL TO SIMULATE SOIL ORGANIC MATTER FRACTIONS UNDER EUCALYPT, PASTURE AND NATIVE FORESTS IN BRAZIL

ABSTRACT

The Carbon Accounting Model, FullCAM, was developed by the Australian Greenhouse Office in 2000. It has been successfully calibrated for several Australian conditions. The afforestation on areas previously occupied by pasture, as has been taking place with eucalypt in Brazil, is a valid and potential attempt to offset greenhouse gas emissions. The aim of this study was to calibrate the FullCAM model to simulate soil organic matter (SOM) fractions dynamics under short-rotation eucalypt plantations, pasture and native vegetation (rainforest and Cerrado) located in the main eucalypt growing States of Brazil: (i) São Paulo (SP), (ii) Espírito Santo (ES), (iii) Minas Gerais (MG), and (iv) Bahia (BA), where good long-term datasets for tree growth, SOM fractions (humin, light and microbial biomass), and soil use records were available. So, the C stock was determined in the total organic C (TOC), humic substances (HS), light fraction (LF), and microbial biomass (MB) pools in the 0-20 cm layer. The model performance was checked by comparing observed and predicted values, and calculation of the model efficiency (EF). The simulated results showed that in the ES and BA states, the TOC stocks would decrease 0.37 and 0.30 t ha^{-1} yr^{-1}, respectively, after establishment of eucalypt plantation in areas previously occupied by well managed pastures. Also, the C stock of HS was simulated to decrease 0.36 t ha^{-1} yr^{-1} in ES and 0.31 t ha^{-1} yr^{-1} in BA under the new land use. A similar pattern was observed in SP, where the TOC and C stocks of HS and LF were simulated to decrease after substitution of the native vegetation (rainforest and Cerrado) by short-rotation eucalypt. After 28 years of eucalypt cultivation the TOC stock decreased 17.7% (0.21 t ha^{-1} yr^{-1}) in relation to the soil under Cerrado and 18.3% (0.39 t ha^{-1} yr^{-1}) as compared to the rainforest soil. Conversely, in the Jequitinhonha Valley (JV) site (MG), the substitution of native cerrado vegetation resulted in an increase of simulated TOC and C stock of HS, LF and MB pools. After 33 years of eucalypt cultivation the TOC stock increased 5.6% (0.14 t ha^{-1} yr^{-1}) in comparison to the native Cerrado vegetation. The FullCAM model described satisfactorily the C stocks within TOC (EF=0.74) and HS (EF= 0.65). So, the

FullCAM model constitutes an appropriate tool to simulate the changes in soil C after eucalypt afforestation.

Keywords: C sequestration, land use change, afforestation, Cerrado, rainforest.

1. INTRODUCTION

The two main types of native vegetation in Brazil are, in general, the Atlantic forest (rainforest) and the Cerrado. The Atlantic forest is the most biodiverse biome of the world, occupying about 1.3 million km^2 or, in other words, 15 % of the Brazilian territory (www.sosmataatlantica.com.br). The Cerrado represents about 9 % of the total area of tropical savannas in the world. It occurs entirely within Brazil, mostly in the central region, and covers approximately 2 million km^2 (23 % of the country) (Bustamante et al., 2006). Current land use in the Atlantic forest and Cerrado include the conversion from native forest to pasture, agriculture and fast growing tree afforestation. About 40 years ago the planted forests in Brazil occupied little over 400.000 ha. By 1987, Brazil had more than 6 Mha of planted forests. The eucalypt and pine plantations represent 80 % of the total planted area. The production is mainly for pulp and paper industry and for charcoal in steel industry (Bustamante et al., 2006).

The global concern about rising atmospheric CO_2 concentrations that can potentially change earth’s climate conditions has increased the interest to study the soil organic carbon (SOC) after soil use change (Cerri et al., 2007; Paul et al., 2003; Paul & Polglase, 2004). Soil cultivation has a potential to either release or sequester SOC. Consequently, the SOC changes associated with soil cultivation have received considerable attention due to the need to limit gas emissions to the atmosphere (Lemma et al., 2006). The afforestation on areas previously occupied by degraded agriculture and pasture land as has happened with eucalypt in Brazil is admitted as a valid and potential attempt to offset greenhouse gas emissions, and it is a suitable activity under the Kyoto Protocol. Understanding C cycling in afforested areas is especially important in Brazil, the largest contributor to emissions of CO_2 and other greenhouse gases to the atmosphere due to land use changes.

The global soil carbon pool is estimated to contain more than four times as much carbon as in the biotic pool and three times as much as in the atmospheric pool (Lal, 2004). This highlight the importance of soil organic matter (SOM) in the C cycle, because little changes in soil C stocks may have a significant effect upon greenhouse gas emissions. Because of the large size and the complexity of several SOM compartments, precise measurement of soil C stocks in many cases can be unfeasible and cost-forbidding for afforestation projects. So, the utilization of simulation models constitutes an attractive strategy to improve the understanding about the factors that affect the SOM cycling and, hence, to adopt more adequate management practices for SOM maintenance in afforested areas.

Models that permit the simulation of litter dynamics (e.g. GENDEC, DECOMP, CAMFor) and SOM dynamics (e.g. Century, RothC) have been applied with relative success for planted forests (Kirschbaum & Paul, 2002; Paul & Polglase, 2004; Wallman et al., 2006). Because of the reciprocal dependence among the forest growth, SOM cycling, and litter decomposition, it is desirable that SOM models link with models of forest growth, debris deposition (litter and dead roots), debris decomposition and, SOM turnover (Kirschbaum**,** 1999; Richards, 2001). One of these models, FullCAM, is a potential tool to study the processes that control litter production and decomposition and SOM cycling in Brazilian eucalypt plantations. This model has been used with relative success under several climate and soil conditions in Australia (Paul et al., 2002; Paul et al., 2003; Paul & Polglase, 2004; Paul et al., 2006). When well calibrated to Brazilian conditions, the FullCAM may enable to estimate the expected forest growth, litter deposition and SOM turnover in future rotations adding or maintenance under the effect of current and alternative management practices. This will allow the establishment of management practices that are more likely to maintain or even improve SOM in the future. Despite the potential application of such models, data on SOM dynamics in many Brazilian regions under short-rotation eucalypt are scarce and there is no systematic study to evaluate the medium- and long-term soil C cycling and the C balance in these forests.

The FullCAM model

The complete carbon accounting model, FullCAM, has been constructed by the Australian Greenhouse Office in 2000 (Richards, 2001). The FullCAM has components that handle the biological and management processes that affect the C pools and transfers between pools in forest, agricultural, transitional (e.g. afforestation, reforestation, deforestation) and mixed (e.g. Agroforestry) systems. The exchange of C, losses and uptake, between the terrestrial biological systems and the atmosphere are also accounted for. The FullCAM model provides the linkage among the various sub-models (Fig. 1).

The FullCAM model is constituted by several integrated models, but is primarily based in an empiric sub-model nominated carbon accounting model for forests CAMFor developed by the Australian Greenhouse Office (AGO) (Richards & Evans, 2000a) or carbon accounting model for cropping and grazing systems – CAMAg (Richards & Evans, 2000b). The CAMfor sub-model utilises tree growth information (increment in wood and aboveground biomass), management (irrigation, fire, tree mortality), climate (temperature, precipitation) and empirically estimates the mass of tree components, litter, litter decomposition, dead roots and SOC cycling rate. If no information is available for tree growth, the 3-PG sub-model (Landsberg & Waring, 1997) is used to estimate the net primary productivity, which is then transferred to the CAMFor, where it is allocated to several tree components. When litter information such as lignin content, cellulose, soluble C, litter C/N ratio and available mineral N inputs, the litter decomposition can be predict using the GENDEC sub-model (Moorhead & Reynolds, 1991). The C in resistant and decomposable litter compartments in CAMFor is transferred to the fast (soluble), medium (cellulose) and slowly (lignin) compartments in GENDEC based in its biochemical characteristics. The GENDEC then transfers the estimated decomposed litter mass to the CAMFor, where the C cycling rate in soil can be predicted with the CAMFor or by using the RothC sub-model (Jenkinson et al., 1987; Jenkinson et al., 1991).

