FERNANDA DANIELE DE ALMEIDA VALENTE

RECUPERAÇÃO DE ÁREAS MINERADAS DE BAUXITA COM EUCALIPTO E ESPÉCIES FLORESTAIS NATIVAS

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

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APROVADA: 31 de maio de 2017.

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BIOGRAFIA

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RESUMO

VALENTE, Fernanda Daniele de Almeida, D.Sc., Universidade Federal de Viçosa, maio de 2017. **Recuperação de áreas mineradas de bauxita com eucalipto e espécies florestais nativas.** Orientador: Teógenes Senna de Oliveira. Coorientadores: Ivo Ribeiro da Silva e Emanuelle Mercês Barros Soares.

As atividades de mineração, apesar da grande importância para o setor econômico mundial, causam grandes impactos nos atributos físicos, químicos e biológicos do solo, o que leva a busca de estratégias de recuperação destas áreas. A presente tese foi dividida em quatro capítulos, os quais abordaram o crescimento e a estimativa de biomassa, produção e decomposição de serapilheira, fluxos de CO_2 e CH_4 e, por fim, atributos orgânicos do solo. Os objetivos no capítulo 1 foram o de avaliar o crescimento de três coberturas florestais implantadas em área minerada de bauxita: eucalipto (*E. urophylla x E. grandis*), angico (*Anadenanthera peregrina*) e plantio misto composto por 16 espécies florestais nativas no tempo (6, 18, 36 e 56 meses), em quatro tipos de adubação (orgânica - AO, química- AQ, padrão da empresa- AE e orgânica e química combinadas - AO+AQ), bem como estimar a biomassa e os estoques de C do fuste destas árvores aos 56 meses de idade pela volumetria com cubagem rigorosa não destrutiva. Para tanto, o diâmetro, em nível do coleto (DAS), o diâmetro a nível do peito (DAP) e a altura total (Ht) de todas as árvores plantadas foram medidos nas quatro idades. O volume do fuste foi estimado aos 56 meses de idade por meio da cubagem rigorosa das árvores pelo método não destrutivo para obtenção de equações alométricas. A adubação não influenciou na Ht de angico, porém, o DAS das árvores foi influenciado pela adubação aos 18, 36 e 56 meses de idade. O eucalipto, aos 6, 36 e 56 meses, apresentou maiores Ht's nas adubações AO+AQ e AO e as menores em AE, assim como, o DAS. No tratamento com espécies nativas, a AE proporcionou as menores Ht's aos 18, 36 e 56 meses, porém, a adubação não influenciou o DAS destas árvores. O eucalipto apresentou estimativas de biomassa e estoque de C quatro vezes maiores que aquelas de angico e o plantio misto de espécies nativas em AO+AQ. No capítulo 2, objetivou-se determinar a produção e a taxa de decomposição da serapilheira e seus componentes, bem como, a ciclagem de nutrientes do folhedo e galhos de três coberturas florestais ao longo de 30 meses de avaliação. Eucalipto e nativas não diferiram quanto a serapilheira aportada, bem como, serapilheira acumulada no solo. A taxa de decomposição da serapilheira de angico e nativas foi maior na época chuvosa. As maiores concentrações e conteúdos de P, K, Ca e Mg no folhedo foram observadas nas espécies nativas. No terceiro capítulo avaliou-se os fluxos de CO_2 e CH_4 nos solos das áreas mineradas e recuperadas com as três coberturas florestais, bem como, no solo da área sem cobertura e mata nativa não minerada. O efluxo de CO_2 do solo foi maior em área de vegetação natural (Mata) e menor nas áreas sem qualquer tipo de cobertura (Sem Cob). Entre as espécies plantadas o efluxo de CO_2 não variou significativamente, porém, observou-se maior efluxo de CO_2 nos meses de maior umidade do solo. A respiração heterotrófica do solo foi a que mais contribuiu para o efluxo total de CO_2 do solo, sendo a contribuição do *litter* responsável pelos maiores valores. Foi observado influxo de CH_4 pelo solo para todas as áreas estudadas. No último capítulo objetivou-se avaliar a influência das coberturas florestais e tratamentos de adubação nos estoques de C e N totais do solo e suas frações. Os estoques de C e N totais não apresentaram diferenças entre as coberturas florestais estudadas, exceto a mata nativa que apresentou os maiores estoques. O C lábil e o da biomassa microbiana foram os atributos que mais sinalizaram mudanças em decorrência das aplicações dos tratamentos após mineração de bauxita. A implantação de coberturas florestais em área pós mineração permitiu o aumento do IMC (Índice de Manejo de Carbono) em relação a área Sem cobertura camada de 0-60 cm.

