UNIVERSIDADE FEDERAL DE VIÇOSA

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

Augusto Miguel Nascimento Lima
Doctor Scientiae

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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

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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).

CONTEÚDO

CHAPTER III

Calibration of the FullCAM model to simulate soil organic matter cycling under eucalyptus, pasture and native forests in Brazil

Resumo

LIMA, Augusto Miguel Nascimento, Universidade Federal de Viçosa, Abril de 2008. Dinâmica das frações da matéria orgânica do solo sob povoamentos de eucalipto no Brasil e sua modelagem com modelos integrados. Orientador: Ivo Ribeiro da Silva. **Conselheiros:** Nairam Félix de Barros, Eduardo de Sá Mendonça e Roberto Ferreira de Novais.

O seqüestro de C no solo constitui uma importante alternativa para decrescer a emissão de CO_2 para atmosfera. Dentre as estratégias recomendadas para mitigar a emissão de gases do efeito estufa para a atmosfera tem-se o reflorestamento com eucalipto em áreas anteriormente ocupadas por cultivo agrícola e pastagens degradadas no Brasil. Apesar de práticas de manejo adequadas para obtenção de elevadas produtividades de madeira ser utilizada 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 eucalipto nos estoques de C e N das frações da MOS até a profundidade de 1 m em solos de diferentes texturas em relação aos usos de 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 na camada de 0-20 cm 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 às 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 uso do solo foram determinados os estoques de C (COS) e N (NOT) no solo, substâncias húmica (SH), fração leve (FL) e 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. O eucalipto (entre linhas – EL) apresentou maiores estoques de C no solo (115,0 t ha^{-1}), SH (100,1 t ha^{-1}) e FL (6,5 t ha^{-1}) que a pastagem

(COS = 93,0 t ha^{-1}, SH = 81,5 t ha^{-1}, FL = 2,7 t ha^{-1}) nos primeiros 60 cm no grupo de solos argilosos. Similar comportamento foi observado quando comparou este eucalipto com a cana-de-açúcar nas camadas de 0-10, 0-40 e 0-60 cm. Não houve diferenças nos estoques de NOT entre eucalipto (EL), pastagem e cana-de-açúcar nos grupos 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 (EL) apresentou maior estoque de N na FL (0,28 t ha^{-1}) que o solo sob pastagem (0,10 t ha^{-1}) e cana-de-açúcar (0,16 t ha^{-1}) na camada de 0-100 cm. Os solos arenosos sob eucalipto, pastagem e cana-de-açúcar apresentaram menores estoques de C nas SH, fração ácido fúlvico (FAF) e fração ácido húmico (FAH) em relação ao solo sob floresta nativa nas camadas de 0-10, 0-20, 0-40 e 0-100 cm. Similar comportamento foi observado para os estoques de C e N da FL em todas as camadas do solo estudadas. Em relação ao segundo objetivo, foram selecionadas áreas que tem sido cultivada 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 Century decresceram após 37 anos sob pastagens degradadas em áreas anteriormente ocupadas por mata nativa em BO e VG. O estabelecimento do eucalipto resultou no acréscimo de 0,29 e 0,44 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 (r = 0,72, R^2 = 0,51, n = 37, RMSE = 10,87 %). A manutenção da casca do eucalipto após a colheita resulta no aumento do seqüestro de C no solo. Para estudar o terceiro objetivo, compararam-se os estoques de C do solo (COS), SH, FL e BM observados com os estoques de C nessas frações simulados pelo FullCAM mediante o cálculo do valor de eficiência do modelo (EF). Os resultados indicaram que em ES e BA, os estoques de COS 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 de COS, SH e FL simulados decresceram após substituição da floresta nativa por eucalipto. Por outro lado, após 33 anos de cultivo com eucalipto os estoques de COS aumentaram 5,6% em relação ao Cerrado no Vale do Jequitinhonha – MG. O modelo FullCAM descreveu satisfatoriamente apenas os estoques de COS (EF=0,74) e SH (EF= 0,65) mostrando a necessidade de estudos adicionais na calibração para as demais frações da MOS.

Abstract

LIMA, Augusto Miguel Nascimento, Federal Viçosa University, April/2008. Soil organic matter fractions dynamics under eucalyptus plantations in the main afforested region of Brazil. Supervisor: Ivo Ribeiro da Silva. Co-supervisor: Nairam Félix de Barros, Eduardo de Sá Mendonça and Roberto Ferreira de Novais.

The soil C sequestration is one of the most important alternatives to decrease the CO_2 emission to the atmosphere. Among the strategies to mitigate the greenhouse gas emission to the atmosphere has the eucalyptus afforestation in former degraded pasture and agriculture lands in Brazil. Despite utilization of adequate management practices for achievement high wood productivity, the impact of theses forestry practices on soil organic matter (SOM) stocks of afforested areas in Brazil is unknown. Thus, the aims of this study were: i) to evaluate the eucalyptus 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 eucalyptus chronosequences and different soils orders as well as to evaluate the impact of eucalyptus 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 eucalyptus 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). In relation to the first aim, we selected commercial eucalyptus plantations located nearby native forest (Atlantic forest or Cerrado), pasture and sugar cane in two great soils groups: clayey (± 66% of clay) and sandy (± 9% of clay). So, for each soil use it was determined the C and N stocks of soil (TOC and TON), humic substances (HS), light fraction (LF), and microbial biomass (MB) in the 0-10, 10-20, 20-40, 40-60 and 60-100 cm layers. The results indicated that the clayey soils, in general, have higher C and N stocks in SOM fractions in comparison to the sandy soils. The eucalyptus soil (between rows – BR) presented higher C stocks in soil (115.0 t ha^{-1}), HS (100.1 t ha^{-1}) and LF (6.5 t ha^{-1}) than the pasture soil (SOC = 93.0 t ha^{-1}, HS = 81.5 t ha^{-1}, LF = 2.7 t ha^{-1}) in the first 60 cm in the clayey soils group. A similar behaviour was observed when compared this eucalyptus to the sugar cane soil in the 0-10, 0-40 and 0-60 cm layers. There were no differences in the NOT stocks among the eucalyptus (EL), pasture and sugar cane soils

in the clayey and sandy soils groups. All soil uses had lower N stocks in the humic fractions than the native forest soil in the 0-60 cm in the clayey soils group. The eucalyptus soil (EL) had higher N stock in LF (0.28 t ha^{-1}) than the pasture (0.10 t ha^{-1}) and sugar cane (0.16 t ha^{-1}) soils in the 0-100 cm layer. The sandy soils under eucalyptus, pasture and sugar cane had lower C stock in HS, fulvic acid fraction (FAF) and humic acid fraction (HAF) than the native forest soil in the 0-10, 0-20, 0-40 and 0-100 cm layers. A similar behaviour was observed for the C and N stocks in LF in all studied soil layers. In relation to the second aim, we selected areas with eucalyptus cultivation time of 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 showed that the C stocks simulated by the Century model decreased after 37 years under degraded pasture in areas previously occupied by native forest in BO and VG. The eucalyptus establishment resulted in increase of 0.29 e 0.44 t ha^{-1} $year^{-1}$ of C in BO and VG, respectively. The C stocks in distinct soil orders were adequately estimated by the Century model ($r = 0.72$, $R^2 = 0.51$, $n = 37$, RMSE = 10.87 %). The maintenance of eucalyptus bark on site after harvesting resulted in increase of the C sequestration in soil. To study the third aim, we compared the observed C stocks of soil (SOC), HS, LF and MB with the C stocks in these fractions simulated by the FullCAM model by calculation of the model efficiency value (EF). The results showed that in ES and BA, the simulated SOC stocks decreased 0.37 and 0.30 t ha^{-1} $year^{-1}$, respectively, after the eucalyptus establishment in former well managed pasture. A similar behaviour was observed in SP where the simulated C socks in soil (SOC), HS and LF decreased after replacement of native forest by eucalyptus. On the other hand, after 33 years of eucalyptus cultivation the SOC stocks increased 5.6 % in relation to Cerrado in Jequitinhonha Valley – MG. The FullCAM model works well only for the SOC (EF=0.74) and HS (EF= 0.65) stocks showing the necessity to additional study in calibration of model for other SOM fractions.

CHAPTER 1

Changes in organic carbon and nitrogen pools after eucalyptus establishment in soils with contrasting texture in São Paulo State, Brazil

Abstract

Planting short-rotation eucalyptus is a rapidly expanding activity in Brazil, but its impact on soil carbon (C) and nitrogen (N) pools is little known. Thus, this study aimed at evaluating the influence of eucalyptus on C and N stocks of the total (TOC – total organic C, TON – total organic N), humic fractions, light fraction (LF), and microbial biomass (MB) pools down to 1 m deep in comparison to the native forest, pasture, and sugar cane soils in the São Paulo State, Brazil. We selected commercial eucalyptus plantations located adjacent to the native forest (Atlantic forest or Cerrado-savanna), pasture and sugar cane fields. The soils were divided in two great groups according to clay content: clayey (± 66% of clay) and sandy (± 9% of clay). So, for each land use it was determined C and N stocks of soil, humic fractions, LF, and MB in the 0-10, 10-20, 20-40, 40-60 and 60-100 cm layers. The eucalyptus stands had soil samples taken from the row (R) and between-rows (BR)**.** The results showed that the clayey soils group, in general, has higher C and N stocks in SOM fractions than the sandy soils group. The eucalyptus soil (BR) had higher C stock within TOC (115.0 t ha^{-1}), humic substances (HS) (100.1 t ha^{-1}), and LF (6.5 t ha^{-1}) than the pasture soil (TOC = 93.0 t ha^{-1}, HS = 81.5 t ha^{-1}, LF = 2.7 t ha^{-1}) up to 60 cm deep in the clayey soils group. A similar behaviour was observed when compared the eucalyptus soil (BR) with the sugar cane soil in the 0-10, 0-40 and 0-60 cm layers. Otherwise, all other soil uses had lower TOC stocks than the native forest soil in the first 20 cm deep in the clayey and sandy soils group. There were no differences in the TON stocks among eucalyptus (BR), pasture and sugar cane soils in both soil groups. However, the eucalyptus soil had 3.5 t ha^{-1} of TON lower than the native forest soil up to 60 cm deep in the clayey soil group. All soil uses also had lower N stocks in humic fractions than the native forest soil up to 60 cm layer. The eucalyptus soil (BR) had higher N stock in LF (0.28 t ha^{-1}) than the pasture (0.10 t ha^{-1}) and sugar cane (0.16 t ha^{-1}) soil up to 1 m deep. The eucalyptus 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 eucalyptus, pasture and sugar cane soils had lower C stocks in HS, fulvic acid fraction (FAF), and humic acid fraction (HAF) than the native forest soil in the 0-10, 0-20, 0-40 and 0-100 cm layers. A similar behaviour was observed for the C and N stocks in LF in all soil layers. However, the eucalyptus soil (BR) had larger C stock in MB (2.2 t ha^{-1}) than the native forest (1.55 t ha^{-1}) and pasture (1.48 t ha^{-1}) soils in the 0-100 cm layer. Otherwise, the eucalyptus soil had lower N stock in MB than the sugar cane soil in the 0-20, 0-60 and 0-100 cm layers. The clay content is very important to maintain or increase soil C under eucalyptus afforestation in Brazil.

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

1. Introduction

The areas under tropical forest and cerrado in Brazil are being reduced very fast, where stimulated by the growing demand by 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 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, pasture and short-rotation forest plantation. About 40 years ago the planted forest in Brazil occupied little over 500 ha. By 1987, Brazil had more than 6 Mha of planted forest, and more than one third was located in the southeast region. Eucalyptus and Pinus 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 growth, tree species (e.g. eucalyptus) has been carried out in former pasture and agricultural land. The productivity (capacity of CO_2 sequestration) of commercial eucalyptus plantations in Brazil is very variable (15-80 m^3 ha^{-1} $year^{-1}$ of stem) and it depends on water and nutrient availability if we consider that solar radiation and temperature are not limiting (Barros and Comeford, 2002). Although intensive management practices applied to short-rotation eucalyptus plantations may guarantee rapid growth and higher economic returns than native forests, 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 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 is playing 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 turnover times (Stevenson, 1994) and, that the recalcitrant 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 straight forward (Haynes, 1999). Furthermore, several factors affect the magnitude and quickness of SOM changes including land use, soil type, climate and original vegetation (Post & Kwon, 2000; Paul et al., 2002). Consequently, the physical fractionation of SOM and biological analysis combined with chemical analysis can be important strategies in process-oriented SOM research (Christensen, 2001).

There are some evidences that the clay particles play important roles in SOM dynamics (Barthès et al., 2008; Traoré et al., 2007; McLauchlan, 2006). In a study carried in Australia with soils under eucalyptus, 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, clayeyer soil presented larger SOC contents and lower mineralization C rates. Also, in a study with short-rotation eucalyptus plantations in Brazil, Lima et al. (2006) observed that the clay content was one of the most important characteristics to accumulate SOM in the 0-20 cm layer of soil previously occupied by pasture.

The aim of this study was to evaluate the influence of the eucalyptus plantations in the C and N stocks of soil, humic fractions, light fraction, and microbial biomass down to 1 m deep in soils with contrasting texture in comparison with native forest, pasture, and sugar cane in São Paulo, the State with the second largest eucalyptus plantation in Brazil.

2. Material and methods

2.1. Site description

This study was carried out in commercial eucalyptus plantations located in the Luiz Antônio county (21º33'18" S and 47º42'16" W), distant about 300 km from the São Paulo county, São Paulo State, Brazil. The mean annual precipitation is 1481 mm and most of it falls between November and March. The mean annual temperature is 23 ^{o}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) interspersed by clayey soils (Oxisol) derived from basalt.