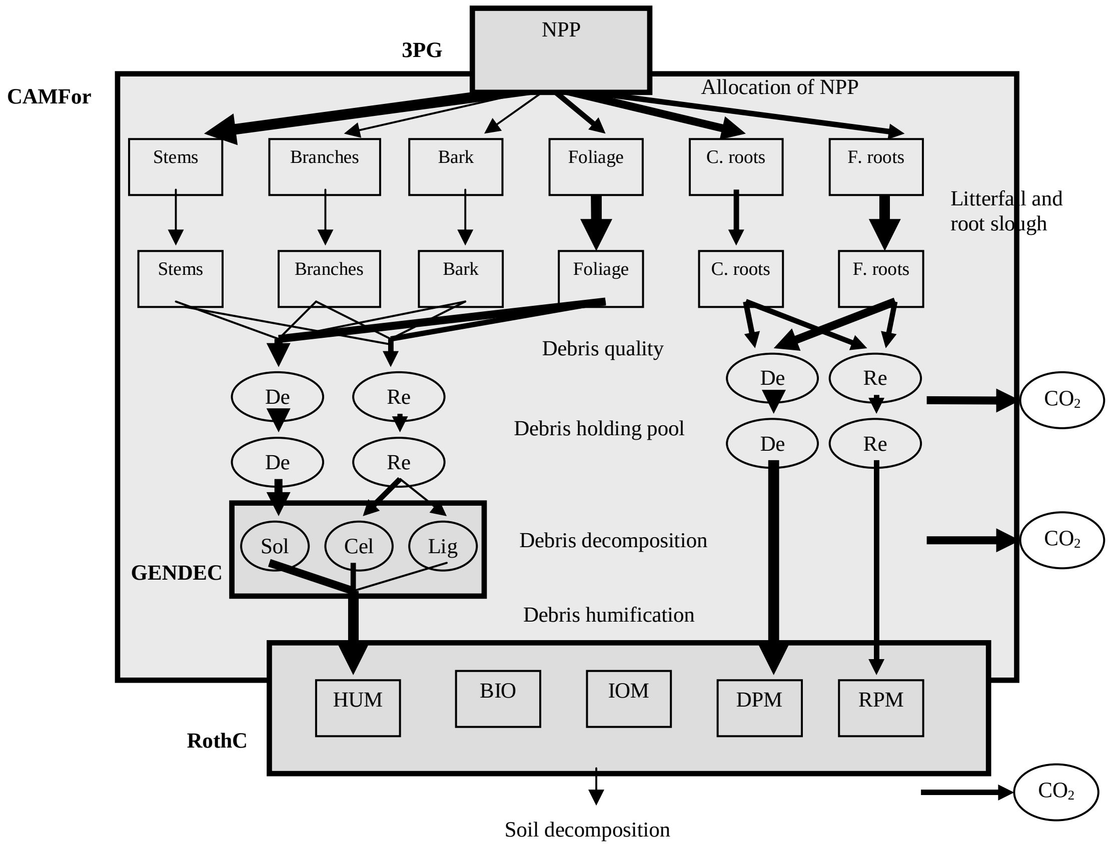

Figure 1. Structure of the FullCAM model configured for forestry systems and based on the empirical C tracking sub-model CAMFor, with the possibility to link to process-based sub-models for predicting of tree growth (3-PG), litter microbial decomposition (GENDEC) and soil C turnover (RothC). De and Re refer to decomposable and resistant material in the CAMFor sub-model, respectively. Sol refers to soluble, Cel refers to cellulose, and Lig refers to lignin in the GENDEC sub-model. In the RothC sub-model, HUM refers to humified material, BIO refers to microbial biomass pool, IOM refers to inert organic matter, and DPM and RPM refer to decomposable and resistant plant material, respectively.

In the RothC sub-model, the SOM decomposition is simulated considering the clay content, temperature, water content and plant species. This model simulates six soil carbon pools: (i) decomposable plant material (DPM); resistant plant material (RPM); (iii) slow microbial biomass pool (BIO-S); (iv) fast microbial biomass pool (BIO-F); (v) humified organic matter (HUM); and (vi) organic matter inert to biological attack (IOM). The presence of this inert SOM compartment basically differentiates the RothC from other SOM decomposition models. Fresh litter and dead roots may include decomposable and resistant pools divided based on pre-defined ratios and that decompose at different rates to produce CO_2, BIO, and HUM. All SOM pools (except

IOM) in RothC decompose at defined rates (following a first order kinetics), which are changed by temperature, soil moisture deficit, and a plant protection factor as described by Jenkinson (1990).

The aim of this study was to calibrate the FullCAM model to predict SOM cycling under short-rotation eucalypt plantations, pasture and native forest (rainforest and Cerrado) in four main eucalypt growing States in Brazil.

2. MATERIAL AND METHODS

2.1. Sites description

This study was carried out in commercial eucalypt stands, pastures and native vegetation (rainforest or Cerrado - Savanna) located in four main eucalypt growing States in Brazil: (i) São Paulo (SP), (ii) Espírito Santo (ES), (iii) Minas Gerais (MG), and (iv) Bahia (BA), where long-term datasets for tree growth, SOM fractions, and land use history were available (Tables 1 and 2). The soils in these States were used to estimate the magnitude of C changes across a range of land use change, C inputs, climate, edaphic conditions, and management practices.

(i) São Paulo

Two areas under eucalypt plantations were selected (Table 2). Adjacent areas of native vegetation (rainforest or Cerrado) characteristic of land cover before the eucalypt establishment were also chosen. The Cerrado site is dominated by sandy soils (Quartzipsamment), while the rainforest (Atlantic forest) site is on very clayey, fertile Oxisols derived from basalt. For both sites, the eucalypts was first planted manually in 1973, after slashing and burning the rainforest and Cerrado in a density of 1,333 plants ha^{-1}. The plants were fertilized with NPK (4-28-6) + 0.3 % Cu + 0.7 % Zn and reactive rock phosphate. It was also applied NPK (10-00-20) + 0.3 % B + 2.4 % Mg as maintenance fertilization. After seven years of growth, the eucalypt trees were clear cut and the trunk removed from the site. The tree residues were burned to conduct the second rotation. Since the third rotation the burning practice was discontinued. In all rotation the debarking was performed off site with no return to the field. All management practices were carried out mechanically.

Table 1. Climate, localization, and eucalypt species (clone) used for simulation of SOM dynamics with the FullCAM model in each studied area

	State					
	Espírito Santo	Minas Gerais			Bahia	São Paulo
		BO	VG	JV		
Climate	Aw	Aw	Cwa	Cwa	Af	Cwa
Mean annual rainfall (mm)	101.5	96.7	93.8	97.0	140.1	109.9
Mean annual air temperature (^{o}C)	23.4	24.9	22.0	20.6	23.1	23.4
Open pan-evaporation (mm)	110.7	109.6	95.0	107.9	114.3	113.4
Latitude (S)	19º48’	19º14’	18º42’	17º51’	16º17’	21º33'
Longitude (W)	40º17’	42º24’	42º41’	42º51’	39º09’	47º42'
Altitude (m asl)	55	250	850	1,100	71	500
Eucalypt species (clone)	*E. grandis x E. urophylla*	*E. urophylla*	*E. urophylla*	*E. urophylla*	*E. grandis x E. urophylla.*	*E. grandis x E. urophylla*
Pasture productivity (t ha^{-1})	10.9	3.5	5.5	-	12.4	-
Soil order	Ultisol	Oxisol	Oxisol	Oxisol	Ultisol	Quartzipsamment or Oxisol

Cwa = humid sub-tropical; Aw = tropical wet-dry; Af = tropical wet; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley.

Table 2. Main characteristics of the sites under eucalypt plantations utilized for calibration of the FullCAM model

State (site)	Native forest	Previous land use	Rotation number	Current stand age	(1) Stem productivity	Clay	Silt	Sand
				(yr)	(Mg C ha^{-1}yr^{-1})	--------------(g kg^{-1})-----------		
ES	Rainforest	Pasture	4	7.6	8.1	250	30	720
MG (BO)	Rainforest	Pasture	4	6.2	7.7	580	40	380
MG (VG)	Rainforest	Pasture	4	5.2	12.3	700	50	250
MG (JV)	Savanna	Savanna	3	10.0	15.0	780	60	90
BA	Rainforest	Pasture	1	7.7	16.1	90	30	880
SP	Savanna	Savanna	4	2.0	10.0	90	20	890
SP	Rainforest	Rainforest	4	2.0	10.0	640	180	180

ES = Espírito Santo; MG = Minas Gerais; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley; BA = Bahia; SP = São Paulo; Savanna = Cerrado; (1) at 7,0 years old.