ABSTRACT

VALENTE, Fernanda Daniele de Almeida, D.Sc., Universidade Federal de Viçosa, May, 2017**. Recovery of mined areas of bauxite with eucalyptus and native forest species**. Adviser: Teógenes Senna de Oliveira. Co-advisers: Ivo Ribeiro da Silva and Emanuelle Mercês Barros Soares.

Mining activities are important to the world economic sector, but cause great impacts on the physical, chemical and biological attributes of the soil and there is a need of strategies to recover these areas. The present thesis is divided in four chapters, which address the growth and the estimation of biomass, litter production and decomposition, CO_2 and CH_4 fluxes and, finally, organic soil attributes. In Chapter 1 aim to evaluate the growth of trees in three forest coverings implanted in bauxite mined area: eucalyptus (*E. urophylla x E. grandis*), angico (*Anadenanthera peregrina*) and mixed planting composed of 16 native forest species in time (6, 18, 36 and 56 months), in four types of fertilization (organic - AO, chemical - AQ, company standard - AE and combined organic and chemical - AO+AQ), and to estimate biomass and carbon stocks (C) of the trees stem at 56 months old by the volumetry with strict non destructive counting. The diameter at ground level (DAS), the diameter at breast height (DAP) and total height (Ht) of all planted trees were measured at the four ages. The stem volume was estimated at 56 months old by rigorous tree - borne counting using the non - destructive method to obtain allometric equations. Fertilization did not influence the Ht of angico, however, the DAS of the trees was influenced by fertilization at 18, 36 and 56 months old. Eucalyptus, at 6, 36 and 56 months, presented higher Ht's in AO+AQ and AO fertilization and the lowest in AE, as well as DAS. In the treatment with native species, the AE provided the lowest Ht's at 18, 36 and 56 months, however, the fertilization did not influence the DAS of these trees. Eucalyptus presented estimates of biomass and C stocks four times higher than Angico and mixed planting of native species in AO+AQ. In Chapter 2, the objectives were to determine the production and rate of decomposition of the litter and its components, and the nutrient cycling of leaf and branches of three forest cover over 30 months of evaluation. Eucalyptus and native did not differ to quantity of litter deposited to soil, as well as litter accumulated in the soil. The decomposition rate of native and angico litter was higher in the rainy season. The highest concentrations and contents of P, K, Ca and Mg in the leaflet were observed in the native species. In Chapter 3 the CO_2 and CH_4 fluxes were evaluated in the soils recovered with the three forest coverages, as well as in the soil of the uncovered area and in the native forest not mined. Soil CO_2 efflux was higher in natural vegetation area (Mata) and lower in areas without cover (Sem Cob). Among the planted species the CO_2 efflux did not change significantly, however, it was observed a greater efflux of CO_2 in the months of greater soil moisture. The heterotrophic respiration was the principal contributor to the total soil CO_2 efflux, with the contribution of the litter responsible for the highest values. Influx of CH_4 was observed for all the studied areas. In Chapter 5 the aim was to evaluate the influence of forest cover and fertilization treatments on the C and N stocks of the soil and its fractions. The C and N stocks did not show differences between the forest cover studied, except in the native forest that presented the largest stocks. The labile C and the microbial biomass were the attributes that most signaled changes due to the applications of the treatments after bauxite mining. The implantation of forest cover in the post mining area allowed the increase of the IMC (Carbon Management Index) in relation to the area without cover layer of 0-60 cm.