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

The soils were divided in two great groups according to their clay content: clayey and sandy soil (Table 1). In the clayey soils group were selected adjacent areas under native vegetation (Atlantic forest), pasture, eucalyptus and sugar cane. In the sandy soils group were selected areas under native vegetation (dense cerrado), pasture, eucalyptus and sugar cane. 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 eucalyptus 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 eucalyptus planting, the trees were clear cut and the trunk removed from the area. The eucalyptus 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 eucalyptus plantations were in the fourth rotation currently (two year-old). The tree density was 1333 plants ha^{-1} with average diameter at breast height (DBH) of 49.8 cm and average height of 25 m. All management practices were carried out mechanically due to favourable topography. The harvests were conducted with utilization of Feller plus Camblumck equipment.

The eucalyptus stands selected for soil sampling covered approximately 10 ha, and they were located in the middle slope position. Because silvicultural practices, such as fertilization and harvest residue deposition may be localized, soil samples were collected in two positions: between tree rows (BR) and in the tree row (R) in the 0-10, 10-20, 20-40, 40-60 and 60-100 cm soil layers. Each replicate was separated by more than 500 m and it consisted of a composite of four soil samples randomly collected 20 m apart from each other. A similar procedure was used for sampling in adjacent native forest, pasture and sugar cane areas. 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. Three replicates were randomly assigned to each stand.

2.2. Soil analysis

After air drying, soil samples were sieved trough a 2 mm sieve for determination of C and N content 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 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 (TON) 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	S.D.
	(cm)	--------------($g\ kg^{-1}$)	------------		($Mg\ m^{-3}$)
Clayey soil					
	0-10	130	210	660	0.96
	10-20	110	230	660	1.11
Native forest	20-40	100	210	690	1.20
	40-60	90	210	700	1.09
	60-100	100	210	690	0.98
	0-10	130	210	660	1.23
	10-20	130	230	640	1.15
Pasture	20-40	110	220	670	1.14
	40-60	110	220	670	1.11
	60-100	110	220	670	1.02
	0-10	170	180	640	1.16
	10-20	170	190	640	1.19
Euc (row)	20-40	160	190	650	1.15
	40-60	160	180	650	1.08
	60-100	150	180	660	1.03
	0-10	170	190	640	1.07
	10-20	170	170	650	1.13
Euc (between rows)	20-40	160	180	650	1.16
	40-60	160	190	650	1.12
	60-100	150	180	660	1.05
	0-10	140	210	650	1.30
	10-20	140	210	650	1.24
Sugar cane	20-40	120	210	670	1.17
	40-60	120	210	670	1.05
	60-100	120	210	670	1.06
Sandy soil					
	0-10	910	20	70	1.20
	10-20	910	20	70	1.41
Native forest	20-40	920	20	60	1.35
	40-60	920	20	60	1.47
	60-100	930	10	60	1.46

Euc = Eucalyptus, S.D. = soil density

Table 1. Cont.

Land use	Layer	Sand	Silt	Clay	S.D.
	(cm)	--------------(g kg^{-1})------------			(Mg m^{-3})
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
Euc (row)	0-10	880	20	100	1.42
	10-20	900	20	90	1.49
	20-40	900	20	90	1.48
	40-60	890	20	100	1.45
	60-100	890	10	110	1.43
Euc (between rows)	0-10	900	20	90	1.31
	10-20	900	20	90	1.39
	20-40	900	20	90	1.42
	40-60	890	20	100	1.40
	60-100	890	10	110	1.40
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

Euc = Eucalyptus, S.D. = soil density

The chemical fractionation of humic substances was based on differential solubility of organic composts in acid and base solution 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 HS fraction 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 fractions (LF) through flotation in a NaI solution (1.8 Mg m^{-3}) (Sohi et al., 2001). The floating organic matter was collected on a 0,25 mm sieve and 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 of C concentration by the mass of soil in each layer of native forest to avoid management-induced compaction effects on SOM stocks (Lemma et al., 2006).

Data were submitted to analysis of variance (ANOVA) in a completely randomized block design. Treatments means were compared by the protected LSD test (Steel et al., 1997) ($\alpha = 0.05$) using the software SAEG 5.0 (Funarbe, 1993).

3. Results and discussion

The eucalyptus productivity in highly weathered soils is closely related with the SOM levels (Menezes, 2005) and it favors the long-term forestry sustainability (Barros & Comerford, 2002). The SOM roles seem to depend of more limiting factors in each site. In sandy soils it is essential to water retention and nutrient supply, whilst in clayey soils its fundamental role is 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 group, in general, had larger C and N stocks in all SOM fractions than the sandy soils group (Fig. 1 and 2). In general, clayey soils present larger SOM contents and lower C mineralization rates (Mendham et al., 2002; 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). Additionally, the clay content may alter soil moisture, which effects 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 eucalyptus soil (between rows - BR) had larger TOC stocks (115.0 t ha^{-1}) than the pasture soil (93.0 t ha^{-1}) up to 60 cm deep (Fig. 1). A similar behaviour was observed when compared this eucalyptus with the sugar cane soil in the 0-10, 0-40 and 0-60 cm layers. This can be explained by the fact that during soil preparation for planting of the current eucalyptus the harvest residues and litter from the last eucalyptus rotation were windrowed together in the between rows position of the current eucalyptus rotation. This is a usual management practice of reduced tillage utilised by the majority of afforestation companies in Brazil, which contributes for lower machinery intervention in soils. Additionally, the roots decay from the last eucalyptus rotation also contributes to accumulate SOM in the current between rows position. The eucalyptus soil (row - R) had 7.7 and 4.5 t ha^{-1} of TOC higher than the pasture and sugar cane soil, respectively, in the 0-10 cm layer. The great changes in soil physical, chemical and biological properties due to the frequent annual interferences for discompaction, fertilization, weed control, etc, quality of C inputs to soil and higher SOM decomposition rates induced by the agricultural systems contribute to decrease C stock in relation to eucalyptus (Murty et al., 2002). In a study evaluating the changes of SOM stocks in eucalyptus chronosequences established in former degraded pastures in the Minas Gerais State, Brazil, Lima et al. (2006) also observed that the eucalyptus cultivation resulted in increase of the TOC stocks (0-20 cm), where larger input of more lignified and aromatic-rich organic residues by eucalyptus was observed (Paul el al., 2003; Sjoberg et al., 2004). The eucalyptus soil had 8.2 t ha^{-1} of TOC lower than the native forest soil up to 20 cm deep. Also, the eucalyptus soil (R) had lower TOC stock than native forest in the 0-40 and 0-60 cm layers.

A distinct effect of land use was observed on SOM of the sandy soil group (Fig. 1). The eucalyptus cultivation (R) led to larger TOC stocks (47.3 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. The eucalyptus soil (BR) only presented larger TOC stock (43.4 t ha^{-1}) when compared with the pasture soil in the 0-40 cm layer. Nonetheless, all soil uses caused a decline in TOC stock when compared with the native forest soil in the 0-10, 0-20 and 0-60 cm layers. A similar behaviour was observed when compared the pasture, eucalyptus (BR), and sugar cane soil with the native forest soil in the 0-40 and 0-100 cm layers, showing more once that the native forest use 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 eucalyptus. Additionally, the lower mean annual temperature (19.4 ^{o}C) could favor the SOM maintenance after long-rotation eucalyptus establishment.

There were no differences in the TON stocks among eucalyptus, pasture, and sugar cane soils in all analysed soil layers (Fig. 2). Despite eucalyptus soil showed higher C stocks (as described above), its N stocks no increased showing that qualitative aspects of inputs and structural composition are fundamental in SOM dynamics. On the other hand, the eucalyptus soil had 3.5 t ha^{-1} of TON lower than the native forest soil up to 60 cm deep. Also, the eucalyptus soil (R) had 3.3 t ha^{-1} of TON lower than the native forest soil in the 0-100 cm layer. The native forest soil is an environment where disturbances from management practices such as eucalyptus planting and harvest no exist (lower N loss by volatilization and leaching), contributing for greater N stocks. Evaluating the soil physico-chemical characteristics in a tropical dry deciduous native forest, regenerated forest and eucalyptus plantation close to Jharsuguda in the western part of Orissa, Behera and Sahani (2003) observed that the TOC and NOT concentrations were comparatively lower in the eucalyptus 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 TON concentration in the cultivated, grazing and eucalyptus soils than that under native forest. The great number of plant species in the native forest area and, additionally, the N biological fixation by some plants (e.g. leguminous) contributes substantially to maintain or increase the N stock in soil. In the sandy soil group, the pasture, eucalyptus plantation (R and BR) and sugar cane soils also had lower TN stocks than the native forest soil (cerrado) in the 0-20, 0-40 and 0-60 cm layers

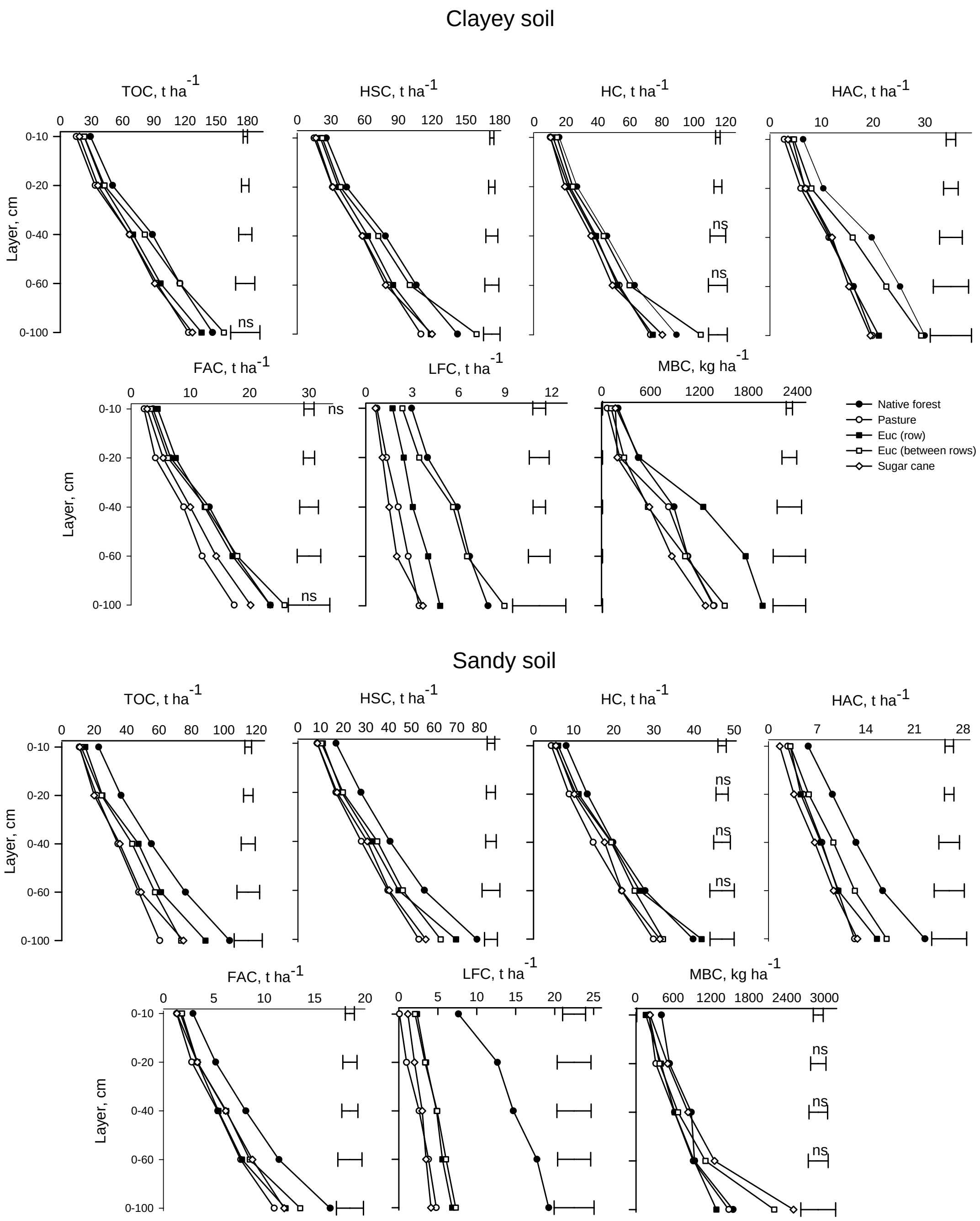

Fig. 1. Total organic carbon (TOC), humic substances C (HSC), humin fraction C (HC), humic acid fraction C (HAC), fulvic acid fraction C (FAC), light fraction C (LFC), and microbial biomass C (MBC) stocks in the clayey and sandy soils groups at different depths.