(ii) Espírito Santo

The eucalypt stand evaluated was planted in early 70s in the coastal region of the ES State in area previously occupied by pasture. It was chosen to be representative of the soil and management conditions dominant in this region (Table 2; Fig. 2). Additionally, adjacent areas under pasture (*Brachiaria sp.*) and native forest (rainforest) located nearby the eucalypt stands were selected. The pasture was established in 1950s in area previously occupied by native forest and it was used for extensive cattle ranching up to 1969, when the eucalypt cultivation started. The pasture had good appearance, without visible surface erosion. The first eucalypt rotation was established after burning and plowing the pasture, in a 3x3 m tree spacing (1.111 pl/ha). Just after planting, the seedlings were fertilized with NPK (6-30-6) and natural rock phosphate. Also, NPK (20-05-20) was used for maintenance fertilization. After 7 years of growth, the trees were harvested. The whole trunk was taken off from the site and only the branches and leaves remained on site. The plant residues were burned after harvest up to 1985 (second rotation). All management practices during the conduction of eucalypt rotations were mechanized due to favorable topography.

(iii) Minas Gerais

Two eucalypt plantations were selected in two distinct regions in Rio Doce Valley, Minas Gerais State: Belo Oriente (BO) and Virginópolis (VG) (Table 2; Fig. 2). Besides the eucalypt stands, in each region an adjacent native forest (Atlantic forest) and pasture were selected. In both regions the eucalypt stands replaced degraded pasture in 1969. The pastures (*Melinis minutiflora)* were established in early 30s after slashing and burning the native forest. The pasture was utilized for extensive cattle ranching with no fertilizer or lime use until 1969, when it was replaced by the eucalypt plantation. The pastures throughout the region were overgrazed, and erosion was apparent. The first eucalypt stands were planted manually after burning the pasture. Following 7 years of growth, the plants were manually cut and the stem plus bark removed from the site. The use of fire after harvest was carried out until the third eucalypt rotation. Another eucalypt site was chosen in a distinct biome in the Jequitinhonha Valley (JV), MG (Table 2). Beside the eucalypt, an adjacent area under native vegetation (cerrado) was selected. The first eucalypt rotation was planted in a 3x2 m tree spacing (1,667 pl/ha) in 1974, after slashing and burning the native vegetation. After 10 years of growth, the eucalypt trees were harvested and the stem together with bark was taken from the area. The branches and leaves remained on site after harvesting.

Figure 2. Overview of land use change in the main eucalypt growing States of Brazil.

(iv) Bahia

One representative area under eucalypt plantation was selected in this state (Table 2; Figure 2). Additionally, areas under pasture and native vegetation (rainforest) adjacent to the eucalypt were selected. The pasture (*Brachiaria sp.* and *Panicum sp.*) was planted in early 1970s after slashing and burning of the native forest. The current pasture was in good vegetative condition, with no evident surface erosion. The eucalypt was established in early 90s after burning and plowing of pasture and soon after the eucalypt planting, the seedlings were fertilized with NPK (5-38-5) fertilizer and reactive natural phosphate, but no maintenance fertilizer was applied. After 10 years of growth, the trees were harvested with a harvester and the stem was taken out from the site with all the plant residues left on soil surface. The use of fire to clear the area was not a standard practice in this region. Due to favorable topography all management practices from planting to harvesting were accomplished mechanically.

2.2. Soil sampling and analysis

Soil samples were collected between eucalypt trees rows in the 0-20 cm layer, after digging a pit about 40 cm deep. Also intact soil samples were taken to determine soil density. Four replicates were randomly taken from each stand. Each replicate was separated by approximately 500 m and consisted of a composite of four soil samples randomly collected 5 m apart from each other. A similar procedure was executed for pasture and native forest soil sampling. We admitted that pseudo-replication is a limitation of this study, as in many other paired-site studies (Vesterdal et al., 2002; O'Brien et al., 2003; Chen et al., 2004, Lima et al., 2006). Since each stand within a given site was set apart by at least several meters and other eucalypt stands, we have confidence in that randomness and independency was ensured and a valid statistical analysis was warranted.

The soil samples were air dried and passed through a 2 mm sieve. Soil sub-samples were taken for texture analysis (Table 2). Additional soil sub-samples were ground in an agate mortar to pass a 100 mesh (0.149 mm) sieve for total organic carbon (TOC) determination by a wet-chemical procedure (Yeomans and Bremner, 1988) and for C determination in humic substances fractions (HS) by the IHSS procedure (Swift, 1996). The following fractions HS were obtained based on differential solubility in alkali and acid solutions: fulvic acids (FAF), humic acids (HAF), and humin (HF). By summing the FAF, HAF, and HF it was obtained the value for the humic substances (HS). The C content in the HS was determined via a wet-chemical procedure (Yeomans and Bremner, 1988). The microbial C was determined by the irradiation-extraction procedure (Islam and Well, 1998) and the light fraction (LF) of SOM was separated by physical fractionation with a NaI solution (1.8 kg L^{-1}) based on the procedure proposed by Sohi et al. (2001). After physical fractionation, the C content of the LF was determined by dry combustion in an elemental analyser (Perkin-Elmer serie II CHNS/O). Carbon stocks in the several SOM fractions were calculated by multiplying the C concentration in each fraction by the mass of soil under native forest to correct for management-induced compaction effects on SOM stocks (Lemma et al., 2006).

2.3. Calibration of the FullCAM model

The eucalypt productivity as well as the net primary productivity (NPP) for each site was calibrated using the increment method in the CAMFor sub-model due to the available actual productivity and climate data (temperature, rainfall, and pan-evaporation) for each site (Tables 1 and 2). The NPP allocation and the turnover rate for each plant compartment (e.g. foliage, branches and bark) were also predicted using the CAMFor.

Data of total dry mass (384.4 t ha^{-1}) and litterfall (6.5 t ha^{-1} yr^{-1}) for the native forest (rainforest) were available only for the Espírito Santo State. This productivity was used for the native forest (rainforest) in the other studied sites. The total productivity of dense cerrado (savanna) (67.1 t ha^{-1}) was obtained from Ottamar et al. (2001), while the litterfall datum was obtained only for the São Paulo State (5.6 t ha^{-1}) (Cianciaruso, 2006). During the FullCAM calibration it was considered a tree mortality rate of native forest of 1 % yr^{-1}. Swaine et al. (1987) considered the mortality rate of tropical forest to be around 1-2 % yr^{-1}. Due to fire event the aboveground C converted to charcoal was 5 %, while the aboveground C release as CO_2 to the atmosphere was 39 % according to Fearnside (1996, 2002).

During the calibration of the RothC sub-model, the C inputs to soil pools must be well calibrated. Thus, for each study site, the FullCAM prediction of biomass accumulation and litterfall were simultaneously fitted to some observed data. Early calibration of the FullCAM model using the dataset (Table 2) indicated that the original decomposition rate constants of decomposable plant material (DPM), resistant plant material (RPM), humified material (HUM), and microbial biomass (BIO) pools available in the model (default values) were not adequate to predict the soil carbon turnover under native forest, pasture and eucalypt plantations. Therefore, we had to fit these decomposition constants in order to minimize the difference between predicted and observed values of SOM compartments, considering that the quantity of C in each RothC soil pool decays exponentially with time if there is no new C flowing into the pool, and that theses rates are also affected by temperature, topsoil moisture and soil cover. Another adjustment required during the FullCAM calibration was the C partitioning during the debris decomposition between that lost as CO_2 and the remaining that enters into to the soil, considering that the decomposable compartments loose higher C-CO_2 to atmosphere than the resistant compartments.

The measured TOC stocks were compared with the TOC stocks simulated by the FullCAM model, while the measured C stock of HS was compared with the simulated C stock of HS. Also, the measured C stock of LF was compared with the C stock of plant material simulated by the FullCAM model (DPM + RPM), whereas the measured C stock of MB was compared with the simulated C stock of MB (BIO-Fast + BIO-Slow).

After calibration, it was determined how well the FullCAM model predicted the C mass within these pools by calculating the model efficiency (EF), a statistic analogous to R^2, as defined by Soares et al., (1995):

$$EF = 1 - \left(\frac{\sum (yi - \hat{y}i)^2}{\sum (yi - \overline{y})^2} \right)$$

where y_i are the measured/observed values, $\hat{y}i$ are the predicted values, $\overline{y}$ is the mean of the measured values. The EF values may be negative or positive with a maximum value of 1. A negative value indicates that the simulated values describe the trend in the measured data less well than a mean of the observations. A positive value indicates that the simulated values describe the data much better than the mean of observations, with a value of 1 indicating a perfect fit.