INTRODUÇÃO GERAL

A degradação do solo implica na redução da capacidade produtiva do sítio, promovendo alterações nas propriedades físicas, químicas e biológicas do solo. As principais causas da degradação são o desmatamento, métodos de cultivo inadequados, uso de agroquímicos e atividades de mineração (LAL; STEWART, 1992). Portanto, a perda da qualidade do solo, determinada por suas propriedades físicas, químicas e biológicas, dentro das restrições impostas pelo clima, inclui também um componente determinado pelas decisões de uso da terra (tipo de exploração) e práticas de manejo (modo de exploração) (DORAN; ZEISS, 2000).

As atividades de mineração estão entre as atividades antrópicas que causam drásticos distúrbios ao solo embora, em geral, não atinja grandes extensões territoriais quando comparados a outras atividades de uso da terra, como agricultura e hidroelétricas, por exemplo. O seu grau de degradação depende da intensidade desta interferência no solo, do volume explorado e do rejeito produzido (CARNEIRO et al., 2008; PARROTTA; KNOWLES, 2001). Entre os principais distúrbios causados nas propriedades do solo pelas atividades de mineração pode-se citar o aumento da compactação e da densidade do solo, a redução do espaço poroso, a baixa capacidade de infiltração de água, as restrições à penetração do sistema radicular, a redução da microbiota do solo pela remoção e estocagem por longos períodos da camada superficial do solo, o declínio da matéria orgânica do solo e a deficiência e/ou excesso de nutrientes (SHRESTHA; LAL, 2011).

Entre os processos vitais para a funcionalidade do ecossistema destaca-se o ciclo do C que exerce funções reguladoras sobre as transformações e ciclagem dos demais elementos no solo, catalisados pela atividade dos microrganismos (CARNEIRO et al., 2008). Desta forma, a manutenção da matéria orgânica do solo em área minerada é fundamental para a conservação ou reativação da ciclagem de nutrientes e desta maneira promover o sucesso na reabilitação da área explorada (SCHWENKE; MULLIGAN; BELL, 1999). Além disso, a importância da matéria orgânica do solo para a estabilidade dos agregados, retenção de água e aeração do solo significa que o seu declínio afeta a emergência das plântulas e a penetração da raiz em algumas áreas reabilitadas (SCHWENKE; MULLIGAN; BELL, 1999).

Entre as principais causas da diminuição da matéria orgânica do solo, proporcionada pelas atividades de mineração estão a ausência da entrada de material orgânico pela completa remoção da vegetação; a destruição da estrutura do solo, expondo a matéria orgânica do solo à degradação microbiológica; a retirada e estocagem da camada superficial do solo por longos períodos, acelerando a oxidação da matéria orgânica do solo; e a mistura de horizontes superficiais e subsuperficiais levando a sua diluição (BANNING et al., 2008; SCHWENKE; MULLIGAN; BELL, 1999; SCHWENKE; MULLIGAN; BELL, 2000a, 2000b; STAHL et al., 2002; TIBBETT, 2008; WARD, 2000). Observou-se a redução acentuada dos estoques da matéria orgânica do solo e da atividade microbiana nos primeiros anos após o retorno da camada superficial com a acelerada oxidação e desbalanço entre a entrada de C com a vegetação implantada e as perdas pela decomposição.

Dentre os atributos orgânicos que mais se alteram com as mudanças no uso e manejo do solo e que primeiro sinalizam aumento em decorrência das atividades de recuperação da área degradada estão aqueles associados a matéria orgânica particulada (MOP) (FIGUEIREDO; RESCK; CARNEIRO, 2010; LEHMANN; CRAVO; ZECH, 2001; TIBBETT, 2008), a biomassa microbiana (ANDERSON; INGRAM; STAHL, 2008; CARNEIRO et al., 2008) e o C lábil (BLAIR; LEFROY; LISLE, 1995).