3.2. *Humic substances carbon and nitrogen*

The eucalyptus soil (BR) had 49.5 and 39.5 t ha $^{-1}$ of the C stock in HS higher than the pasture and sugar cane soil, respectively, up to 100 cm deep in the clayey soil group (Fig. 1). Also, the eucalyptus soil (R) had larger C stock in HS (20.7 t ha $^{-1}$) than the pasture (15.1 t ha $^{-1}$) and sugar cane (16.5 t ha $^{-1}$) soils in the 0-10 cm layer. The more recent adoption of reduced tillage and the organic residue maintenance on soil surface after harvest might contribute to increase C stock in HS. However, the eucalyptus soil (R) had lower C stock in HS (118.7 t ha $^{-1}$) than the native forest soil (142.5 t ha $^{-1}$) in all studied soil profile. Probably, fire utilization during the two first rotations of eucalyptus contributed for C loss as CO_2 to the atmosphere resulting in smaller C input, besides favoring soil erosion. Evaluating the soil and water loss due to hydric erosion in eucalyptus plantations in Brazil, Pires et al. (2006) observed that the burning of organic residues after harvesting contributes to increase soil and water loss. They suggested that the fire events increased water repellence and, consequently, decreased water infiltration rate into soil. The eucalyptus soil (BR) had larger C stock in HF than all other soil uses in the 0-100 cm layer. The eucalyptus soil (BR) also had larger C stock in HAF than the sugar cane soil in the 0-60 and 0-100 cm layers. Comparatively with the pasture soil, the eucalyptus (BR) also had larger C stock in HAF in the 0-10, 0-40 and 0-100 cm layers, and larger C stock in FAF in the 0-20, 0-40 and 0-60 cm layers. A similar behaviour was found when compared the eucalyptus soil (R) with the pasture soil in the 0-20, 0-40 and 0-60 cm layers for the C stock in FAF. Nevertheless, when compared to the native forest soil, the eucalyptus soil (R) had lower C stock in HF (0-10 cm), and C stock in HAF in all studied layers. In a study carried out in Australia, Chen et al. (2004) observed that the substitution of 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 in environmental conditions and less susceptible for biological decomposition (Six et al., 2002). Additionally, the interaction with fine soil particles (clay and silt) contributes to the HAF stabilization in soil.

In the sandy soil group, the eucalyptus soil had larger C stocks in SH (69.6 t ha $^{-1}$ in R and 62.8 t ha $^{-1}$ in BR) than pasture (53.2 t ha $^{-1}$) and sugar cane (56.3 t ha $^{-1}$) soils in the 0-100 cm layer (Fig. 1). Differently, all soil uses had lower C stock in SH and FAF than the native forest soil up to 1 m deep. The pasture, eucalyptus (BR) and sugar cane also had lower C stock in HF than the native forest soil in the 0-10 and 0-100 cm layers. 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 the 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.

The clayey soil under eucalyptus plantation (R and BR) 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. 2). On the other hand, the eucalyptus soil (R and BR) had lower N stock in this fraction (8.1 t ha $^{-1}$ in R and 8.3 t ha $^{-1}$ in BR) 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. With exception of the 0-60 layer, it was found that the eucalyptus soil (BR) had larger N stock in HAF than the pasture soil in all other soil layers. Also, the eucalyptus soil (R) had higher N stock in this fraction (0.8 t ha $^{-1}$) than the pasture soil (0.5 t ha $^{-1}$) in the two more superficial soil layers. In addition, this eucalyptus had a larger N stock in HF (0-10 cm) and FAF (0-40 cm) when compared to the pasture soil.

In the sandy soils group, the pasture (1.2 t ha $^{-1}$), eucalyptus (1.4 t ha $^{-1}$ in R and 1.3 t ha $^{-1}$ in BR) 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. 2). Similarly, the eucalyptus (R and BR) and pasture soils had lower N stock in SH than the native forest soil in the 0-40 and 0-60 cm layers. All soil uses also presented lower N stock in 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 soil disturbs by agricultural use results in break down of soil aggregates and increased C and N mineralization

(Balesdent et al., 2000). Otherwise, there were no differences among pasture, eucalyptus (R and BR) and sugar cane soils in the N stocks in SH, HAF and FAF up to 40 cm deep. The eucalyptus soil stored lower N in HF (0.5 t ha $^{-1}$ in R and 0.4 t ha $^{-1}$ in BR) than the sugar cane soil (0.6 t ha $^{-1}$) up to 20 cm deep. Also, the eucalyptus (R) (0.8 t ha $^{-1}$) and pasture (0.7 t ha $^{-1}$) soils had lower N stocks in HF than the sugar cane soil (1.1 t ha $^{-1}$) in the 0-40 cm layer.

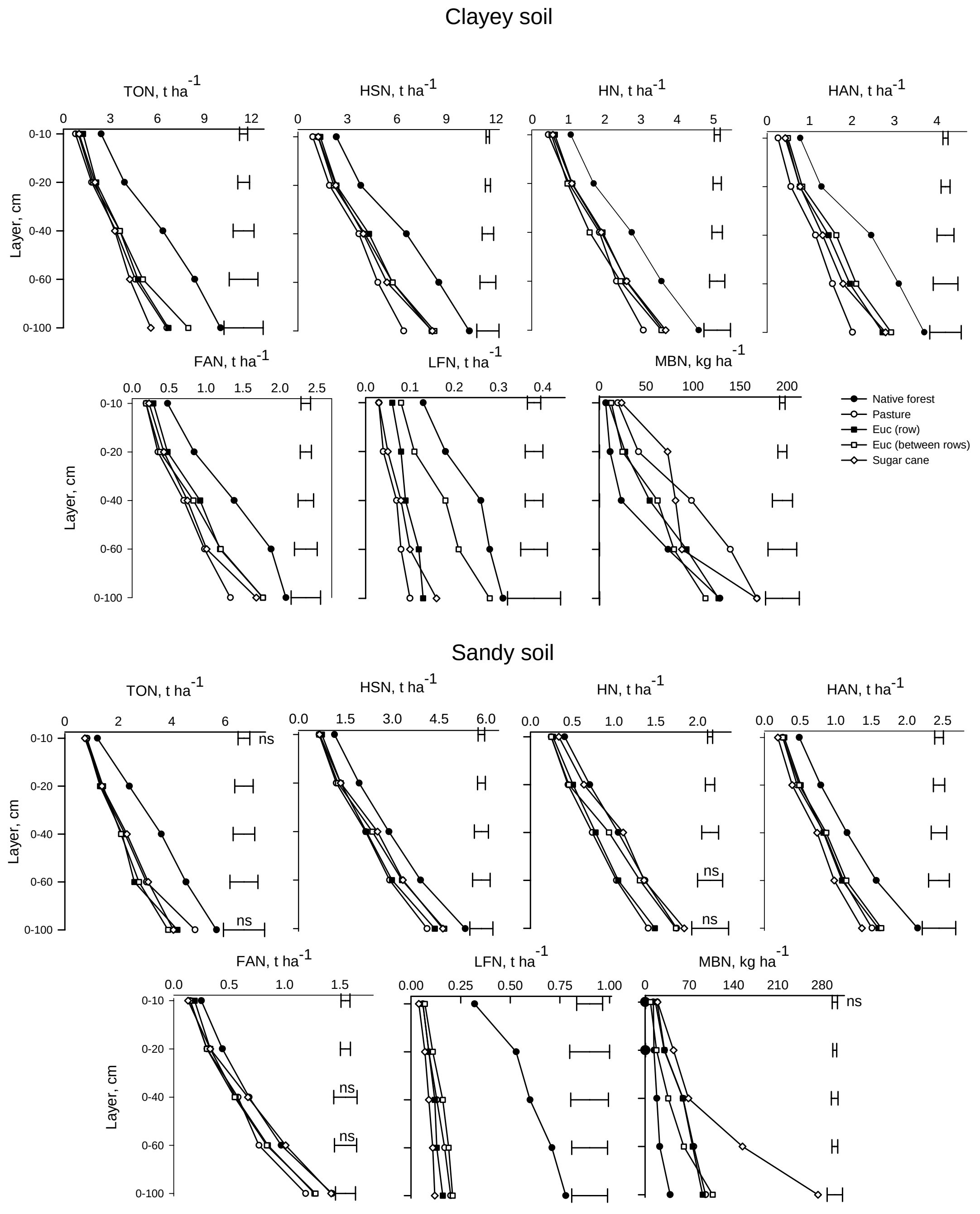

Fig. 2. Total organic nitrogen (TON), humic substances N (HSN), humin fraction N (HN), humic acid fraction N (HAN), fulvic acid fraction N (FAN), light fraction

N (LFN), and microbial biomass N (MBN) stocks in the clayey and sandy soil groups at different depths.

3.3. Carbon and nitrogen in light fraction and microbial biomass

In the clayey soils group, the eucalyptus soil (BR) had larger C stock in LF (8.9 t ha $^{-1}$) than the pasture (3.4 t ha $^{-1}$) and sugar cane (3.7 t ha $^{-1}$) soils in all layers (Fig. 1). The eucalyptus soil (R) also showed the same trend in the 0-10 and 0-40 cm layers. Furthermore, this eucalyptus had larger C stock in LF than sugar cane in the 0-20 and 0-60 cm layers. The LF is composed basically 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 eucalyptus 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 increase of C stocks in LF after approximately 34 years of short-rotation eucalyptus plantation in areas previously under degraded pasture in Brazil. Oppositely, the pasture (2.7 t ha $^{-1}$), eucalyptus (R) (4.0 t ha $^{-1}$) and 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 eucalyptus soil (R) presented larger C stocks in MB than native forest, pasture and sugar cane in soil layer deeper than 40 cm (Fig. 1). 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 eucalyptus 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 development. 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. On the other hand, the eucalyptus (BR) and pasture soils had lower C stocks in MB than the native forest soil in the 0-10 cm layer.

There were no differences of C stock in LF among pasture, eucalyptus (R and BR) and sugar cane soils in all analysed layers in the sandy soil group (Fig. 1). Nonetheless, the pasture (4.8 t ha $^{-1}$), eucalyptus (6.8 t ha $^{-1}$ in R and 7.3 t ha $^{-1}$ in BR) and sugar cane (4.1 t ha $^{-1}$) soils stored less C in 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 eucalyptus afforestation increased both POM amount and quality in comparison with cerrado, showing once more that the clay content contributes for POM accumulation (physical and colloidal protection) under eucalyptus plantation in relation to our sandy soil. Similarly, the native forest soil stored more C in MB than soils under all other uses in the 0-10 cm layer. On the other hand, the eucalyptus (BR) (2202.5 kg ha $^{-1}$) and sugar cane (2507.7 kg ha $^{-1}$) soils had larger C stock in this fraction than the native forest (1551.9 kg ha $^{-1}$) and pasture (1481.9 kg ha $^{-1}$) soils in the 0-100 cm layer.

The eucalyptus soil (BR) had larger N stocks in LF (0.28 t ha^{-1}) than the pasture (0.10 t ha^{-1}) and sugar cane (0.16 t ha^{-1}) soil up to 1 m deep in the clayey soils group (Fig. 2). A similar behaviour was found when the eucalyptus soil (R) (0.06 t ha^{-1}) was compared to the pasture (0.03 t ha^{-1}) and sugar cane (0.03 t ha^{-1}) soil in the 0-10 cm layer. However, all soil uses had lower N stock in LF than the native forest soil up to 60 deep. In a study evaluating the impact of conversion from native forest to eucalyptus in Ethiopia, Ashagrie et al. (2005) observed lower N and C stocks in LF in the eucalyptus 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 eucalyptus (R and BR) soils had lower N stock in MB than the pasture and sugar cane soils up to 20 cm as well deeper soil layer (0-100 cm).

There were no differences in N stocks in LF among pasture, eucalyptus (R and BR) and sugar cane soils in all analysed layer in the sandy soils group, but their N stocks in this fraction were smaller than those observed for the native forest soil (Fig. 2). Evaluating the changes of NOT and N stock in LF down to 1 m deep after conversion from Mulga (*Acacia aneura*) to pasture and crop 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, pasture and eucalyptus (R and BR) soils had lower N stock in MB than the sugar cane soil in the 0-20, 0-60 and 0-100 cm layers. Also, the native forest (23.3 kg ha^{-1}) and eucalyptus (BR) (61.5 kg ha^{-1}) soil had lower N stock in this fraction than the pasture soil (77.0 kg ha^{-1}

4. The clay content is very important to maintain or increase soil C stock under eucalyptus afforestation in Brazil.

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CHAPTER II

Modelling soil organic carbon after four short eucalyptus rotations in former pasture land in southeast 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 turnover and the long time that usually take to SOM stocks changes to be observed, the modelling constitutes a very important tool to understand the SOM cycling in forest soil. 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 commercial eucalyptus plantations 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 different soil order at eight regions in the Rio Doce Valley cultivated with eucalyptus, and (iii) to evaluate the impact of removal of the eucalyptus bark from the sites during harvest operation on the C stocks. In the Belo Oriente (BO) region, short-rotation eucalyptus plantations has been cultivated for 4.0; 13.0, 22.0, 32.0 and 34.0 years, while in the Virginópolis (VG) 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 simulated C stocks by the Century model decreased after 37 years of degraded pasture in areas previously covered by native forest in the BO and VG regions. The substitution of degraded pasture by eucalyptus in the early 70`s led to increases of 0.29 and 0.44 t ha^{-1} $year^{-1}$ of C in BO and VG, respectively. Soil C stocks under eucalyptus cultivated in distinct soil order in eight independent regions with variable edapho-climate conditions were adequately estimated with the Century model (r = 0.72, R^2 = 0.51, n = 37, root mean square error - RMSE = 10.87 %), despite in conditions with lower soil C stock the model super-estimated the C stock in the 0-20 cm layer. Model simulation results indicate that the maintaining of the eucalyptus bark on site after harvest resulted in increased C sequestration in soil. Thus, the Century model has a great potential to detect changes in the C stocks in distinct soil order under eucalyptus, 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 concentration in the atmosphere and, minimise environmental problems (Izaurralde et al., 2006). Several studies have shown the soil organic carbon (SOC) potential to decrease the CO_2 concentration in the atmosphere (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 narrowly related with long term production sustainability due to soil quality (Morris et al., 1997; Mendham et al., 2004). Recently it was found that SOM content is the soil characteristic that better correlated with the eucalyptus productivity (Menezes, 2005).