3. RESULTS

3.1. Total organic carbon and humic substances carbon

Measured C stocks

The Atlantic forest soil in ES had a TOC stock of 38.5 t ha^{-1} and a C stock in HS of 34.4 t ha^{-1}. The clearing of the forest for pasture cultivation led to a decrease in the TOC and HS stocks to 35.6 and 29.1 t ha^{-1}, respectively (Fig. 3). These stocks were further reduced to 20.9 and 22.1 t ha^{-1} following the substitution of pasture by eucalypt. An opposite behaviour was observed in BO and VG (MG), where the degraded pasture soils had much lower TOC stocks (31.5 t ha^{-1} in BO and 53.2 t ha^{-1} in VG) and C stock in HS (27.7 t ha^{-1} in BO and 47.6 t ha^{-1} in VG) than those under the rainforest soil (TOC = 53.0 t ha^{-1} in BO and 82.3 t ha^{-1} in VG; HS = 45.9 t ha^{-1} in BO and 75.6 t ha^{-1} in VG), but the eucalypt soil showed a recover in the TOC stocks (41.6 t ha^{-1} in BO and 67.4 t ha^{-1} in VG) and the C stock in HS (40.6 t ha^{-1} in BO and 62.8 t ha^{-1} in VG).

Likewise, in JV (MG) the eucalypt soil had a higher TOC stock (46.0 t ha^{-1}) than under the cerrado soil (43.6 t ha^{-1}). However, the C stock in HS of the eucalypt soil (42.3 t ha^{-1}) was slightly lower than that in the cerrado soil (43.2 t ha^{-1}). In BA site, the C stocks in the native forest soil were 35.9 and 36.5 t ha^{-1} in TOC and HS, respectively. The pasture cultivation (20 years) reduced these C stocks to 28.5 and 31.5 t ha^{-1}. The more recent eucalypt cultivation further reduced the TOC stock and C stock in HS to 26.0 and 24.5 t ha^{-1}, respectively. Similarly, the eucalypt soil in SP also had lower TOC stocks (24.8 and 41.9 t ha^{-1}) and C stocks in HS (19.5 and 37.6 t ha^{-1}) than those under the cerrado (sandy) and rainforest (clayey) soils which had the TOC stocks of 36.5 and 50.2 t ha^{-1}, and C stocks in HS of 27.8 and 43.9 t ha^{-1}, respectively.

Simulated C stocks

According to simulations by FullCAM, the introduction of eucalypt resulted in a decrease in the TOC stock and C stock in HS in comparison to pasture and rainforest in ES, MG (BO) and BA (Fig. 3). The model predicted that the eucalypt soils in ES, MG (BO) and BA, respectively, would have TOC stocks of 26.3, 40.6 and 31.7 t ha^{-1},while the pasture soil had 38.2, 46.2 and 34.1 t ha^{-1}, and the rainforest soil stored 42.4, 68.8 and 39.9 t ha^{-1} of TOC. Concerning the HS pool, the eucalypt soil stored 24.9, 37.4 and 29.4 t ha^{-1} of C, while the pasture soil had 36.3, 45.4 and 31.9 t ha^{-1}, and the rainforest soil had 37.8, 62.1 and 35.3 t ha^{-1} in ES, MG (BO) and BA, respectively. Oppositely, the eucalypt soil had greater TOC stocks (55.0 in VG and 52.5 in JV) than the pasture soil in VG (54.5 t ha^{-1}) and the cerrado soil in JV (47.9 t ha^{-1}). The eucalypt soil also had higher C stocks in HS (46.9 t ha^{-1})) than under cerrado (43.4 t ha^{-1}) in JV (MG). The TOC stock (27.5 and 49.3 t ha^{-1}) and the C stock in HS (24.5 and 45.9 t ha^{-1}) in the eucalypt soil was lower than in the cerrado (TOC = 33.5 t ha^{-1}, HS = 29.2 t ha^{-1}) and rainforest (TOC = 60.3 t ha^{-1}, HS = 54.5 t ha^{-1}) soils in SP.

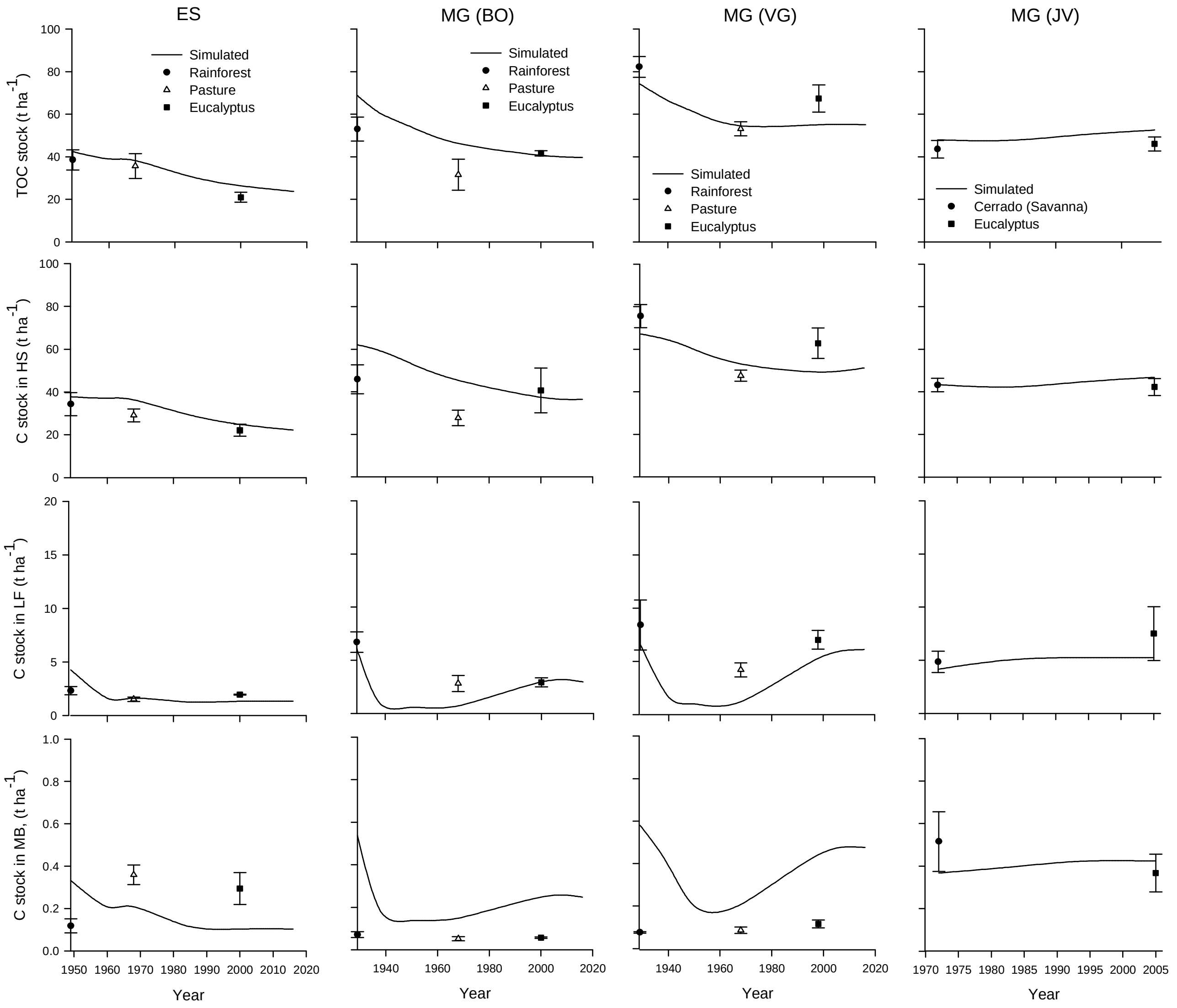

Figure 3. Observed (symbols) and simulated (lines) TOC (total organic carbon) stocks and C stocks in the HS (humic substances), LF (light fraction), and MB (microbial biomass) pools (0-20 cm) for the native vegetation, pasture and eucalypt soils in calibration of FullCAM. ES = Espírito Santo; MG = Minas Gerais; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley.