A recuperação de áreas mineradas é motivo de esforços por parte das empresas do setor e dos órgãos ambientais, universidades e institutos de pesquisas, que buscam procedimentos eficazes para restabelecer os processos essenciais do solo e dos ecossistemas alterados (CARNEIRO et al., 2008). O processo de recuperação do solo em áreas degradadas deve ter como princípio básico o retorno de condições mínimas para o estabelecimento e crescimento das plantas (MUKHOPADHYAY; MAITI; MASTO, 2013). Portanto, a intervenção humana visando à revegetação de áreas degradadas é de grande importância, já que o processo natural de sucessão florestal pode simplesmente não ocorrer (MACHADO et al., 2013; SHRESTHA; LAL, 2006). Surge, então, o desafio de elaborar técnicas alternativas de recuperação da qualidade do solo que permitam o estabelecimento e o desenvolvimento de culturas nestas áreas alteradas pelas atividades de mineração.

A implantação de espécies florestais na recuperação de áreas degradadas tem como objetivo melhorar o solo por meio de vários processos. Dentre estes estão a manutenção ou aumento da matéria orgânica, o desenvolvimento das comunidades microbianas via aporte de material orgânico de parte aérea e raiz, a absorção de nutrientes abaixo do alcance das raízes da vegetação herbácea, o aumento da infiltração e armazenamento de água, a redução das perdas de nutrientes por erosão e lixiviação, a ciclagem de nutrientes via produção e a decomposição de serapilheira (LEÓN; OSORIO, 2014; MUKHOPADHYAY; MAITI; MASTO, 2013; SINGH; RAGHUBANSHI; SINGH, 2004), contribuindo, assim, para melhoria nas propriedades do solo durante o tempo em que se encontra em reabilitação.

Este trabalho teve como objetivos avaliar: (*i*) o crescimento e a biomassa de espécies arbóreas; (*ii*) a produção e taxa de decomposição da serapilheira aportada ; (*iii*) os fluxos de CO_2 e CH_4; e (*iv*) os principais atributos orgânicos e biológicos do solo de área minerada de bauxita em recuperação com espécies florestais nativas e exótica, submetidas a diferentes tipos de adubação.

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Chapter 1

GROWTH, BIOMASS AND C STOCKS IN FOREST COVER PLANTED IN AN AREA OF BAUXITE MINING IN RECOVERY

RESUMO

A implantação de coberturas florestais em áreas degradadas pela mineração é uma alternativa para mitigar o aumento da concentração de CO_2 na atmosfera pela fixação do C na biomassa das árvores. Objetivou-se avaliar o crescimento de três coberturas florestais implantadas em área minerada de bauxita, em quatro tipos de adubação, e estimar a biomassa e os estoques de C do fuste destas árvores aos 56 meses de idade. O crescimento em altura (Ht) e os diâmetros à altura do solo (DAS) e do peito (DAP) foram determinados em todas as árvores das três coberturas florestais: eucalipto (híbrido *Eucalyptus urophylla x Eucalyptus grandis)*, angico (*Anadenanthera peregrina*) e plantio misto composto por 16 espécies florestais nativas, aos 6, 18, 36 e 56 meses de idade. Quatro tratamentos de adubação foram testados: padrão da empresa (AE), orgânica (AO), química (AQ) e orgânica + química (AO+AQ). O delineamento utilizado foi o de blocos ao acaso com parcelas subdivididas e três repetições. O volume do fuste foi estimado aos 56 meses de idade por meio da cubagem rigorosa das árvores pelo método não destrutivo para obtenção de equações alométricas. A adubação não influenciou na Ht de angico, porém, influenciou o DAS destas árvores aos 18, 36 e 56 meses de idade. O eucalipto, aos 6, 36 e 56 meses, apresentou maiores Ht's nas adubações AO+AQ e AO e as menores em AE, assim como, também observado no DAS. A adubação influenciou a Ht das espécies florestais nativas aos 18, 36 e 56 meses, com AE apresentando os menores valores. Já no DAS, a adubação não influenciou os resultados, destacando o grupo das espécies pioneiras que apresentaram maiores crescimentos em Ht e DAS em relação às não pioneiras. As árvores de eucalipto apresentaram estimativas de biomassa (255 Mg ha^{-1}) e de estoques de C (120 Mg ha^{-1}) quatro vezes maiores que as de angico e as nativas em AO+AQ, as quais não apresentaram diferenças entre si e nem entre os tipos de adubação utilizados. Diante dos resultados concluiu-se que as espécies florestais plantadas em área minerada de bauxita apresentaram crescimento, estimativa de volume, biomassa e estoques de C comparáveis a áreas não mineradas, sendo o eucalipto, a cobertura florestal que apresentou maior crescimento, biomassa e estoques de C aos 56 meses de idade.