Soil use changes have potential to 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 area, as has occurred with short-rotation eucalyptus in Brazil. 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. 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 increase in soil C stocks (0-20 cm) after four eucalyptus 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 after 20 years of eucalyptus cultivation the SOM stock return to adequate levels.

Considering the complexity of factors that control the SOM dynamics and the long time that need to SOM changes be observed and quantified, researchers have looked for alternatives to understand better SOM. These complex relations can be better understood by using of modelling together with dataset 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 eucalyptus short-rotation in Brazil, particularly in Minas Gerais State, in regions with distinct soil and climate conditions, where stands have been harvested and the residues managed in several manners. The effects of eucalyptus establishment on SOM dynamics are unknown. So, the aims of this study were: (i) to evaluate the SOM dynamics using the Century model to simulate the changes of C stocks for two eucalyptus chronosequences; (ii) to compare the C stocks simulated by Century with the C stocks in different soil order at eight regions in the Rio Doce Valley with eucalyptus, and (iii) to evaluate the impact of eucalyptus bark removal from the sites during harvest on the C stocks.

2. Material and methods

The present study involved the utilization of the Century model for simulating the dynamics of C stocks after the eucalyptus 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 eucalyptus plantations, this study evaluated the performance of the Century model in simulating the temporal changes pattern for two eucalyptus chronosequences. Also, it was simulated the SOC stocks for independent eucalyptus stands located in eight regions with distinct soil order and climate. Because eucalyptus bark is removed from site to energy production, we also simulated the effect of removal of the eucalyptus bark from the site in the long-term SOM stocks.

2.1. The eucalyptus plantations chronosequences

The chronosequences of the eucalyptus plantations are located in the Belo Oriente (BO) and Virginópolis (VG) regions. The BO region has altitude of 250 m above sea level, annual mean temperature of 25 °C, and eucalyptus stem without bark productivity of 26 m^3 ha^{-1} $year^{-1}$. The soil is a clayey Yellow Latosol (Oxisol). The VG region has altitude of 850 m above sea level, annual mean temperature of 22 °C, and eucalyptus stem without bark productivity of 42 m^3 ha^{-1} $year^{-1}$. The soil is a Red Latosol (Oxisol). The distance between those two regions is approximately of 100 km, which offers a good opportunity to join the C addition and the different edaphic-climate conditions (mainly altitude and clay content) with the SOM dynamics after three decades of short-rotation eucalyptus establishment in areas previously occupied by degraded pasture. The rotation length in all regions is around 7-8 years.

In the BO region, eucalyptus plantations has 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 pasture located near the eucalyptus stands were also selected for sampling. Currently, the total area with eucalyptus in each region covers approximately 30,000 ha. The eucalyptus sites selected for soil sampling covered approximately 10 ha, and they were located in the middle slope position. They were chosen to be representative in each region. Soil samples were collected between tree rows in the 0–20 cm layer after carefully 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 stand as close as possible to harvest age. The same procedure was used to sample adjacent native forest and pasture.

Table 1

Cultivation, age and physical characteristics for the 0-20 cm layer soils of two chronosequences of eucalyptus 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
Eucalyptus	4.0	290	90	620	1.22
Eucalyptus	13.0	360	50	590	1.14
Eucalyptus	22.0	240	70	690	1.15
Eucalyptus	32.0	310	40	650	1.40
Eucalyptus	34.0	370	50	580	1.41
			Virginópolis		
Native forest	-	320	40	640	0.87
Pasture	-	300	50	650	0.91
Eucalyptus	8.0	450	30	520	1.13
Eucalyptus	19.0	240	70	690	0.96
Eucalyptus	33.0	250	50	700	0.93

S.D. –Soil density

In each region, the Tropical forest (IBGE, 1993) is constituted by trees in average higher 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*, *Sorocea bonplandii*, *Brosimum sp.*, etc. 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 under grazing. So, there was laminate erosion due to the annual burn resulting in soil less protected against rain direct impact, which resulted in degraded pastures. In 1969, the eucalyptus plantation replaced the pasture. The first eucalyptus cultivation (*Eucalyptus urophylla*) was planted manually after burning the pasture. After a seven year-rotation the trees were harvested (clear cut) and removed from the area. Then, the tree residues were burned to clear the area for the second rotation. Until the third eucalyptus rotation, 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 canceled since the fourth rotation. In all rotations debarking was performed off site with no bark returned to the site. The second rotation was coppiced and the others were new plantings. Except to the harvest, the management practices were carried out manually due to the steep relief.

2.2. The eight distinct regions in the Rio Doce Valley

The eucalyptus plantations established in eight distinct regions in the Rio Doce Valley are: 1. Belo Oriente (BO), 2. Nova Era (NE), 3. Santa Bárbara (SB), 4. Virginópolis (VG), 5. Sabinópolis (SAB), 6.

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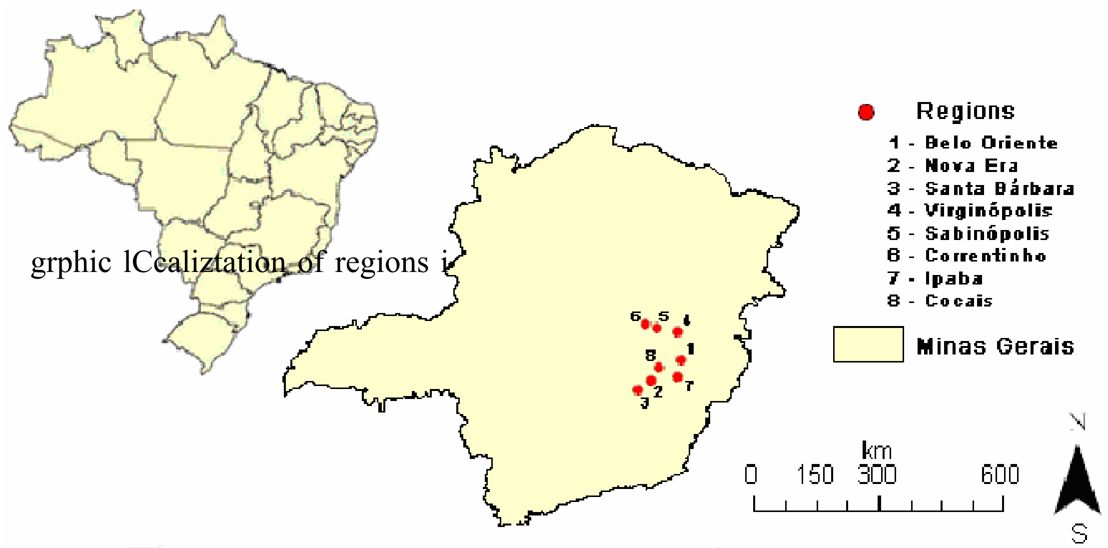

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Climate characteristics and altitudes of the studied areas (sites)

Site	PPT	$\overline{T}_{anual}$	$\overline{T}_{max}$	$\overline{T}_{min}$	Altitude
	mm	-----------------°C-----------------			a.s.l.
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 maxima temperature, $\overline{T}_{min}$ = Average minimum temperature, a.s.l. = above sea level.

Sites in eight distinct regions with eucalyptus plantations for 28 years (four rotations) were selected in different soil order (Table 3). Furthermore, we also selected areas under native forest (Atlantic forest) that were near the eucalyptus plantation as reference. The management practices since the substitution of the native forest by pasture and more recently by eucalyptus were similar as described above.

Table 3

Soil order, use, texture and soil density in the 0-20 layer of soils under native forest and eucalyptus plantations and eucalyptus productivity for the eight regions in study

Soil order	Soil use	Sand	Silt	Clay	S.D.	Eucal. stem produc.
		--------------($g\ kg^{-1}$)-------------			($Mg\ m^{-3}$)	($m^3\ ha^{-1} yr^{-1}$)
			Belo Oriente (BO)			
Oxisol	Native forest	280	50	670	1.14	
Oxisol	Eucalyptus	250	60	690	1.41	28.43
Inceptisol	Eucalyptus	280	70	650	1.42	27.00
Entisol	Eucalyptus	480	190	330	1.46	29.00
			Nova Era (NE)			
Inceptisol	Native forest	420	90	490	1.10	
Oxisol	Eucalyptus	530	30	440	1.27	34.57
Inceptisol	Eucalyptus	370	80	550	1.17	27.71
			Santa Bárbara (SB)			
Oxisol	Native forest	420	90	490	1.24	
Oxisol	Eucalyptus	390	110	500	1.26	34.57
Inceptisol	Eucalyptus	430	100	470	1.45	29.90
			Virginópolis (VG)			
Inceptisol	Native forest	520	120	360	1.22	
Oxisol	Eucalyptus	220	60	720	1.07	43.85
Inceptisol	Eucalyptus	370	100	530	0.85	35.14
			Sabinópolis (SAB)			
Oxisol	Native forest	390	60	550	1.15	
Oxisol	Eucalyptus	340	50	610	1.26	30.71
Inceptisol	Eucalyptus	220	100	680	1.22	33.00
			Correntinho (COR)			
Oxisol	Native forest	60	130	810	0.84	
Oxisol	Eucalyptus	60	100	840	0.97	35.00
Inceptisol	Eucalyptus	220	100	680	1.22	35.00
			Ipaba (IP)			
Inceptisol	Native forest	320	80	600	1.26	
Oxisol	Eucalyptus	310	60	630	1.55	29.28
Entisol	Eucalyptus	640	120	240	1.65	29.28
			Cocais (CO)			
Inceptisol	Native forest	500	100	400	1.07	
Oxisol	Eucalyptus	340	50	610	1.13	34.58
Inceptisol	Eucalyptus	440	110	450	1.18	38.57

S.D. –Soil density

2.3. Soil analysis

Soil samples were air-dried and passed through a 2 mm sieve. It was realised soil textural analysis (Tables 1 and 3). Soil samples were also ground in an agate mortar to pass in 100 mesh (0.149 mm) sieve for the organic C determination by a wet

– chemical procedure (Yeomans & Bremner, 1988). The C stocks in each soil use were calculated by multiplicating the SOC concentration by the soil mass of native forest, to avoid the effect of soil compaction.

2.4. Calibration of the Century model

The Century (Parton et al., 1987, 1993) constitutes a model to evaluate alterations of SOM stocks by soil use changes, climate and management practices (Kelly et al., 1997). Initially, this model was used to simulate the biomass production and the SOM dynamics in pasture in the prairie ecosystem of the United States (Parton et al., 1987), and modified to be used also in forest (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 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).

The century 4.0 parameterisation (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 native forest, pasture and eucalyptus were obtained from the literature, and when ever possible from studies carried out in specific conditions (Dantas, 2000; Skorupa, 2001; Lazari, 2001; Leite, 2001; Lima et al., 2006). Once adequately calibrated for the BO region, we evaluated the performance of Century to simulate the SOM dynamics in the other chronosequence and eight independent regions (see below).

The equilibrium simulation of soil C stock utilizing 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 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 soil use changes on SOM.

2.5. Evaluation of the Century model previously calibrated

It was evaluated the performance of Century for the VG eucalyptus chronosequence and for eucalyptus under different soil order at eight regions in study. This included climate data (temperature, precipitation), soil texture, soil C stocks, soil density, soil use and management practices (historic use, burn, harvest type, etc). The soil C stocks were estimated by the Century model 4.0, in that the estimated values were compared with measured values for each region. Additionally, the effect of removal or maintenance of the eucalyptus bark on site after harvest in the soil C stocks was simulated for the BO and VG region for a period of approximately 100 years, starting in 2003. For those simulations it was considered a productivity of eucalyptus bark of 7.8 and 12.7 t ha^{-1} for BO and VG, respectively.

The results were compared by calculating the difference (%) between simulated values and measured values for each soil order and region in study. Also, all results were compared by the simple linear correlation coefficient (r) and root mean square error (RMSE).

$$RMSE = \sqrt{\left(\frac{\sum_{i=1}^{n} (P_i - \overline{O}i)^2}{n} \right)}$$

Where P_i are the predicted values, $\bar{O}_i$ are the mean measured values, and n is the number of paired values.

3. Results

3.1. Measured SOC stocks

The BO region

Under the equilibrium condition, the SOC stock for native forest was 53.0 t ha^{-1} (Fig. 2). The results showed variation in the SOC stock when the native forest was replaced by pasture, which in turn was substituted by short-rotation eucalyptus. The native forest presented stable SOC stock up to 1931, but there was a reduction of 40.5 % due to the establishment of pasture (31.5 t ha^{-1}). On the other hand, four rotations of eucalyptus plantation in soils previously under degraded pasture favoured the increase of the SOC stock. After 34 years of eucalyptus cultivation the observed SOC stock was 41.5 t ha^{-1} (31.7% greater than in the soil under pasture).

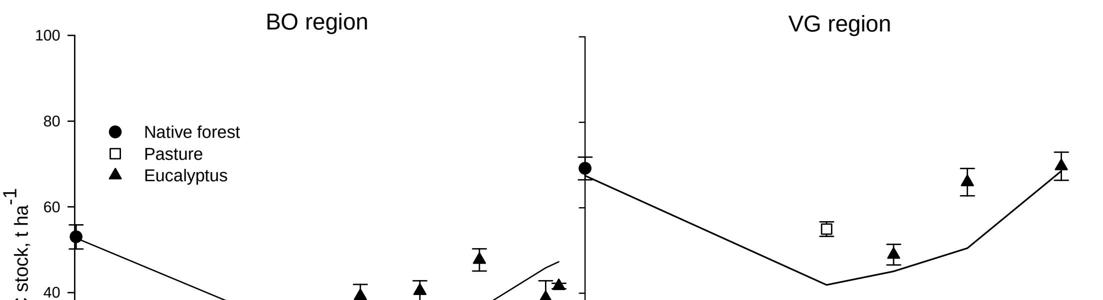

Fig. 2. Observed (symbols) SOC stocks and simulated (solid line) SOC stocks by Century for the 0-20 cm layer of soils under chronosequence of the eucalyptus plantation in the Belo Oriente (BO) and Virginópolis (VG) regions.