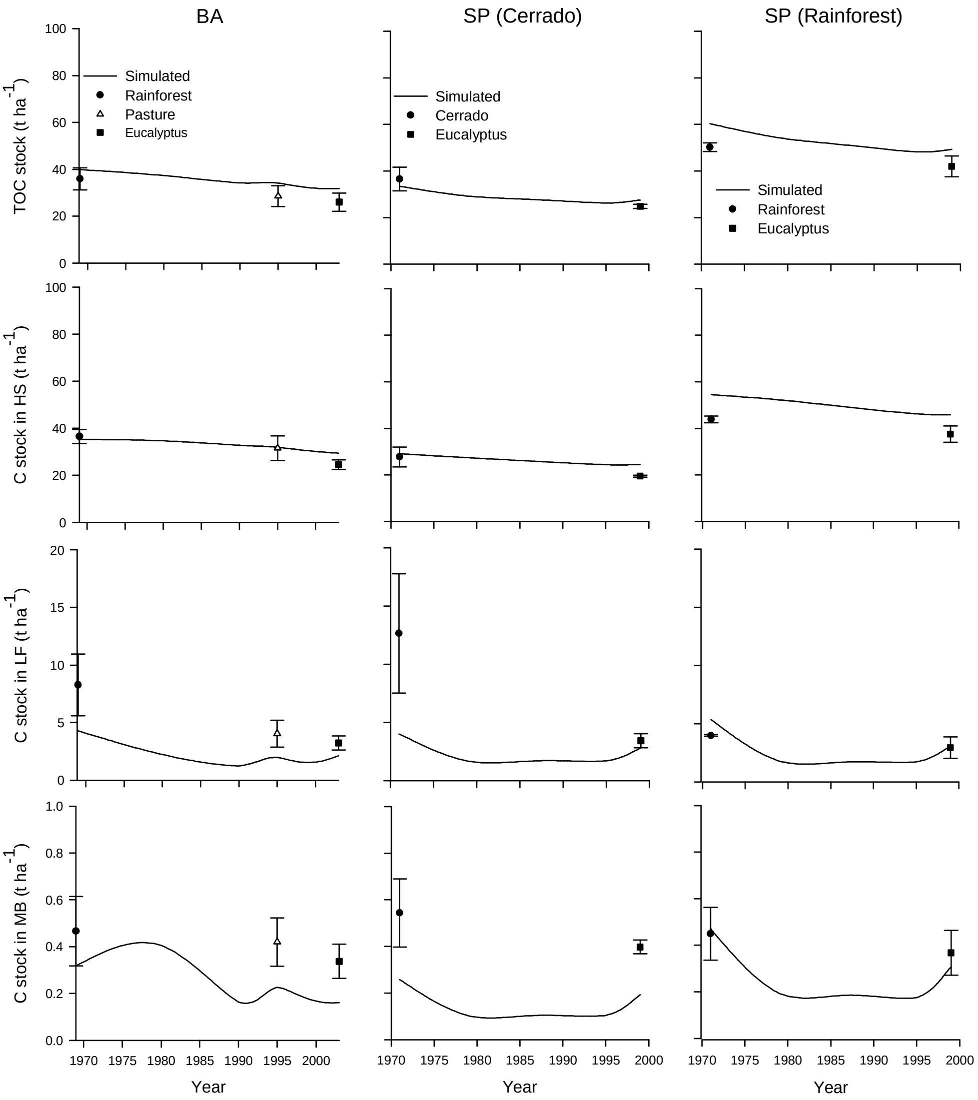

Figure 3. Cont. BA = Bahia; SP = São Paulo.

3.2. Light fraction and microbial biomass carbon

Measured C stocks

The eucalypt soil had slight higher C stock in the light fraction (1.9 t ha^{-1} in ES and 2.9 t ha^{-1} in BO) than the pasture soil in ES (1.5 t ha^{-1}) and BO (2.8 t ha^{-1}), which in turn were lower than those of the rainforest soil in both sites (2.3 and 6.7 t ha^{-1} in ES and BO, respectively) (Fig. 3). The eucalypt soil also showed higher C stocks in the light fraction (7.0 t ha^{-1} in VG and 7.5 t ha^{-1} in JV) than the pasture (4.2 t ha^{-1}) and cerrado (4.9 t ha^{-1}) soils in VG and JV (MG), respectively. Contrarily, the eucalypt soil had lower C stock in the light fraction (3.2 t ha^{-1}) as compared to the pasture soil (4.0 t ha^{-1}) in BA. The eucalypt soil also had lower C stock in microbial biomass (0.34 t ha^{-1} in BA, 0.37 t ha^{-1} in JV (MG), and 0.29 t ha^{-1} in ES) than the pasture (0.42 t ha^{-1}) and rainforest (0.47 t ha^{-1}) soils in BA, cerrado soil (0.52 t ha^{-1}) in JV (MG), and pasture soil (0.36 t ha^{-1}) in ES. On the other hand, the eucalypt soil had a 0.11 t ha^{-1} C stock in this fraction in comparison to 0.09 t ha^{-1} in the pasture soil and 0.08 t ha^{-1} in the rainforest soil in VG (MG) (Fig. 3).

The eucalypt soil had a 3.4 t ha^{-1} C stock in the light fraction as compared to the 12.6 t ha^{-1} C stock in the cerrado soil in SP. In the forest foil there were more C stocked (3.9 t ha^{-1}) in the light fraction than in the eucalypt soil. The eucalypt soils also had lower C stocks in the microbial biomass (0.40 and 0.37 t ha^{-1}) than the Cerrado (0.54 t ha^{-1}) and rainforest (0.45 t ha^{-1}) soils in SP.

Simulated C stocks

The FullCAM model predicted that the eucalypt soil had higher C stocks in the light (2.9 and 5.3 t ha^{-1}) and in the microbial biomass (0.25 and 0.44 t ha^{-1}) than the pasture soil (LF = 0.7 and 1.2 t ha^{-1}, MB = 0.15 and 0.21 t ha^{-1}) in BO and VG (MG), respectively (Fig. 3). Similarly, the eucalypt soil was predicted to have higher C stocks in the light (5.3 t ha^{-1}) and in the microbial biomass (0.42 t ha^{-1}) than in the cerrado soil (LF = 4.2 t ha^{-1}, MB = 0.37 t ha^{-1}) in JV (MG). Conversely, the simulation results indicated that the eucalypt soil would store less C in the light fraction (1.3 t ha^{-1}) and microbial biomass (0.10 t ha^{-1}) than the pasture (LF = 1.6 t ha^{-1}, MB = 0.21 t ha^{-1}) and rainforest (LF = 4.3 t ha^{-1}, MB = 0.33 t ha^{-1}) in ES, as well as lower C stock in the microbial biomass (0.16 t ha^{-1}) than the pasture (0.23 t ha^{-1}) and rainforest (0.32 t ha^{-1}) soils in BA. In SP, the model simulation for the eucalypt soil indicated lower C stocks in the light fraction (2.8 and 3.1 t ha^{-1}) and microbial biomass (0.19 and 0.31 t ha^{-1}) than the cerrado (LF = 4.0 t ha^{-1}, MB = 0.26 t ha^{-1}) and rainforest (LF = 5.4 t ha^{-1}, MB = 0.47 t ha^{-1}) soils, respectively.

3.3. Calibration of the FullCAM model

After calibration, the model showed EF values of 0.74 unit for TOC, 0.65 unit for HS, 0.11 unit for the light fraction, and -0.87 unit for the microbial biomass (Fig. 4). The FullCAM model over-estimated the TOC stock and C stock in HS, light fraction and microbial biomass in situations where actual C stocks were lower.

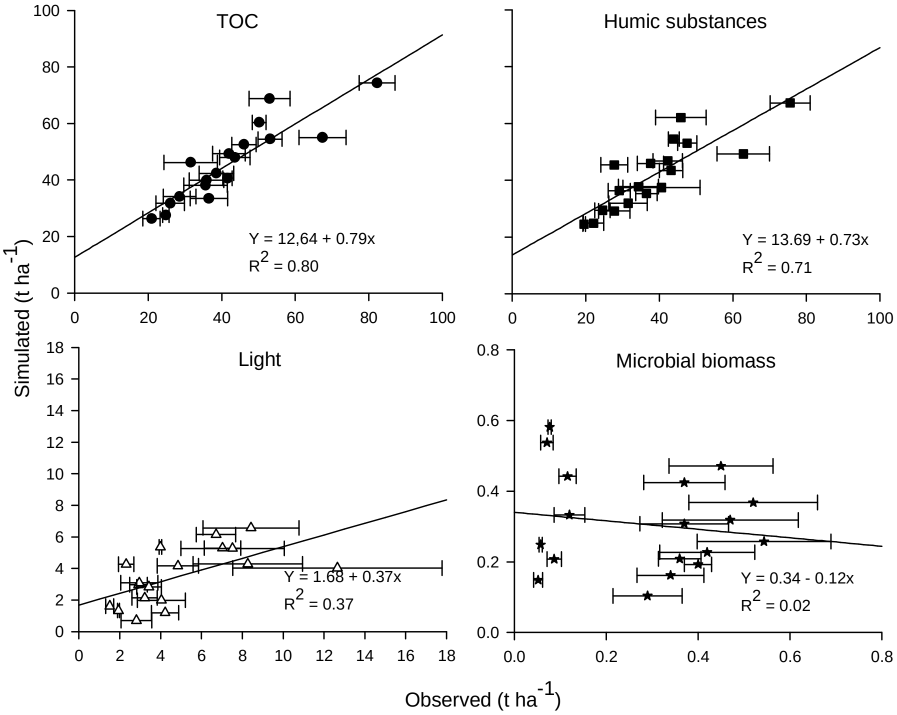

Figure 4. Relationship between observed and simulated C stocks of SOM fractions (0-20 cm) for calibration soil datasets of the FullCAM model. EF soil datasets were found to be: TOC = 0.74 units; HS = 0.65 units; LF = 0.11 units; MB = -0.87 units.