ABSTRACT

The implementation of forest cover in areas degraded by mining is an alternative way of mitigating the increase in CO_2 concentrations in the atmosphere by fixing the C in tree biomass. The aim of this study was to evaluate the growth of three types of forest cover planted in an area of bauxite mining with four sorts of fertiliser, and to estimate the biomass and C stocks of these trees at an age of 56 months. Growth in height (Ht), and diameter at ground level (DGL) and chest height (DBH) were determined in all trees of the three types of forest cover: Eucalyptus (*Eucalyptus urophylla x Eucalyptus grandis* hybrid*)*, Angico (*Anadenanthera peregrina*) and a mixed plantation comprising 16 native forest species at 6, 18, 36 and 56 months of age. Four fertilisation treatments were tested: the standard fertiliser used by the company (SF), organic fertiliser (OF), chemical fertiliser (CF) and an organic+chemical fertiliser (OF+CF). The experimental design was of randomised blocks, with subdivided plots and three replications. Trunk volume was estimated at 56 months by rigorous cubing using the non-destructive method to obtain the allometric equations. Fertilisation did not influence Ht in the Angico, however it did influence the DGL of those trees at 18, 36 and 56 months of age. At 6, 36 and 56 months, the Eucalyptus displayed greater values for Ht under OF+CF and OF fertilisation, with the lowest values under SF, also seen for DGL. Fertilisation influenced the Ht of the native forest species at 18, 36 and 56 months, with SF having the lowest values. Fertilisation had no influence on the results for DGL, except for the group of pioneer species that showed greater growth for Ht and DGL than did the non-pioneer species. The Eucalyptus displayed estimates for biomass (255 Mg ha^{-1}) and C stocks (120 Mg ha^{-1}) that, under OF+OC, were four times greater than those of the Angico and native species, which showed no differences to one another or for the type of fertiliser used. Considering the results, it was concluded that the forest species planted in an area of bauxite mining showed growth, and estimates of volume, biomass and C stocks comparable to those of unmined areas, the Eucalyptus being the forest cover with the greatest growth, biomass and C stocks at 56 an age of months.

KEY WORDS: mineral and organic fertilization; degraded area; brasilian Altantic florest;

1. INTRODUCTION

The increased release of CO_2 into the atmosphere through such human activity as the burning of fossil fuels and changes in land use has caused major disruptions in the global C cycle and is considered to be one of the causes of possible climate change. The forest sector is one of the viable alternatives for mitigating the increase in CO_2 concentrations in the atmosphere through the fixation of carbon by trees (Melo & Durigan, 2006).

Forest species are different from other species as they have the ability to fix C for long periods and store it in the form of wood (Litton *et al*., 2007). Its residence time in the ecosystem depends among other factors, on the age of the plant, the component where the C is allocated, and the intended use of the wood (Diaz-Balteiro & Rodriguez, 2006). In this respect, tropical forests have great potential for mitigating CO_2 emissions through the conservation, management and recovery of degraded environments (Brown, 1997).