The VG region

The observed SOC stock for the soil under native forest was 69.2 t ha^{-1} in the VG region (Fig. 2). For pasture, it was observed a SOC stock of 55.0 t ha^{-1}, reduction of 20.5% of SOC in comparison with that under native forest. The short-rotation eucalyptus led to an increase of 26.8% (69.7 t ha^{-1}) in the SOC stock in comparison with the pasture use.

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. 2). Otherwise, four eucalyptus rotations resulted in a SOC stock of 47.2 t ha^{-1}, an increase of 63.3% 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 native forest in the VG region (Fig. 2). The pasture soil presented 37.9% lower SOC stock (41.9 t ha^{-1}) than that under previous vegetation (native forest). The model indicates that 33 years of eucalyptus cultivation resulted in a 63.7% (68.6 t ha^{-1}) increase of the SOC stock in relation to the previous pasture use.

3.3. Comparison between observed and simulated SOC stocks for different soil order at the eight regions

The SOC stocks simulated by the Century model were, in general, very similar to the observed SOC stocks (r = 0.72, Fig. 5), especially those in the BO and Santa Barbara (SB) regions, where the differences varied from -15,7% for the Inceptisol under eucalyptus in SB to +11.6% for the Oxisol under native forest in the BO region (Fig. 3).

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. Otherwise, in the VG region the difference was only -5.8%. In the NE and VG regions, the simulated SOC stocks for the Oxisols under eucalyptus were 23.3% and 14.1% lower than the observed SOC stocks, respectively. In NE, the simulated SOC stock differed only -3.9% from the observed SOC stock for the Inceptisol under eucalyptus, while that for the VG region the difference was -28.5%.

For the Sabinópolis (SAB) and Correntinho (COR) regions, the estimated SOC stocks for the Oxisol under native forest differed -18.7% and +17.7% in comparison to the observed SOC stock, respectively. For the Oxisol under eucalyptus the difference was -12.4% in SAB and +15.5% in COR. In the Inceptisol under eucalyptus the estimated SOC stock was only 2.7% higher than the observed SOC stock in the SAB region and only 4.3% less than the observed SOC stock in the COR region.

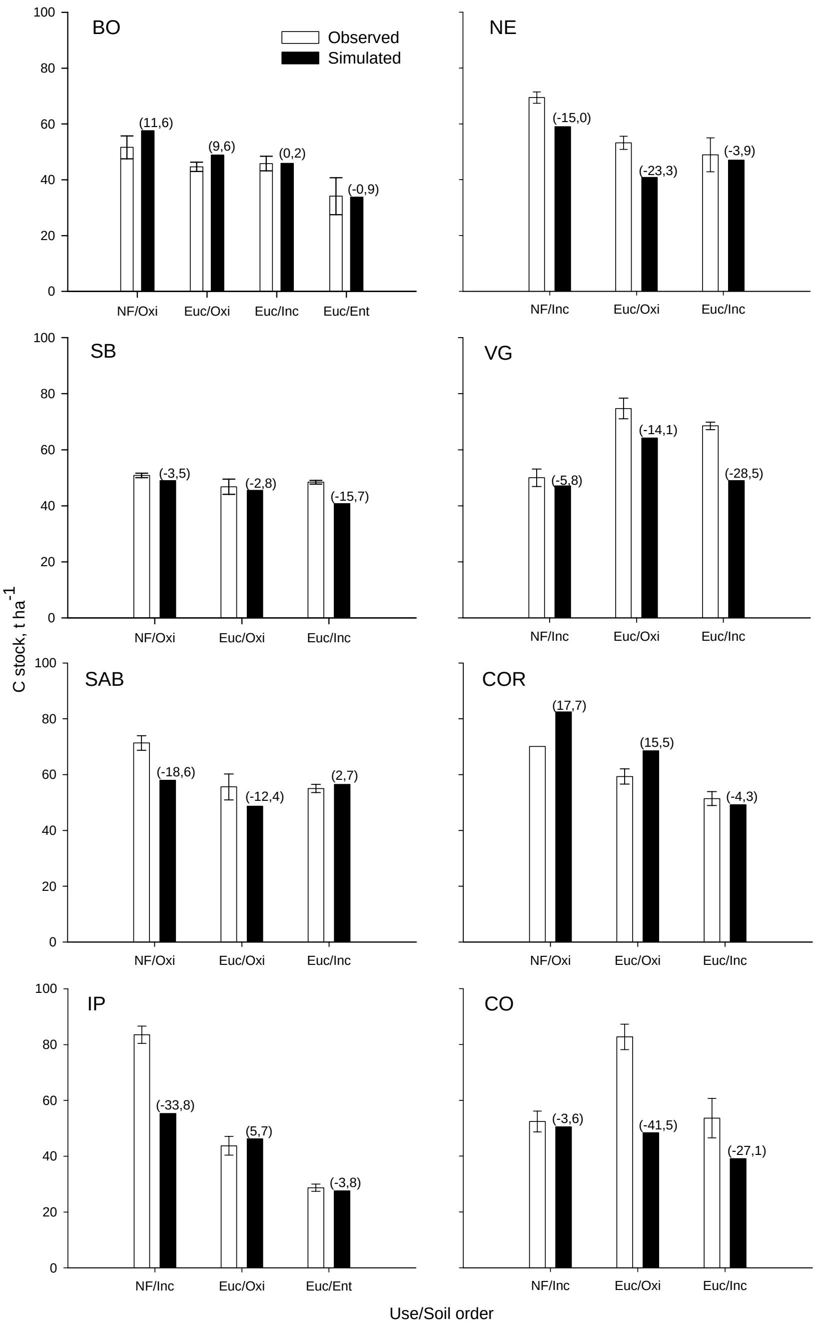

Fig. 3. Observed and simulated SOC Stocks for the 0-20 cm layer of soils of the Belo Oriente (BO), Nova Era (NE), Santa Bárbara (SB), Virginópolis (VG), Sabinópolis (SAB), Correntinho (COR), Ipaba (IP) and Cocais (CO) regions. The values between parentheses refer to the difference (%) between simulated and observed values. NF – Native forest, Euc – Eucalyptus, Oxi – Oxisol, Inc – Inceptisol, Ent – Entisol.

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 eucalyptus the difference of the simulated SOC stock in comparison to the observed SOC stock was +5.7% in the IP region and -41.5% in the CO region. In the IP region, the estimated SOC stock by Century was only 3.8% smaller than the observed SOC stock for the Entisol under eucalyptus. However, for the Inceptisol under eucalyptus in the CO region the difference was -27.1%.

3.4. Effect of removal or maintenance of the eucalyptus bark after harvest on SOC stocks

After 100 years (13 rotations) of eucalyptus plantations (starting in 2003) the SOC stocks simulated by the Century model would increase 31.2 t ha^{-1} (0.3 t ha^{-1} yr^{-1}) and 80.1 t ha^{-1} (0.8 t $ha^{-1}yr^{-1}$) in the BO and VG regions, respectively (Fig. 4).

The bark maintaining on site after harvest during 100 years (starting 2003) resulted in an increase of the SOC stock in the BO and VG regions (Fig. 4). In the BO region, the increase was 3.9%. In other words, with the removal of bark the SOC stock would be 77.8 t ha^{-1}, while the maintenance of the bark on site would result in a SOC stock of 80.8 t ha^{-1}. In the VG region, the maintenance of the eucalyptus bark on soil surface after harvest would result in an increase of 3.6% in the SOC stock. So, the maintenance of bark would result in a SOC stock of 154.3 t ha^{-1} in comparison to the SOC stock of 149.0 t ha^{-1} with the removal of bark from the site.

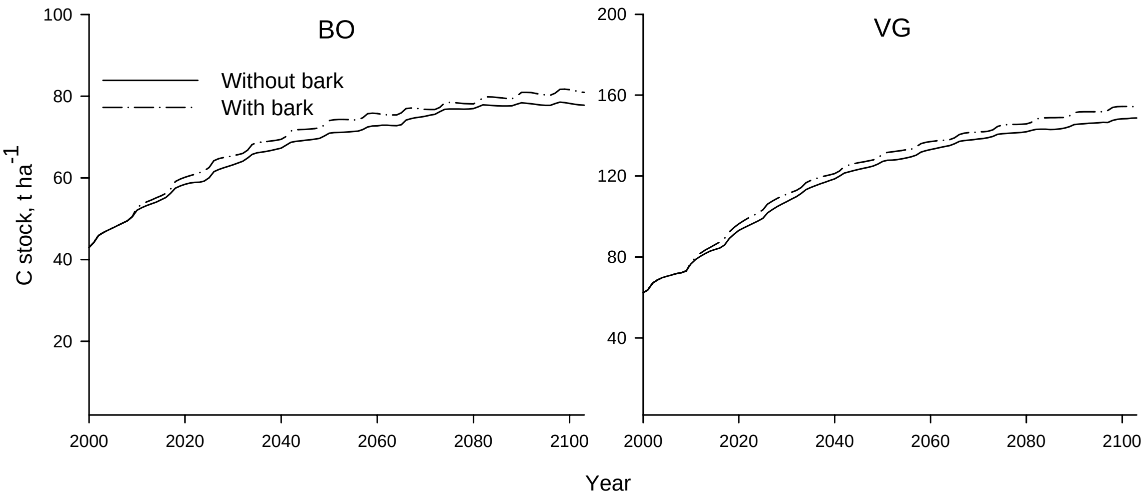

Fig. 4. Long-term simulated organic C stocks in the 0-20 cm layer of soils in the Belo Oriente (BO) and Virginópolis (VG) regions managed with or without removal of the eucalyptus bark (starting 2003) on soil surface after harvest.

4. Discussion

The positive correlation (r = 0.72) between simulated and observed SOC stocks for all studied regions (Fig. 5) supports 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). However, under conditions with lower soil C stock the Century super-estimated the C stocks in the 0-20 cm layer (Fig. 5). The efficiency of the model also can be assessed by calculating of the root mean square error (RMSE) (Cerri et al., 2007). The RMSE of 10.9% indicates that the difference between measured and simulated values on average was small, showing accurate results. This value is comparable with those found by Cerri et al. (2007) (in general, around 10 % or less) who used the Century model to simulate data from 11 land use change chronosequences in the Brazilian Amazon.

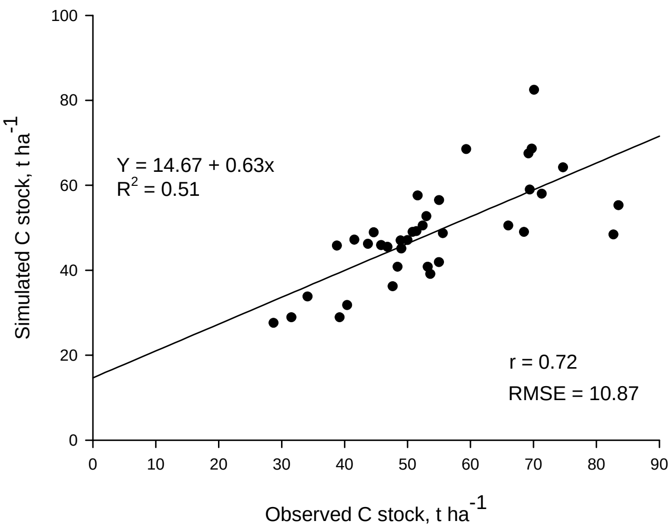

Fig. 5. Relationship between the observed and simulated SOC stocks by the Century model for all regions in study. r = simple correlation coefficient, RMSE = root mean square error.

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

The soil use changes have great regional and local implications in the C cycle. The observed and simulated SOC stocks by the Century model showed a reduction after substitution of native forest by pasture in the BO and VG regions (Fig. 2). That decrease can be attributed to the adopted management practices for pasture, mainly extensive grazing with low inputs and annual burn, resulting in larger CO_2 emission. Utilizing the Century model Polyakov & Lal (2004) observed that the erosion has preponderant role on SOM loss and on CO_2 emission. Otherwise, simulating SOC changes in 11 land use chronosequences from the Brazilian Amazon with the RothC and Century models, it was predicted that forest clearance and conversion to well managed pasture would cause an initial decline in soil C stock (0-20 cm depth), followed by slow recover to levels exceeding those under native forest in the majority of cases (Cerri et al., 2007).

The establishment of the eucalyptus plantation in the BO and VG regions resulted in an increase of the SOC stock in comparison to the pasture use (Fig. 2). In the BO region the increment was 0.29 t ha^{-1} $year^{-1}$, while for the VG region it was 0.44 t ha^{-1} $year^{-1}$. Successive eucalyptus rotations with average productivities increasing from 15 m^3 $ha^{-1}year^{-1}$ in the 60s to 35 m^3 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 during the establishment of the eucalyptus 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 of C sequestration of the VG region is somewhat similar to that found for the milder subtropical region of Brazil.