4. DISCUSSION

The clay content, temperature, rainfall, and plant productivity are among the most important factors that control SOM dynamics (Watts et al., 2006; Dalmolin et al., 2006; Tan et al., 2004; Rigobelo & Nahas, 2004). The native forest, pasture and eucalypt soils had higher C stocks in the SOM fractions in the VG region (MG) (Fig. 3). The higher clay content and lower annual mean temperature in this region (Tables 1 and 2) may have favoured the C sequestration in such soil. In general, clayey soils present higher SOC contents and lower C mineralization rates (Mendham et al., 2002; Bird et al., 2003). In the clay fraction organic C is stabilised mainly by association with soil minerals, what result in protection against biologic degradation (Shang & Tiessen, 1998; Percival et al., 2000**;** Schulten & Leinweber, 2000; Kaiser et al., 2002; Dalmolin et al., 2006). In a study carried out with Ferralsols along a climosequence in southern Brazil, Dalmolin et al. (2006) observed that the organic matter stocks increased from the lowest to the highest elevation sites (440-950 m asl) due to increase in rainfall and decrease in temperature. This influence was more pronounced in the heavy clayey

Ferralsols. Lower temperature results in a decline in microbial activity, which favours SOM accumulation. In fact, Lima et al. (2006) employed variations in the natural abundance of ^{13}C to demonstrate that SOM turnover in the VG regions was much slower than in the BO region. Furthermore, despite the fact that several studies in Brazil have demonstrated that eucalypt productivity and litterfall increase in regions with greater mean annual rainfall (Santana, 2000; Stape et al., 2002; Rigobelo & Nahas, 2004), the slightly lower annual rainfall in the VG region is not sufficient to limit eucalypt growth and thus, the high plant productivity and residue deposition contributed substantially to accumulate soil C under the eucalypt stands.

Afforestation of former pasture land generally results in reduction of SOM contents (Davis & Condron, 2002; Sicardi et al., 2004). In the present study short-rotation eucalypt cultivation in areas previously occupied by improved pastures resulted in a decrease of TOC stocks, reaching an average loss of 0.37 and 0.30 t ha^{-1} yr^{-1} in ES and BA, respectively (Fig. 3). A similar behaviour was observed for the C stocks in HS, which decreased 0.36 and 0.31 t ha^{-1} yr^{-1}. This can be explained by the decline in net primary productivity (NPP) following the eucalypt establishment in these regions (Fig. 5). In a Study evaluating the eucalypt impact in SOC fractions of areas previously occupied by pasture in Australia, Paul and Polglase (2004) observed that in sites previously occupied by improved pasture the afforestation resulted in decline of the C stocks in HF. Evaluating the SOC stocks after conversion from grassland to pine afforestation in the Ecuadorian Andes, Farley et al. (2004) also observed that the SOC stock (0-10 cm) decreased from 5.0 kg m^{-2} in grasslands to 3.5 kg m^{-2} in 20-25 year-old pine stands. Pastures allocate about 30-50% of C fixed by photosynthesis to formation and maintenance of root system (Kuzyakov & Domanski, 2000) with fast cycling time, while forest coarse roots have long turnover time. Furthermore, forests deposit organic residues on soil surface where the conditions to decomposition are more favourable (Post & Kwon, 2000).

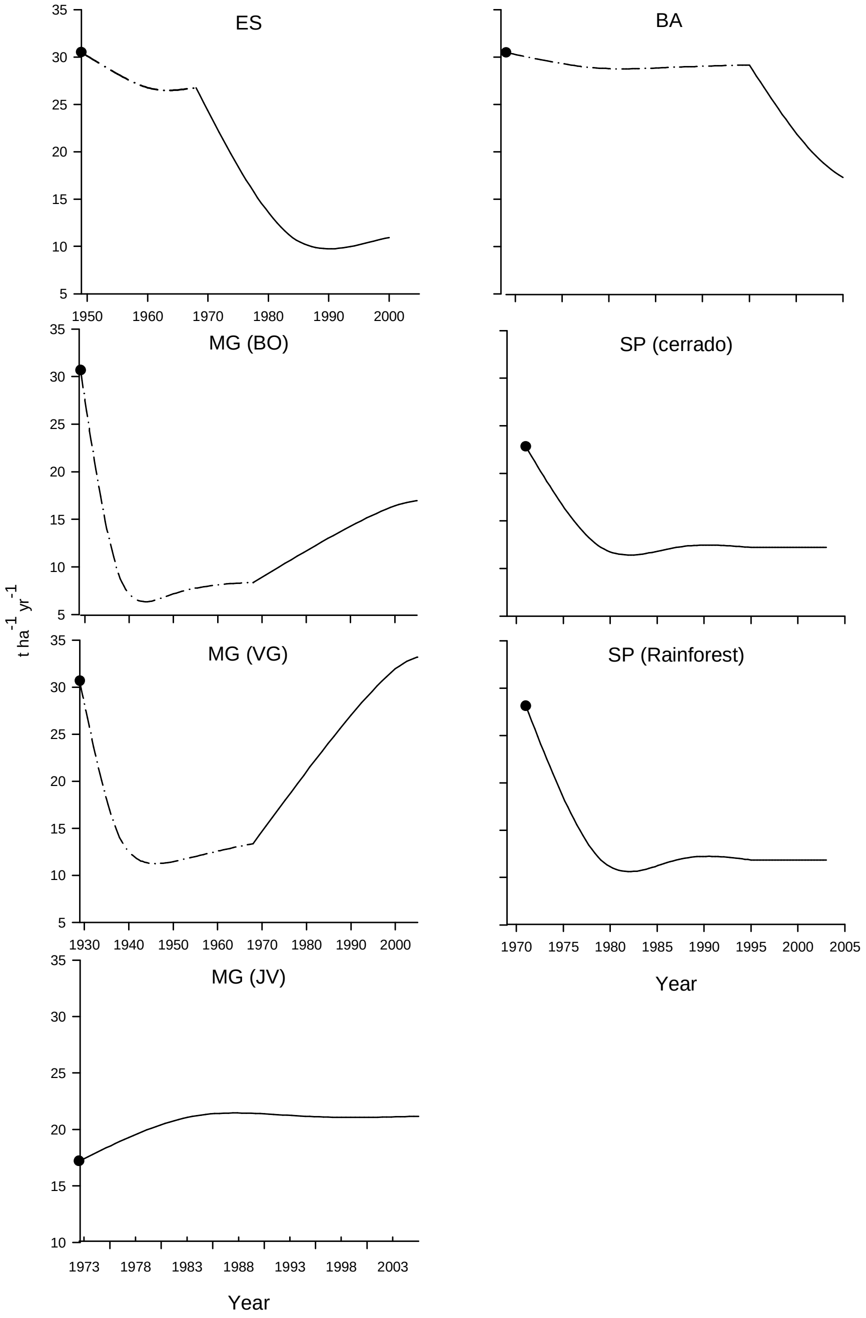

Figure 5. Simulated NPP values for the native forest (●), pasture (dash dot line), and eucalypt (solid line) soils in calibration dataset of the FullCAM model. NPP = net primary productivity; tdm = ton dry matter; yr = year; ES = Espírito Santo; MG = Minas Gerais; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley; BA = Bahia; SP = São Paulo.

In a global review about changes in soil C stocks (0-30 cm) following afforestation on ex-pastoral land, Paul et al. (2002) found that the soil C, on average, initially decreased 0.32% yr^{-1} during the first 10 years before gradually increasing

1.16% yr^{-1} for the first 40 years. Among the main reasons that contributed for this decline/recover patter it has been postulated (Paul et al., 2002) that: (i) at the time of plantation establishment there is little input of fresh C to soil as NPP is small and goes to building biomass. At the same time, residues from previous pasture decompose leading to net loss of C. So, even when the C input from residues under plantations is greater than under pasture, the soil C is initially decreased because of a lag in C being transferred from residue to soil; (ii) much of the NPP in plantation is allocated to long-lived woody components that are temporarily or permanently removed by harvesting from the soil C cycle; (iii) input from the more lignified, resistant plant material increases as the plantation develops.