Forest recovery coupled with intensive management may be an important tool for storing atmospheric C in degraded tropical environments (Schulze *et al*., 2000). Estimating C accumulation over time is a good way to evaluate the success of recovery programs and to indicate best practices for forest management and conservation (Shimamoto *et al*., 2014). However, traditional silvicultural techniques applied to plantations of forest restoration in Brazil are limited to low levels of nutrient application and the limited control of invasive plants (Souza & Batista, 2004), reducing the success of recovery programs in degraded areas.

Under intensive management for the recovery of degraded areas, the choice of the species to be planted is also very important to the success of the recovery program. The use of tree legumes with the ability to fix N_2 from the atmosphere through symbiosis with N_2-fixing bacteria leads to the belief that these trees can be used to revegetate highly degraded soils and accelerate the recovery process (Chaer *et al*., 2011). In highly altered soils, such as occur in mining areas and where the organic matter content tends to be very low, the introduction of tree species, especially N_2-fixing legumes, tends to significantly increase the levels of C in the soil (Christopher & Lal, 2007).

There are few studies of restoration plantations that include biomass and C modelling, leaving an information gap regarding the potential of these forests as CO_2 sinks (Miranda *et al.*, 2011). Therefore, estimating biomass in the aerial parts of trees remains an important source of uncertainty concerning the C balance in tropical regions, partly due to the scarcity of estimates of aerial biomass and of the variation for landscape and types of forest (Houghton *et al.*, 2009).

The aim of this study therefore, was to evaluate the growth of three types of forest cover planted in an area of bauxite mining under four types of fertiliser, and to estimate the biomass and C stocks of the tree trunks at 56 months.

2. MATERIAL AND METHODS

2.1. Characterisation of the study area and experimental design

The study was carried out in the town of São Sebastião da Vargem Alegre, in the Forest Zone (*Zona da Mata*), of the State of Minas Gerais (MG), Brazil (21°1'58" S and 42°35'8" W), at an altitude of 780 m, in an area of bauxite extraction by The Brazilian Aluminium Company - Votorantim Metais. Following mining activities, the topsoil, stored for approximately one year, was returned to the original area during the process of topographic reconfiguration. Shortly after, the terrain was decompacted using a subsoiler at a depth of 60 cm. The predominant soil in the region is a typic dystrophic Red-Yellow Latosol.

According to the Köppen classification, the climate in the region is of type Cwa, with hot and rainy summers, a well-defined dry season, and average annual precipitation and temperatures of 1,287 mm and 20.3ºC respectively (INMET, 2016). Climate data for precipitation and maximum, average and minimum temperatures were obtained from a meteorological station installed in the experimental area (Figure 1).