The results highlight the great potential that the short-rotation eucalyptus has to increase C sequestration in soil of areas previously occupied by degraded pastures. One question remains, however, 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 not permitted gains of 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 in soil previously occupied by pasture decreased the SOC in 12 %, while the implantation of large foliage species (*Eucalyptus e 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 estimate that the return of C to initial level will occur with approximately 20 years of cultivate with eucalyptus.

The sensibility of the Century model for variation of 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 long-term. So, it can be utilized in decisions that look for increase soil C. The SOC stocks simulated by the Century model for native forest, pasture and eucalyptus plantations in the VG chronosequence were higher than the SOC stocks in the BO chronosequence (Fig. 2). Additionally, the increase rate of SOC stock following 100 years of eucalyptus plantations in the VG region was higher than in the BO region (Fig. 4). 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 eucalyptus, 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 less mineralization C rates. Studying Ferralsol profiles along a climosequence in Southern Brazil, Dalmolin et al. (2006) observed that the organic matter increased from the lowest to the highest sites (440-950 m altitude) as result of increase in humidity and decrease in temperature. This influence was more pronounced in the clayey heavy 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 (42 m^3 ha^{-1} yr^{-1}) was higher than in the BO region (26 m^3 ha^{-1} yr^{-1}) which contributes substantially to increase the organic residue deposition and, consequently, SOC stocks (Leite, 2001). Integrating informations of historic use, climate and soil with utilization of 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 study carried out in the Brazilian Amazon, Cerri et al. (2004) found encouraging results for the TOC, total N, microbial biomass C pools and delta ^{13}C as a function of management in a chronosequence of the pasture cultivation in areas previously occupied by native forest.

The C stocks simulated by Century in different soil orders were, in general, close to the observed values (Fig. 3). Also, simulating the SOC stocks for different management systems in Brazil, Leite et al., (2004) found small differences of simulated values in comparison to the observed values (0.4-7.0 %). However, in another study realized for soil under plough in Hungary, Falloon & Smith (2002) observed that the simulated SOC values were higher than the observed values. For some soil orders such as the Inceptisol under eucalyptus and native forest in the VG and IP regions, respectively, and the Oxisol and Inceptisol under eucalyptus in the CO region, the simulated SOC stocks showed larger discrepancies from the observed values (-28.5% in the Inceptisol under eucalyptus in VG, -33.8% in the Inceptisol under native forest in IP, -41.5 and -27.1 % in the Oxisol and Inceptisol under eucalyptus in CO, respectively). In the tropical soils the formation of Al-MOS complex has important role for SOM mineralization as well as 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 mineralogy, soil pH and aluminium content in formation and stabilization of SOM under tropical conditions.

The following 100 years of the eucalyptus cultivation (starting 2003) simulated by Century resulted in increase of 66.87 % and 116.8 % in the soil C stock in BO and VG, respectively (Fig. 4). As example of hypothetical calculation has:

- Soil density = 1.41 g dm^{-3}
- Layer = 0-20 cm (20 cm)
- 1 ha = 10,000 m^2
- 10 % of clay with free charge
- Clay content = 58 %

Soil volume = 0.2 m x 10,000 m^2 = 2,000 m^3 (2000 000 dm^3)

2000 000 x 1.41 = 2820 000 = 2,820 t ha^{-1} of soil

58 % of clay = 0.58 x 2,820 = 1,636 t ha^{-1} of clay

1,636 x 0.1 (10 %) = 163.6 t ha^{-1} of clay with free charge

So, a soil with characteristics described above has 163.6 t ha^{-1} of clay with free charge. Thus, it has potentially capacity to accumulate 163.6 t ha^{-1} (higher than 77.8 t ha^{-1} in BO) of C due to physical and colloidal protection mainly by oxides and kaolinite in tropical soils. Additionally, after each eucalyptus harvesting (7 years) has a lot input of eucalyptus residues what may contribute to build up the C soil. However, additional study is required to confirm this hypothesis.

Considering the possibility of utilization of eucalyptus afforestation for C sequestration, it is imperative the adequate management practices that maximize the profits and at the same time guarantee the soil C maintenance and the forest growth sustainability. The maintaining of bark, branch and foliages on soil after harvest practices constitutes a good alternative for this. Due to increase in removal of plant biomass (especially the bark) after harvest for several industrial and energetic purposes, it is important to know the long-term impact of residue removal on SOC stock. The Century simulations indicated that the maintenance of the eucalyptus bark on soil surface after harvest resulted in an increase of the C stock of 3.1 t ha^{-1} and 5.4 t ha^{-1} in the BO and VG regions, respectively (Fig. 4). 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 remotion of all residues each year. The harvest residues (foliages, branches and bark) left on the area after harvest is very important source of nutrients such as N, P, K, Ca and Mg (Gama-Rodrigues & Barros, 2002). Additionally, the maintaining of harvest residues is an option which will reduce the leaching of N, improve water content and enhance nutrients supply by mineralization in long-term (O'Connell et al., 2000). Several authors have found that the quality of eucalyptus residues (high lignin content, and C/N rate) contribute to accumulate the C stock of litter and soil following time of eucalyptus cultivation (Gama-Rodrigues & Barros, 2002; Costa et al., 2005). Evaluating the litter decomposition rate in area under *Pinus elliottii*, *Eucalyptus sp*. and native forest in Santa Maria, Rio Grande do Sul State, Kleinpaul et al. (2005) observed higher litter accumulation under *Pinus elliottii* followed by *Eucalyptus sp*. and native forest. Among the possible explanations showed by the authors the higher lignin content of pinus foliage contributed substantially to increase the litter layer what could affect the SOM dynamics in time. Otherwise, organic residues may induce greater N immobilization due to deposition of soluble extractives leached from leaf material to soil mainly in N lack 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 eucalyptus plantations result in increase of 0.29-0.44 t ha^{-1} $year^{-1}$ of C in soil previously with degraded pasture;

2. The SOC stocks simulated with the Century model are positively correlated with the measured values for the several uses and edaphic-climate conditions;

3. Simulations indicate that the maintenance of the eucalyptus 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 cycling under eucalyptus, pasture and native forests in Brazil

Abstract

The Carbon Accounting Model, FullCAM, was developed by the Australian Greenhouse Office. It has been successfully calibrated for several Australian conditions. The afforestation on areas previously occupied by pasture, as has been taking place with eucalyptus in Brazil, is admitted as 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) dynamics under short-rotation eucalyptus plantations, pasture and native vegetation (rainforest and Cerrado) located in the main eucalyptus 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 land use history 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 with comparing observed and predicted values by calculation of the model efficiency (EF). The results showed that in the ES and BA states, the TOC stocks were simulated to decrease 0.37 and 0.30 t ha^{-1} yr^{-1} respectively, after establishment of eucalyptus 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, after eucalyptus establishment. A similar behaviour 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 eucalyptus. After 28 years of eucalyptus 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 forest (Cerrado) by eucalyptus resulted in an increase of simulated TOC and C stock of HS, LF and MB pools. After 33 years of eucalyptus cultivation the TOC stock increased 5.6% (0.14 t

ha^{-1} yr^{-1}) in comparison to the native Cerrado vegetation. The clay content is a fundamental factor that controls the TOC dynamics in areas under short-rotation eucalyptus afforestation. The FullCAM model described satisfactorily the C stocks within TOC (EF=0.74) and HS (EF= 0.65), but it was not as accurate to predict the C stocks within LF (EF= 0.11) and MB (EF= -0.87) pools. So, the FullCAM model constitutes an appropriate tool to simulate the changes in soil C after eucalyptus 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 richest biome in biodiversity 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 central region of the country, covering approximately 2 million km^2 (23 % of the country) (Bustamante et al., 2006). 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 forest in Brazil occupied little over 500 ha. By 1987, Brazil had more than 6 Mha of planted forests. The eucalyptus and pine plantations represent 80 % of total planted area. The production is mainly for cellulose 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 replacement (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 as has happened with eucalyptus in Brazil is admitted as a valid and potential attempt to offset greenhouse gas emission, and it is a suitable activity under 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 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. Because of the complexity of several SOM compartments and, since the soil C represents one of the final pools in the sequestration process by forests, precise measurement of soil C amounts in many cases can be so hard and cost-forbidding for afforestation projects. So, the utilization of simulation models constitutes a good tool to improve the understanding about the factors that affect the SOM cycling and, hence, to adopt more adequate management practices for SOM maintenance.

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 the reciprocal dependence among the forest growth, SOM cycling, and litter decomposition, requires that SOM models link with models of: (i) forest growth, (ii) debris deposition (litter and dead roots), (iii) debris decomposition and, (iv) SOM cycling (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 eucalyptus 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 what the expected forest growth, litter deposition and SOM cycling 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, however, data on SOM dynamics in many Brazilian regions under short-rotation eucalypt plantations 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 aim of this study was to calibrate the FullCAM model to predict SOM cycling under short-rotation eucalyptus plantations, pasture and native forest (rainforest and Cerrado) in four main eucalyptus growing States in Brazil.

2. Material and methods

2.1. Sites description

This study was carried out in commercial eucalyptus plantations, pastures and native vegetation (rainforest or cerrado - savanna) located in four main eucalyptus 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 eucalyptus plantations were selected (Table 2). Adjacent areas of native vegetation (rainforest or cerrado) characteristic of land cover before the eucalyptus 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 eucalyptus was 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 7 year growth, the eucalyptus 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 as result of favourable topography.

Table 1

Climate, localization, and eucalyptus 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
Eucalyptus 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

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 eucalyptus plantations utilized for calibration of the FullCAM model

State (site)	Native forest	Previous land use	Rotation number	Current stand age	Stem productivity	Clay	Silt	Sand
				(yr)	($m^3 ha^{-1} yr^{-1}$)	--------------($g\ kg^{-1}$)----------------		
ES	Rainforest	Pasture	4	7.6	32.2	250	30	720
MG (BO)	Rainforest	Pasture	4	6.2	30.7	580	40	380
MG (VG)	Rainforest	Pasture	4	5.2	49.0	700	50	250
MG (JV)	Savanna	Savanna	3	10.0	60.0	780	60	90
BA	Rainforest	Pasture	1	7.7	64.2	90	30	880
SP	Savanna	Savanna	4	2.0	40.0	90	20	890
SP	Rainforest	Rainforest	4	2.0	40.0	640	180	180

ES = Espírito Santo; MG = Minas Gerais; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley; BA = Bahia; SP = São Paulo; Savanna = Cerrado.

(ii) Espírito Santo

The eucalyptus stand was planted in early 70s in the coastal region of the ES State in area previously occupied by pasture (Table 2). Additionally, adjacent areas under pasture (*Brachiaria sp.*) and native forest (rainforest) located nearby eucalyptus stand 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 eucalyptus cultivation started. The pasture had good appearance, without visible surface erosion. The first eucalyptus 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 foliages remained on site. The plant residues were burned after harvest up to 1985 (second rotation). All management practices during the conduction of eucalyptus rotations were mechanized due to favorable topography.

(iii) Minas Gerais

Two eucalyptus plantations were picked in two regions in Rio Doce Valley, MG State: Belo Oriente (BO) and Virginópolis (VG) (Table 2). In each region an adjacent native forest (Atlantic forest) and pasture were selected. In both regions the eucalyptus 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 eucalyptus plantation. The pastures throughout the region were overgrazed, and erosion was apparent. The first eucalyptus stands were planted manually after burning the pasture. Following 7 years of growth, the plants were manually cut and the stem plus bark took off from the site. The use of fire after harvest was carried out until the third eucalyptus rotation. Another eucalyptus site was chosen in a distinct biome in the Jequitinhonha Valley (JV), MG (Table 2). Beside the eucalyptus, an adjacent area under native vegetation (cerrado) was selected. The first eucalyptus 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 eucalyptus trees were harvested and the stem together with bark was taken from the area. The branches and foliage remained on site after harvesting.

(iv) Bahia

One representative area under eucalyptus plantation was selected in this state (Table 2). Additionally, areas under pasture and native vegetation (rainforest) adjacent to the eucalyptus were selected. The pasture (*Brachiaria sp.* and *Panicum sp.*) was planted early 1970s after slashing and burning of the native forest. The current pasture was in good vegetative conditions, with no evident surface erosion. The eucalyptus was established in early 90s after burning and plowing of pasture and soon after the eucalyptus 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 fire utilization after harvesting was carried out up to 2000. 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 eucalyptus 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.

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). It was obtained the following fractions: fulvic acids (FAF), humic acids (HAF), and humin (HF) based on differential solubility in alkali and acid solution. 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 content in each fraction by the mass of soil under native forest so that confounding effects of management-induced soil compaction would be avoided.

2.3. Calibration of the FullCAM model

The eucalyptus 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 real 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 productivity (384.4 t ha^{-1} dry mass) and litterfall (6.5 t ha^{-1}) for the native forest (rainforest) were available only for the Espírito Santo State. This productivity was used for the native forest (rainforest) in 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 eucalyptus plantations. Therefore, we had to fit these decomposition constants in order to minimize the difference between predicted and observed values of SOM compartments. Another adjust required during the FullCAM calibration was the C partitioning during the debris decomposition between that lost as CO_2 and the reminder that enters into to the soil.

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) as defined by Soares et al., (1995):

$$EF = 1 - \left(\frac{\sum (Oi - Pi)^2}{\sum (Oi - \overline{O})^2} \right)$$

where O_i are the measured/observed values, P_i are the predicted values, $\bar{O}$ 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. Also, deviations of predictions from the true mean were assessed by the mean square error (MSE):

$$MSE = \left(\frac{\sum_{i=1}^{n} (P_i - \overline{O}i)^2}{n} \right)$$

The smaller the MSE, the better the FullCAM explained the observed results.