The NPP and C allocation were demonstrated to be highly correlated to the soil C in areas under eucalypt afforestation in Australia (Paul et al., 2003). The simulated TOC and C stocks in HS and LF were found to decrease after substitution of native forest (rainforest and Cerrado) by eucalypt in SP (Fig. 3). After 28 years of eucalypt cultivation the TOC stock decreased 17.66 % (0.21 t ha^{-1} yr^{-1}) and 18.32 % (0.39 t ha^{-1} yr^{-1}) in relation to the Cerrado and rainforest soil, respectively. The lower C stocks in the eucalypt soil were due to lower NPP of eucalypt compared to native forest (Fig. 5). Furthermore, the management practices such as planting and harvesting in eucalypt areas could lead to soil C loss as CO_2 to the atmosphere. In a review involving worldwide regions, Guo & Gifford (2002) found that, on average, afforestation on land previously under native forest resulted in a 13 % decrease in SOC. The eucalypt establishment resulted in small changes in SOC, while conifer establishment resulted in decrease of 15 % in SOC. Contrastingly, when evaluating the effect of *E. camaldulensis* afforestation on soil C in comparison to the native Cerrado in Brazil, Melo et al. (2004) observed that the eucalypt cultivation resulted in an increase of organic C in the upper soil layers. The lower clay content of eucalypt soils that were previously under Cerrado (9 dag kg^{-1}, Table 2) could have contributed to decline in the soil C after afforestation in the current study. In a study evaluating the impact of eucalypt and pinus afforestation on SOC stocks in the Cerrado region of Brazil, Zinn et al. (2002) observed that the organic C (0-5 cm) was significantly lower under afforested than the control soil (Cerrado), especially in the sandy Entisol. As discussed early, soils with sandy texture are more sensitive to SOC changes when compared to clayey soil (Rawls et al., 2003). The clayey soils offer higher physical and/or colloidal protection to SOM against microbial decomposition by formation of clay-organic complexes (McConkey et al., 2003; Tan et al., 2004; Stevenson, 1994).

The C fraction respired through the decomposition of litter and SOM is an important component influencing soil C changes (Paul et al., 2003). The TOC stocks simulated by FullCAM showed a declining rate of CO_2 emission by soil plus debris pools reaching an average rate of 0.17 t $ha^{-1}yr^{-1}$ in BO and 0.02 t ha^{-1} yr^{-1} in VG after four eucalypt rotations. Besides biological decomposition, the fire event in the two first eucalypt rotations simulated by FullCAM contributed to the litter and soil C loss as CO_2 to the atmosphere (Fig. 6) despite of higher NPP of eucalypt in comparison to pasture (Fig. 5). Mendham et al. (2003) observed that fire event in areas occupied with *E. globulus* in Australia resulted in C and N losses by volatilization, and leaching and erosion of others nutrients from soil. However, the C stock in LF and MB was simulated to increase after eucalypt establishment. The LF is constituted basically by organic residues partially decomposed, and it is strongly influenced by quantity and quality of organic residues deposited on soil (Six et al., 2002). Thus, the LF increment under eucalypt soil in comparison to the pasture soil was due to greater deposition of more lignified organic residue.

The use of modern genetic materials and fine-tuned silvicultural techniques in more recent eucalypt rotations resulted in gains in plant productivity (C sequestration in biomass), evolving from a mean annual increment of 3.8 Mg C $ha^{-1}year^{-1}$ in the 60s to 8.8 Mg C ha^{-1} $year^{-1}$ in recent years (Barros & Comerford, 2002) contribute substantially for higher deposition of organic residues and increase of SOM stocks in Brazilian conditions. The substitution of Cerrado by eucalypt resulted in an increase of TOC and C stocks in HF, LF and MB in the JV region (MG) (Fig. 3). The eucalypt cultivation (33 years) increased 5.63 % (0.14 t ha^{-1} yr^{-1}) the TOC stock in comparison to that under native Cerrado. The NPP of eucalypt was also higher than that of Cerrado (Fig. 5). The high clay content (78 dag kg^{-1}) combined with the high eucalypt stem productivity (60 m^3 ha^{-1} yr^{-1}) is an important factor that contributed for this increase (Table 2). Additionally, the adoption of the minimum tillage without harvest residue burning during the establishment of the most recent eucalypt rotation surely favored such gains. Several authors have found that the quality of eucalypt residues (high lignin content, wide C/N ratio) also contribute to accumulate litter and soil C following eucalypt cultivation (Gama-Rodrigues et al., 2002; Costa et al., 2005).

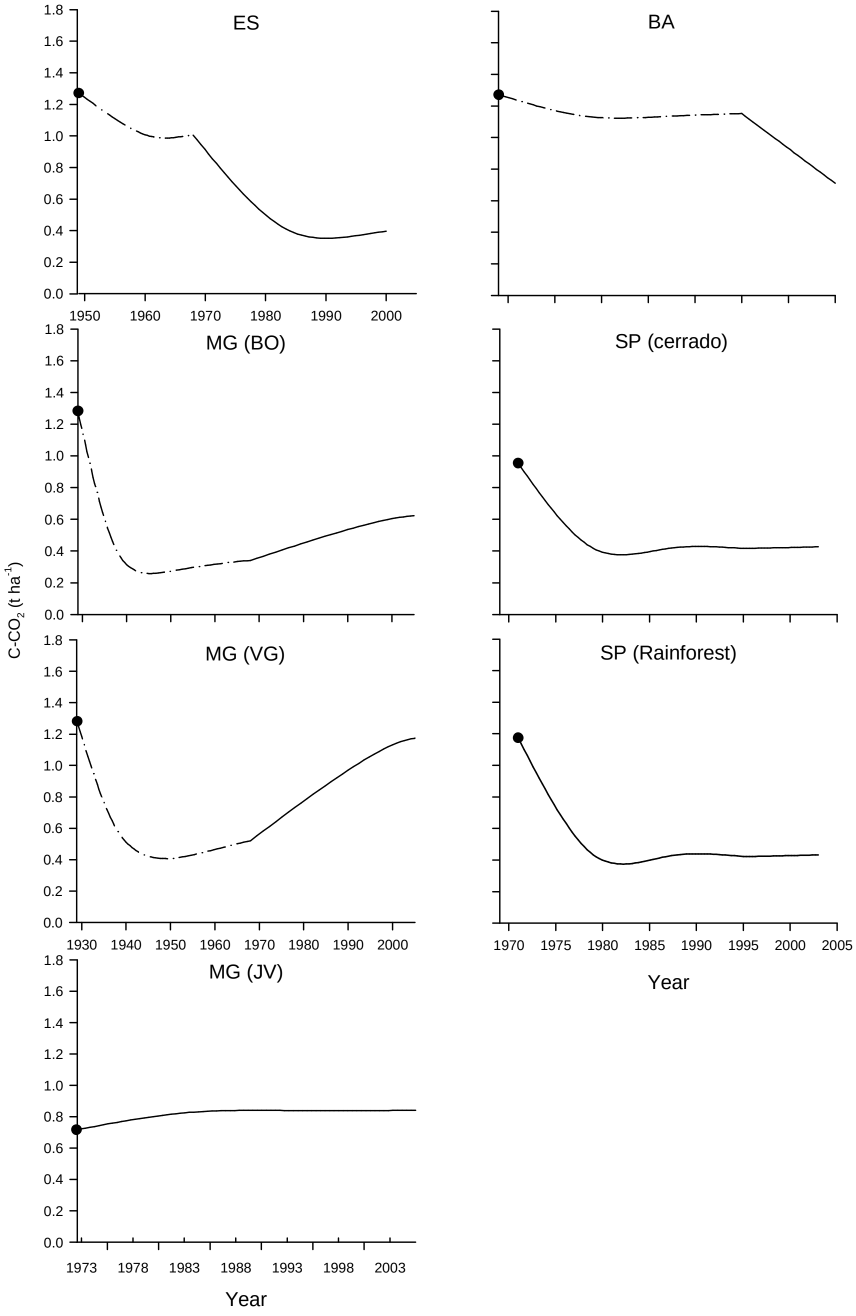

Figure 6. Simulated values of C-CO$_2$ emitted by soil+debris for the native forest (●), pasture (dash dot line), and eucalypt (solid line) areas in calibration of the FullCAM model. ES = Espírito Santo; MG = Minas Gerais; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley; BA = Bahia; SP = São Paulo.