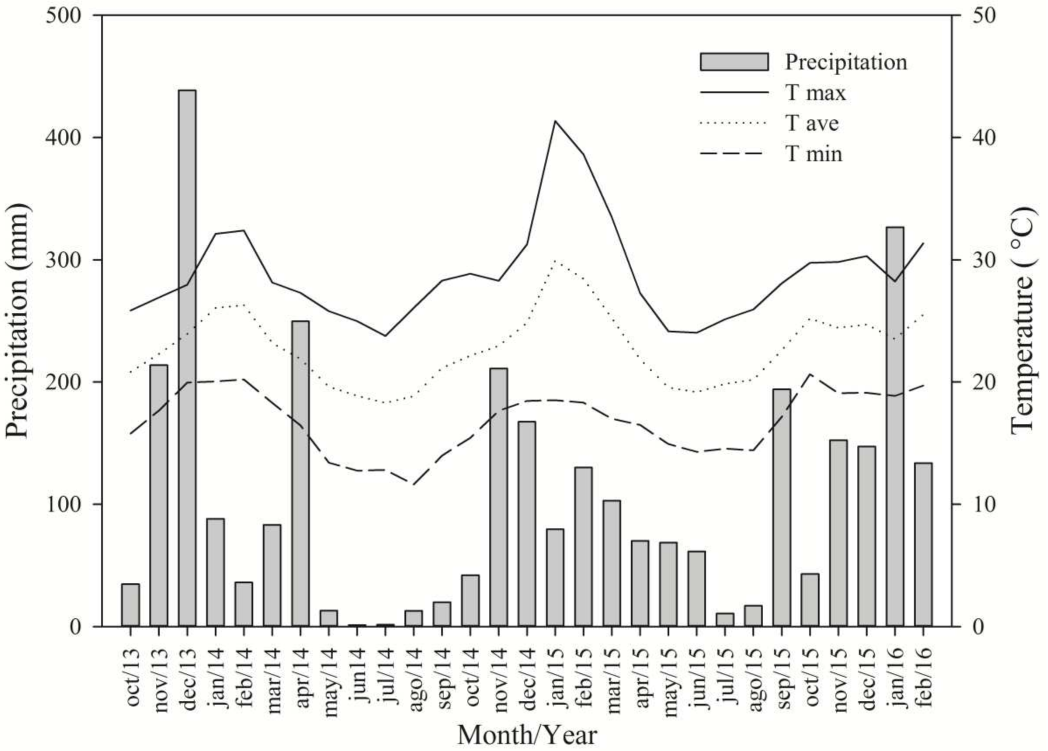

Figure 1 - Average monthly values for precipitation and maximum (T max), minimum (T min) and average (T ave) temperatures in the experimental area, from March 2011 to November 2015, in an area of bauxite mining in São Sebastião da Vargem Alegre, MG.

The area was mined for bauxite in 2009 and reconfigured in 2010. The experiment was set up in March 2011 in the area, reconfigured after mining and in recovery with forest species, using a randomised block design with subdivided plots and three replications. The plots, 40 x 18 m in size, comprised the following forest cover: clonal Eucalyptus (a hybrid from a cross between *Eucalyptus urophylla* and *Eucalyptus grandis* - clone AEC144®) (Euc); Red Angico (*Anadenanthera peregrina* (L.) Speg) (Ap); and a mixed plantation (Nat) consisting of 16 native forest species from the region, Red Angico (*Anadenanthera peregrina* (L.) Speg) - A2, Fig (*Ficus insipida* Willd) - F, Inga cipó (*Inga edulis* Mart.) - I1, Jacare (*Piptadenia gonoacantha* (Mart.) JF Macbr.) - J1, Monkey Ear (*Enterolobium contortisiliquum* (Vell.) Morong.) - O, Silk Floss (*Ceiba speciosa* (A. St.-Hil.) Ravenna) PA1, Soapberry (Sapindus saponaria L.) – S, and Tamanqueira (*Pera glabrata* (Schott) Poepp. Ex Baill.) - C2; forest species considered as pioneers, and the non-pioneer species Catigua (*Trichilia* sp) - C3, Camboata (*Cupania oblongifolia* Mart.) - C1, Garapa (*Apuleia leiocarpa* (Vogel) JF Macbr.) - G, Golden Trumpet

(Handroanthus chrysotrichus (Mart. Ex A. DC.) Mattos) – I2, Jatoba (*Hymenaea courbaril* var. *stilbocarpa* (Hayne) YT Lee & Langenh) – J3, Jequitibá (*Lecythis sp*) – J2, Brazilwood (*Paubrasilia echinata* Lam.) - PA2, and Ariticum (*Annona squamosa* L.) – A1. These native species were planted in Quincunx (4 pioneers, with one climax in the centre) at a spacing of 2 x 1.5 m, using seedlings produced from seeds collected in fragments of Atlantic Forest in the second stage of regeneration (Woodland) in the study region. For the Eucalyptus and Angico, the adopted spacing was 3 x 2 m.