3. Results

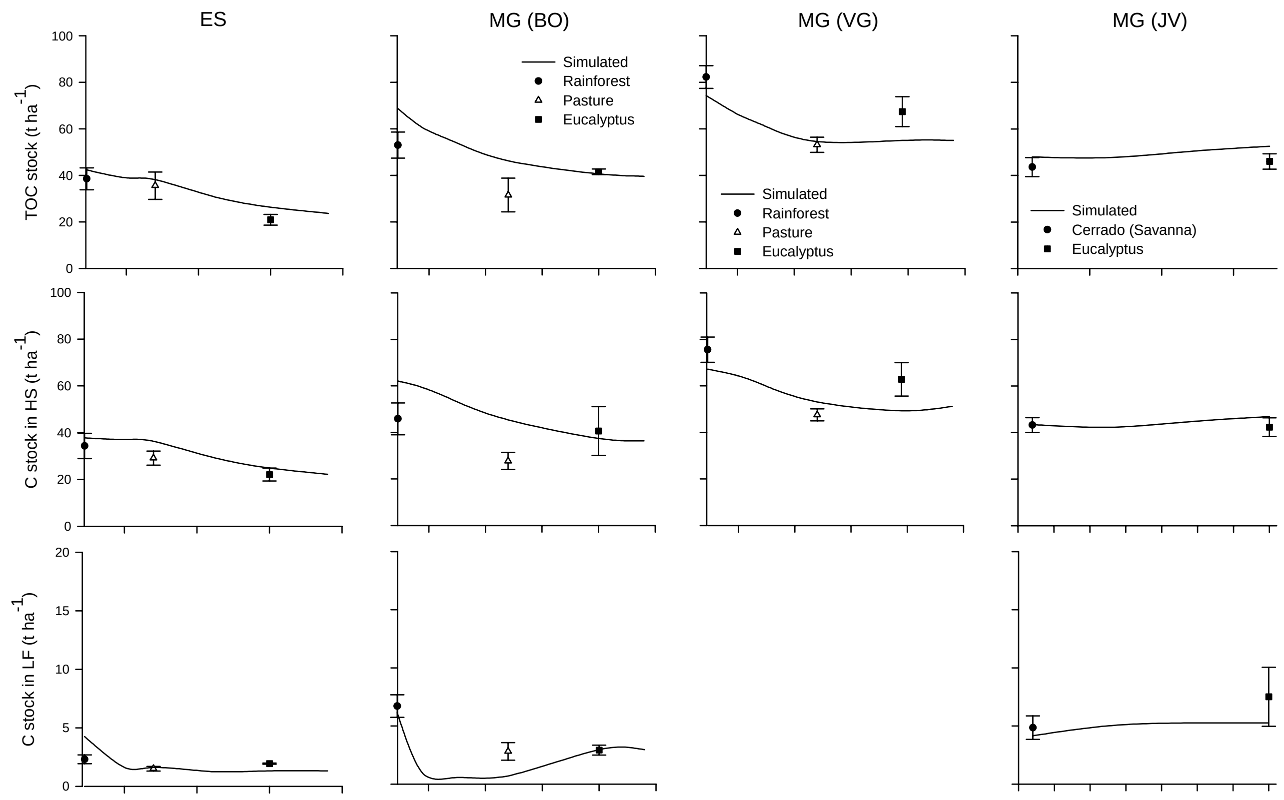
3.1. Total organic carbon and humic substances

Measured C stocks

The Atlantic forest soil in ES had the TOC stock of 38.5 t ha^{-1} and the C stocks in HS of 34.4 t ha^{-1}. The pasture cultivation led to a decrease in the TOC and HS stocks to 35.6 and 29.1 t ha^{-1}, respectively (Fig. 1). These stocks were further reduced to 20.9 and 22.1 t ha^{-1} following the substitution of pasture by eucalyptus. 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 eucalyptus 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, the eucalyptus soil had a higher TOC stock (46.0 t ha^{-1}) than under the cerrado soil (43.6 t ha^{-1}) in JV (MG). Otherwise, the C stock in HS of the eucalyptus soil (42.3 t ha^{-1}) was slightly lower than under the cerrado soil (43.2 t ha^{-1}). In BA, 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 eucalyptus cultivation led to the TOC stock and C stock in HS of 26.0 and 24.5 t ha^{-1}, respectively. The eucalyptus 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 the 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 eucalyptus 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. 1). The model predicted that the eucalyptus soils in ES, MG (BO) and BA, respectively had the 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 eucalyptus 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. Contrarily, the eucalyptus 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 eucalyptus 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 eucalyptus 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.


ES
MG (BO)
MG (VG)
MG (JV)
TOC stock (t ha-1)
C stock in HS (t ha-1)
C stock in LF (t ha-1)
Simulated
Rainforest
Pasture
Eucalyptus
Cerrado (Savanna)
0
20
40
60
80
100
5
10
15

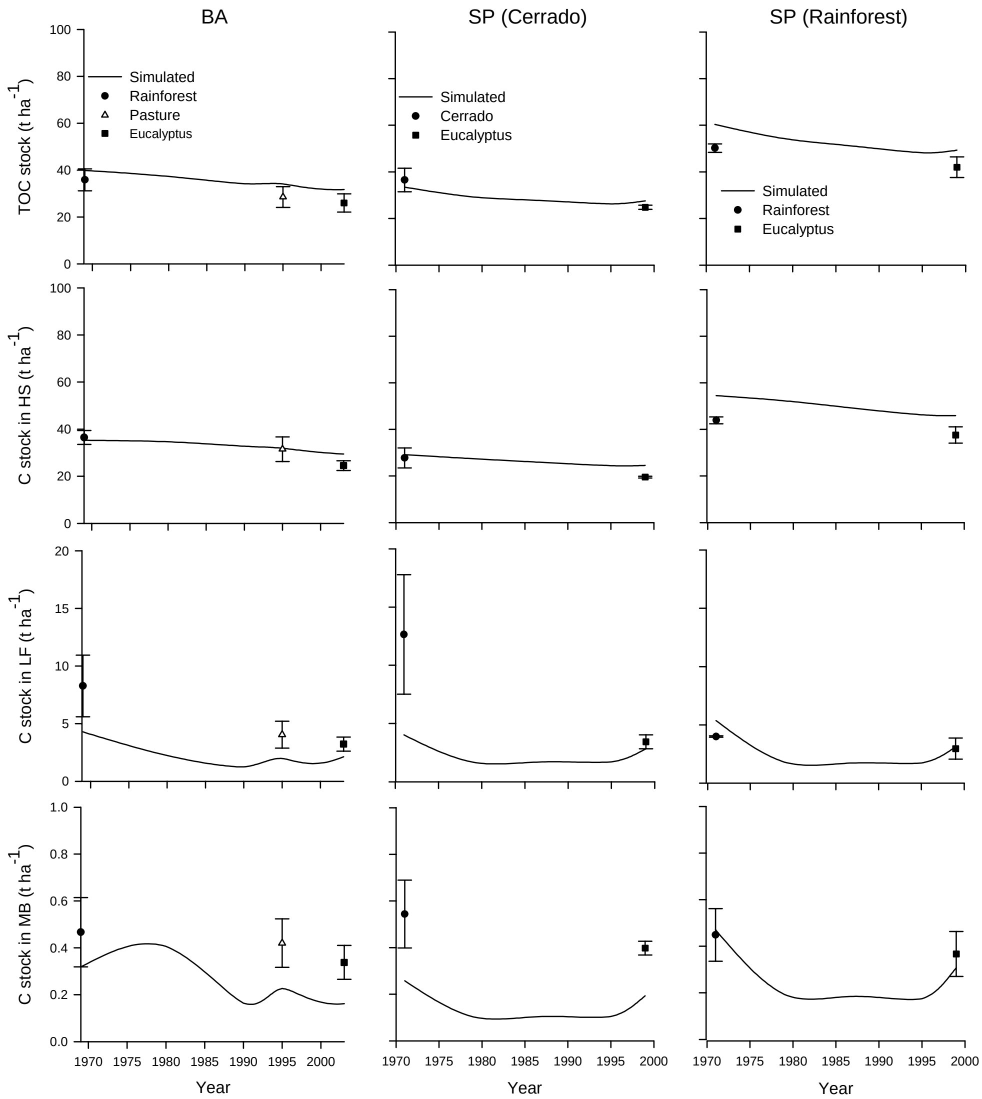


Fig. 1. Cont. BA = Bahia; SP = São Paulo.

3.2. Light fraction and microbial biomass

Measured C stocks

The eucalyptus soil had slight higher C stock in LF (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}) and lower C stock in this fraction than the rainforest soil in both sites (2.3 and 6.7 t ha^{-1} in ES and BO, respectively) (Fig. 1). The eucalyptus soil also showed higher C stock in LF (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 eucalyptus soil had lower C stock in LF of 3.2 t ha^{-1} than the pasture soil (4.0 t ha^{-1}) in BA. The eucalyptus soil had lower C stock in MB (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 eucalyptus soil had C stock in this fraction of 0.11 t ha^{-1} compared to 0.09 t ha^{-1} in the pasture soil and 0.08 t ha^{-1} in the rainforest soil in VG (MG). The eucalyptus soil had the C stock in LF of 3.4 t ha^{-1} in comparison to the C stock of 12.6 t ha^{-1} in the cerrado soil in SP. The eucalyptus soil had lower C stock in LF of 2.9 t ha^{-1} than the rainforest soil (3.9 t ha^{-1}) in SP. The eucalyptus soils also had lower C stocks in MB (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 model predicted that the eucalyptus soil had higher C stock in LF (2.9 and 5.3 t ha^{-1}) and MB (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. 1). Similarly, the eucalyptus soil had higher C stocks in LF (5.3 t ha^{-1}) and MB (0.42 t ha^{-1}) than the cerrado soil (LF = 4.2 t ha^{-1}, MB = 0.37 t ha^{-1}) in JV (MG). Otherwise, the eucalyptus soil stored lower C stock in LF (1.3 t ha^{-1}) and MB (0.10 t ha^{-1}) than the pasture soil (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 MB (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 eucalyptus soil had lower C stocks in LF (2.8 and 3.1 t ha^{-1}) and MB (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 and (MSE) values of 0.74 unit (58.36 t^2/ha^2) for TOC, 0.65 unit (66.28 t^2/ha^2) for HS, 0.11 unit (7.12 t^2/ha^2) for the LF, and -0.87 unit (0.05 t^2/ha^2) for MB (Fig. 2). The FullCAM model super-estimated the TOC stock and C stock in HS, LF and MB under low C stock condition.

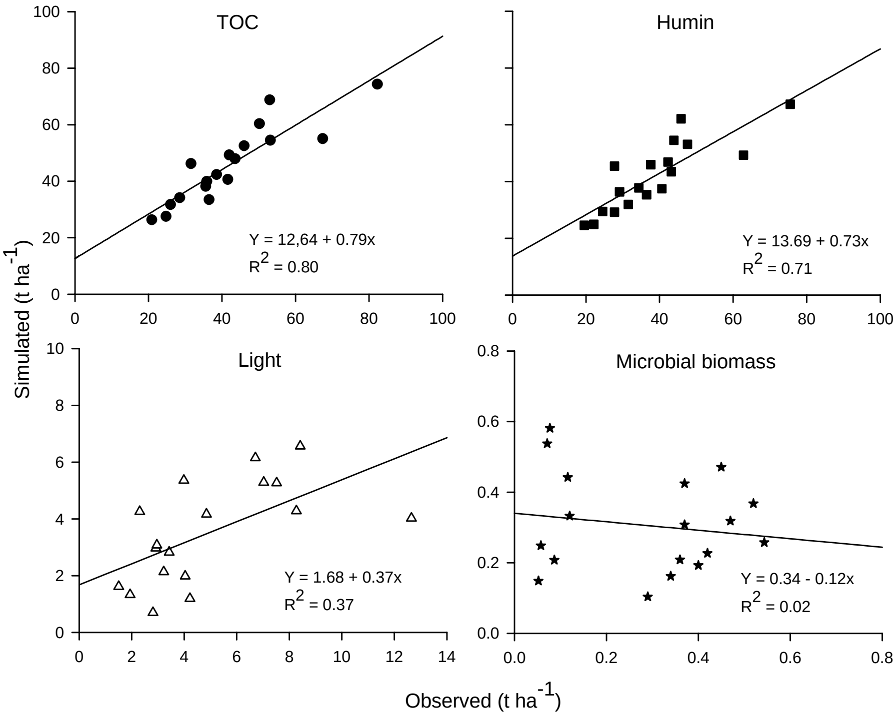


Fig. 2. Relationship between observed and simulated C stocks of SOM fractions (0-20 cm) for calibration soil datasets of the FullCAM model. EF and (MSE) soil datasets were found to be: TOC = 0.74 units (58.36 t^2/ha^2); HS = 0.65 units (66.28 t^2/ha^2); LF = 0.11 units (7.12 t^2/ha^2); MB = -0.87 units (0.05 t^2/ha^2).

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 eucalyptus soils had higher C stocks in the SOM fractions in the VG region (MG) (Fig. 1). Higher clay content and lower annual mean temperature in this region (Table 1 and 2) may have favoured the C sequestration in 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 precipitation and decrease in temperature. This influence was more pronounced in the clayey heavy Ferralsols. Despite the fact that several studies with eucalyptus species in Brazil have demonstrated that eucalyptus productivity and litterfall increase with the increase of mean annual rainfall (Santana, 2000; Stape et al., 2002; Rigobelo & Nahas, 2004), the increase of water availability could stimulate the SOM decomposition by soil microorganisms. Thus, the lower mean annual rainfall (93.8 mm) presented by VG could contribute to maintain SOM stocks under different land uses. Moreover, the high plant productivity and residue deposition in this region contributed substantially to accumulate soil C under eucalyptus soil.