The FullCAM model described adequately the TOC stocks (EF=0.74) and C stock in HS (EF= 0.65), but it was not as accurate to predict the C stocks in LF (EF=

0.11) and MB (EF= -0.87) pools (Fig. 4). Due to the more labile and dynamic nature of the LF and MB fractions, they fluctuate very fast in time, and a single-point measurement may not accurately represent their actual pattern along the rotations of eucalypt. Despite such limitations, the FullCAM model constitutes, in general, an appropriate tool to simulate the changes in soil C after eucalypt afforestation, it over-estimated the C stocks of the SOM fractions under conditions of low soil C stock showing the necessity to investigate the possible reasons that can contribute for this. In a study carried out in areas under eucalypt plantation previously occupied by pasture in Australia, Paul and Polglase (2004) found that the calibration of RothC sub-model in FullCAM was most successful for HS, and to a lesser extent for the resistant plant material (RPM) pool, where there were distinct differences amounts of C between soils from different sites.

5. CONCLUSIONS

1. Short-rotation eucalypt cultivation leads to a decline in the TOC stocks and C stock in HS in comparison to improved pasture in the ES and BA states. Also, the eucalypt results in decrease of the TOC stock and C stock in HS and LF in comparison to rainforest (clayey Oxisol) and Cerrado (sandy Entisol) in the SP state, but it contributed to increase the TOC stock and C stock in HS and LF in comparison to the Cerrado soil in the JV region (MG state).

2. The FullCAM model describes satisfactorily the TOC stock (model efficiency - EF= 0.74) and C stock in HS (EF= 0.65) in soils under native forest, pasture and eucalypt plantation.

3. The FullCAM model is an important tool to estimates the changes in soil C following afforestation as well as to identify important sites factors and processes controlling SOM dynamic in tropical soils.

6. FURTHER WORK REQUIRED

The FullCAM model has been calibrated for the main eucalypt growing States in Brazil, which have distinct vegetations and edapho-climatic conditions. Despite of satisfactory results presented by the model, specific testing is required for the partitioning of C lost as CO_2 to the atmosphere and C that moves to soil during debris decomposition. Moreover, information about the percentage of decomposable and resistant fraction of each plant compartment (e.g. wood, branches, and foliages) is required for Brazilian conditions. Regarding the soil, it is very important to obtain information related to decomposition constant rates for BIO, RPM, DPM, and HUM pools under Brazilian conditions. The RothC sub-model in the FullCAM model has only been calibrated to predict C cycling down to 30 cm layer of soil. Despite the fact that surface layer stores most of SOC and that it is more easily altered by land uses and land use changes, it is possible that deeper soil layers play an important role on long-term C sequestration in afforested soils.

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8. GAP ANALYSIS

The FullCAM model constitutes a complex model to simulate the C flux among soil, debris, plant, and atmosphere. Due to the great number of information that is required to work with FullCAM, its use may be so hard. Among dataset that will be necessary to update in future study under Brazilian conditions have:

Forest

1) Plant properties:

► Turnover percentage (%/yr) of branches, bark, leaves, coarse and fine roots;

► Stem density;

► Growth of the plant components relative to each other (allocation);

► Tree mortality rate;

2) Debris properties:

► Resistant percentage of stem, branches, bark, leaves, coarse and fine roots;

► Breakdown percentage (%/yr) of deadwood, chopped wood, bark litter, leaves litter, coarse and fine dead roots (decomposable and resistant);

► Atmospheric percentages of breakdown products of deadwood, chopped wood, bark litter, leaves litter, coarse and fine dead root (resistant and decomposable);

3) Soil properties:

► Humin encapsulation percentage (encapsulation by clay);

► Decomposition rates multipliers of decomposable plant material (DPM), resistant plant material (RPM), BIO-F, BIO-S and humin;

► Percentage of decomposed DPM, RPM, BIO-F, BIO-S solids that go to BIO-F and humin;

► Percentage of decomposed humin solids that go to BIO-S and humin;

► Ratio of evapotranspiration to open-pan evaporation;

► Ratio of bare-to-covered maximum topsoil moisture deficit (TSMD);

4) Management event properties:

4.1. Harvest:

4.1.1. Destination percentage of tree material in the affected portion:

► Stem – to biofuel, paper and pulp, packing wood, furniture, fiberboard, construction, mill residue, and deadwood;

► Branches - to biofuel, paper and pulp, packing wood, furniture, fiberboard, construction, mill residue, and deadwood;

► Bark - to biofuel, paper, mill residue, and bark litter;

► Leaves - to biofuel and leaf litter;

► Coarse roots - to biofuel and coarse dead roots;

► Fine roots – to fine dead roots.

4.1.2. Destination percentage of litter in the affected portion:

► Deadwood, bark litter, chopped wood, and leaf litter – to biofuel.

4.2. Fire:

4.2.1. Destination percentages of material in the affected portion:

► Tree (stem, branches, bark, and leaves) to atmosphere and debris;

► Debris (deadwood, chopped wood, bark litter, leaf litter, coarse dead roots, and fine dead roots) decomposable and resistant to atmosphere and inert soil.

4.3. Chopper roller:

► Percentage of litter pools converted to chopped wood – Deadwood and bark (decomposable and resistant).

4.4. Termite change:

► New percentage eaten by termites (%/yr) – Deadwood and coarse roots (decomposable and resistant).

Crop

1) Plant properties:

► Turnover percentage (%/yr) of grains, buds, fruits, stalks, leaves, coarse and fine roots;

► Growth of the plant components relative to each other (allocation);

► Crop mortality rate;

2) Debris properties:

► Resistant percentage of grains, buds, fruits, stalks, leaves, coarse and fine roots;

► Breakdown percentage (%/yr) of decomposable and resistant of GBF litter, stalk litter, leaf litter, coarse and fine dead roots;

► Atmospheric percentages of breakdown products (resistant and decomposable) of GBF litter, stalk litter, leaf litter, coarse and fine dead roots;

3) Soil properties:

► Humin encapsulation percentage;

► Decomposition rates multipliers of decomposable plant material (DPM), resistant plant material (RPM), BIO-F, BIO-S and humin;

► Percentage of decomposed DPM, RPM, BIO-F, BIO-S solids that go to BIO-F and humin;

► Percentage of decomposed humin solids that go to BIO-S and humin;

► Ratio of evapotranspiration to open-pan evaporation;

► Ratio of bare-to-covered maximum topsoil moisture deficit (TSMD);

4) Management event properties:

4.1. Harvest:

4.1.1. Destination percentage of crop material in the affected portion:

► GBF – to biofuel, GBF product, hay, straw, silage, and GBF litter;

► Stalks - to biofuel, cane products, hay, straw, silage, and stalk litter;

► Leaves - to biofuel, leaf products, hay, straw, silage, and leaf litter;

► Coarse roots - to biofuel, root products, hay, straw, silage, and coarse dead roots;

► Fine roots – to fine dead roots.

4.1.2. Destination percentage of litter in the affected portion:

► GBF litter, stalk litter and leaf litter – to biofuel.

4.2. Fire:

4.2.1. Destination percentages of material in the affected portion:

► Crop (GBF, Stalks, and leaves) to atmosphere and debris;

► Debris (GBF litter, stalk litter, leaf litter, coarse and fine dead roots) decomposable and resistant to atmosphere and inert soil.

4.3. Grazing change:

► Mass of crop eaten by grazers, each day (tdm/ha) – Grains, buds, fruits, stalk, and leaves;

► Percentage of crop net primary production (NPP) eaten by grazers – Grains, buds, fruits, stalk, and leaves;

► Percentage of crop mass eaten by grazers each day - Grains, buds, fruits, stalk, and leaves;

► New roots slough.

GENERAL CONCLUSIONS

1. The eucalypt afforestation results in increase in soil C stocks in soils previously under poorly managed pastures and low NPP Cerrado vegetation. However, short-rotation eucalypt caused a decline in SOC stocks in sites that were previously under well managed pastures in the Coastal Plains, as well as in inland regions under Cerrado and Atlantic Forest in SP State.

2. The simulation with the Century model of C stocks in soils of different order and that are currently under eucalypt in independent regions with variable climate conditions proved feasible, but additional studies are required to better calibrate the model since the statistical procedure to test the identity of analytical methods (Leite and Oliveira, 2000) suggested that simulated SOC values differed from the observed values.

3. The FullCAM model describes satisfactorily the TOC stock (model efficiency - EF= 0.74) and C stock in HS (EF= 0.65) in soils under native forest, pasture and eucalypt plantation.

4. Further studies are necessary in order to parameterize the simulation models with site-specific information and, more importantly, the models must be validated with independent data collected from well designed and kept long-term experiments, where current and alternative management practices may be tested.