Afforestation of former pasture land generally results in reduction of SOM contents (Davis & Condron, 2002; Sicardi et al., 2004). The eucalyptus cultivation in areas previously occupied by well managed pastures resulted in a decrease rate of TOC stocks of 0.37 and 0.30 t ha^{-1} yr^{-1} in ES and BA, respectively (Fig. 1). 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 decrease of the net primary productivity (NPP) following the eucalyptus establishment in these States (Fig. 3). In a Study evaluating the eucalyptus impact in SOC fractions of areas previously occupied by pasture in Australia, Paul and Polglase (2004) observed that in the 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 cycling time. Furthermore, forests deposit organic residues on soil surface where the conditions to decomposition are more favourable (Post & Kwon, 2000).

In a global review about of 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 gradual increase of 1.16% yr^{-1} for the first 40 years. Among the main reasons that contributed for this has been hypothesised 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 (Paul et al., 2002).

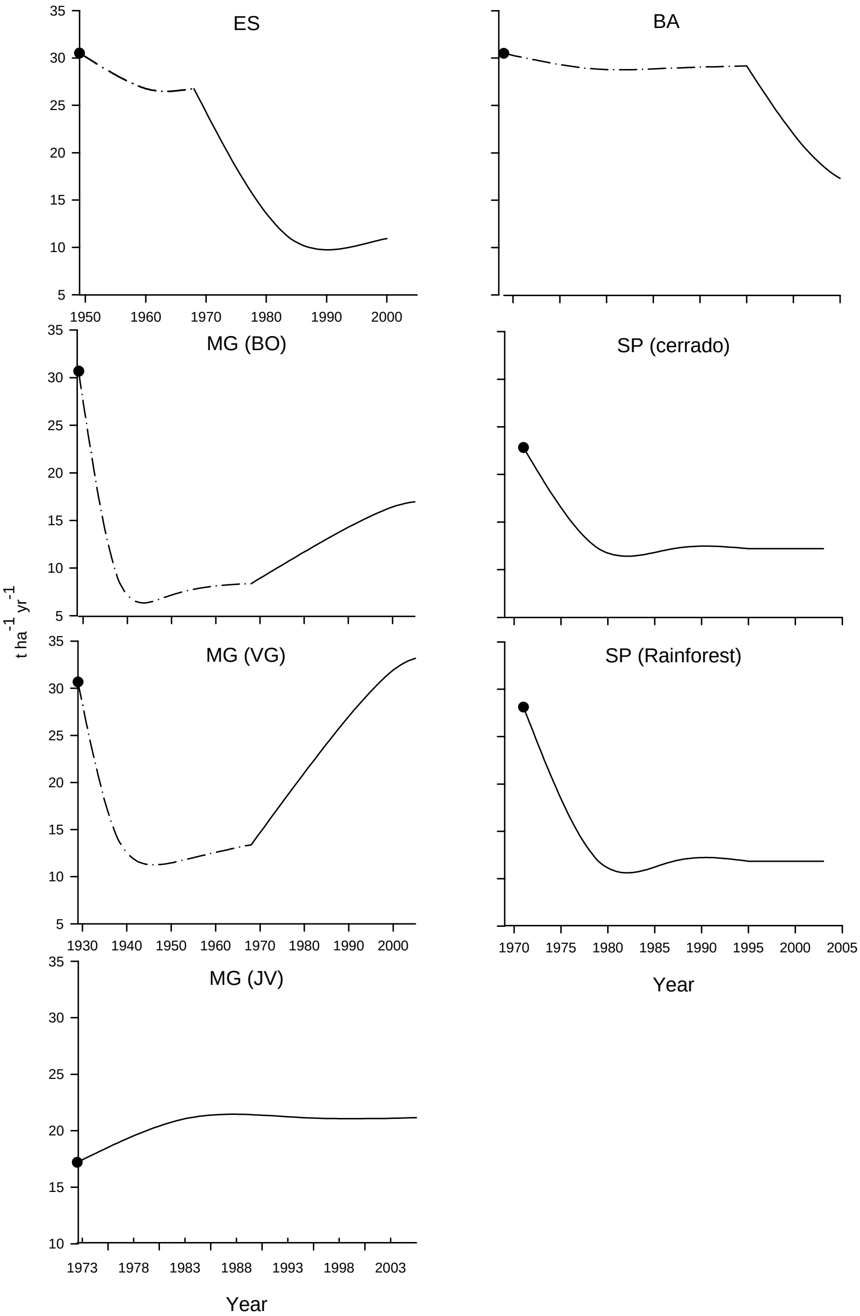


Fig. 3. Simulated NPP values for the native forest (●), pasture (dash dot line), and eucalyptus (solid line) soils in calibration dataset of the FullCAM model. NPP = net primary productivity; tdm = ton dry matter; yr = year; ES = Espírito Santo; MG = Minas Gerais; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley; BA = Bahia; SP = São Paulo.

The NPP and its allocation were demonstrated to be highly correlated to the soil C in areas under eucalyptus afforestation in Australia (Paul et al., 2003). The TOC and C stocks in HS and LF were simulated to decrease after substitution of native forest (rainforest and Cerrado) by eucalyptus in SP (Fig. 1). After 28 years of eucalyptus 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 eucalyptus soil were due to lower NPP of eucalyptus compared to native forest (Fig. 3). Furthermore, the management influence such as planting and harvesting in eucalyptus could lead to soil C loss as CO_2 to the atmosphere. In a review with areas from different world regions, Guo & Gifford (2002) found that, on average, afforestation on land previously under native forest resulted in 13% decrease in SOC. The eucalyptus establishment resulted in little change in SOC, while conifer establishment resulted in decrease of 15% in SOC. Otherwise, evaluating the effect of *E. camaldulensis* afforestation in soil C in comparison to Cerrado in Brazil, Melo respectively. Probably, the fire event in the two first eucalyptus rotations during the simulation by FullCAM contributed to the litter and soil C loss as CO_2 to the atmosphere (Fig. 4) despite of higher NPP of eucalyptus in comparison to pasture (Fig. 3). 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 eucalyptus 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 eucalyptus soil in comparison to the pasture soil was due to higher lignified organic residue deposition.

The improve of silvicultural techniques in latest eucalyptus rotations resulting in a increase of the average stem productivities from 15 m^3 $ha^{-1}year^{-1}$ in the 60s to 35 m^3 ha^{-1} $year^{-1}$ in current years (Barros & Comerford, 2002) may contribute substantially for higher deposition of organic residues and increase of SOM stocks in Brazilian conditions. The substitution of Cerrado by eucalyptus resulted in an increase of TOC and C stocks in HF, LF and MB in JV (MG) (Fig. 1). The eucalyptus cultivation (33 years) increased 5.63% (0.14 t ha^{-1} yr^{-1}) the TOC stock in comparison to cerrado. The NPP of eucalyptus was also higher than cerrado (Fig. 3). The high clay content (78 dag kg^{-1}) together with the eucalyptus stem productivity (60 m^3 ha^{-1} yr^{-1}) are the important factors that contributed for this increase (Table 2). Additionally, the adoption of the minimum tillage without biomass burning during the establishment of the most recent eucalyptus rotation surely contributed for such gains. Several authors have found that the quality of eucalyptus residues (high lignin content, wide C/N ratio) also contribute to accumulate litter and soil C following eucalyptus cultivation (Gama-Rodrigues et al., 2002; Costa et al., 2005). In a study evaluating the impact of eucalyptus 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 afforestation than the control soil (Cerrado), mainly in the sandy Entisol.

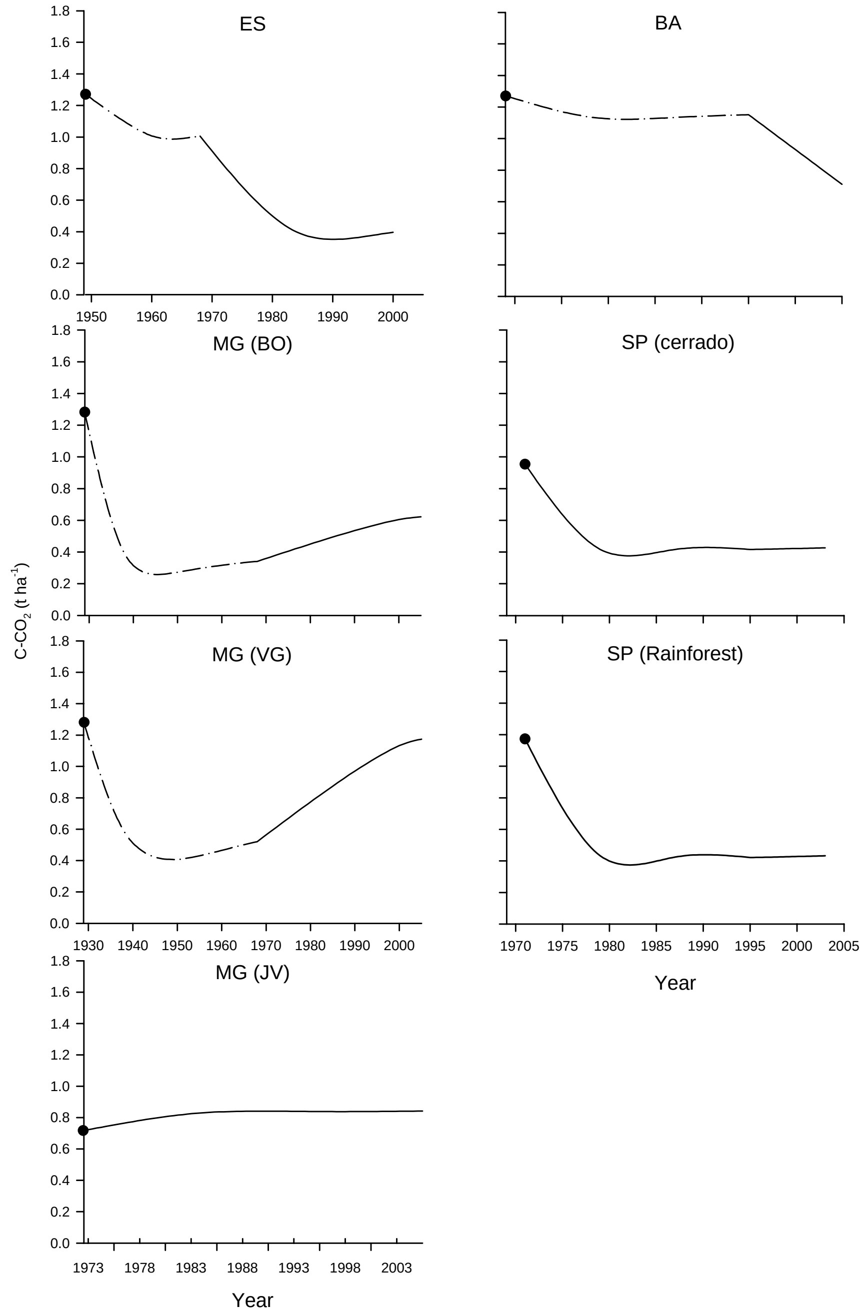


Fig. 4. Simulated values of C-CO_2 emitted by soil+debris for the native forest (●), pasture (dash dot line), and eucalyptus (solid line) areas in calibration of the FullCAM model. ES = Espírito Santo; MG = Minas Gerais; BO = Belo Oriente; VG = Virginópolis; JV = Jequitinhonha Valley; BA = Bahia; SP = 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. 2). Despite the model constitutes, in general, an appropriate tool to simulate the changes in soil C after eucalyptus afforestation, it super-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 eucalyptus 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. The eucalyptus 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 eucalyptus results in decrease of the TOC stock and C stock in HS and LF in comparison to rainforest and Cerrado in the SP state. Otherwise, the eucalyptus cultivation results in increase of the TOC stock and C stock in HS and LF in comparison to the Cerrado soil in JV (MG state).

2. The FullCAM model describes satisfactorily the TOC stock (model efficiency - EF= 0.74) and C stock in HS (EF= 0.65), while its accuracy for predicting the C stock in LF (EF= 0.11) and MB (EF= -0.87) in soils under native forest, pasture and eucalyptus was lower than adequate.

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 eucalyptus growing States in Brazil, which can have distinct vegetations and edapho-climatic conditions. Despite of satisfactory results presented by model, specific testing is required for the partitioning of C in loss 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 must of SOC and that it is must affect by land use and land use changes, it is possible that deeper soil layers play an important role on long-term C sequestration.

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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;

► 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 clayey soils present higher C and N stocks in the SOM fractions than the sandy soils;

2. The eucalyptus afforestation results in increase in C stocks than the degraded pasture in the BO and VG regions (MG). A similar behaviour is observed when compare eucalyptus with Cerrado in Jequitinhonha Valley (MG). Otherwise, the eucalyptus plantation has lower C stocks than native forest and well managed pasture in the ES and BA States. Also, the eucalyptus soil has lower C stock than the Cerrado and Atlantic forest soils in the SP State;

3. The SOC stocks simulated by the Century model are positively correlated with the measured values for the several uses and edaphic-climate conditions;

4. The FullCAM model describes satisfactorily the TOC stock (model efficiency - EF= 0.74) and C stock in HS (EF= 0.65), while its accuracy for predicting the C stock in LF (EF= 0.11) and MB (EF= -0.87) in soils under native forest, pasture and eucalyptus was lower than adequate.

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