The subplots (10 x 18 m) included the standard fertilisation used by the company (SF) in their recovery activities of mined areas, with the propositions under study, which considered the SF, but supplemented with organic fertilisation (OF), chemical fertilisation (CF), and a combination of OF+CF. Six months before planting the trees, SF composed of 2.0 t ha^{-1} dolomitic limestone and 30.0 t ha^{-1} poultry litter (*in natura*, with an average of 30% moisture) was applied over the whole area; the OF was composed of SF and 30 t ha^{-1} poultry litter, and the CF included the application of a further 3 t ha^{-1} dolomitic limestone and 0.75 t ha^{-1} Bayovar natural reactive phosphate for Euc and Ap, and 1.5 t ha^{-1} for Nat. The application of OF+CF was a combination of the two supplementary applications (OF and CF). Part of the dose of poultry litter and limestone was applied to the planting hole and part between the rows, in this case incorporated into the 0-15 cm layer 30 days before planting, so that all the plants received the same dose of fertiliser. The treatments with Euc and Ap received 22% of the dose of poultry litter in the planting hole and 78% between the rows, while the treatment with Nat received 44% in the planting hole and 56% between the rows. Similarly, application of the limestone was carried out so that 25% of the total dose was applied to the holes and 75% between the rows for Euc and Ap; for Nat, 50% was applied to the planting hole and the remainder (50%) between the rows. The reactive natural phosphate was applied to the bottom of the planting holes.

In addition to the fertilisation carried out when planting, the areas also received two doses of top-dressing, the first, one month after setting up the experiment, consisting of 10 kg ha^{-1} N, 22 kg ha^{-1} P, and 8 kg ha^{-1} K when planting the Eucalyptus and Angico, and 20 kg ha^{-1} N, 44 kg ha^{-1} P and 16 kg ha^{-1} K when planting the multiple native species, enriched with micronutrients (1.7 kg ha-1 B, 0.8 kg ha^{-1} Zn, 0.8 kg ha^{-1} Cu) for the Eucalyptus and Angico, and double this dose for the mixed plantation of native species, and placed (in shallow holes) 20 cm to the side of the plants. The second fertilisation was carried out 10 months after starting the treatments, applying 67 kg ha^{-1} N, 17 kg ha^{-1} P, and 67 kg ha^{-1} K to the Eucalyptus and Angico, and 134 kg ha^{-1} N, 34 kg ha^{-1} P, and 134 kg ha^{-1} K to the mixed plantation, in grooves 5 cm deep, in the upper part of the canopy projection area. It should be noted that only treatments with CF and OF+CF received the top-dressing, since this was carried out using chemical fertiliser only.

The main chemical and physical characteristics of the soil in the experimental area at the end of the evaluation period are shown in Table 1.

Table 1 - Chemical and physical properties of a Red-Yellow Latosol in an area of bauxite mining in process of recovery with Eucalyptus (Euc), A. peregrina (Ap) and a mixed plantation of native species (Nat), at 56 months, São Sebastião da Vargem Alegre, MG

Attribute	SF			OF			CF			OF+CF		
	Euc	Ap	Nat	Euc	Ap	Nat	Euc	Ap	Nat	Euc	Ap	Nat
pH	5.28	5.40	5.57	5.78	5.40	5.62	5.57	5.50	5.67	5.48	5.61	5.89
TOC (dag kg^{-1})	2.14	1.98	2.08	2.01	2.01	1.99	2.02	1.95	1.75	2.31	2.23	1.92
TN (dag kg^{-1})	0.14	0.13	0.14	0.15	0.15	0.15	0.13	0.14	0.12	0.17	0.16	0.14
P (mg dm^{-3})	6.40	5.55	5.05	43.07	21.18	11.68	6.12	3.12	15.65	55.95	25.62	16.95
K (mg dm^{-3})	51.50	57.33	39.83	63.00	66.17	56.67	52.17	54.00	71.33	61.33	82.00	72.00
Ca^{+2} (cmol$_c$ dm^{-3})	1.24	1.53	2.11	2.87	3.07	2.48	2.40	2.42	2.77	3.58	3.63	3.22
Mg^{+2} (cmol$_c$ dm^{-3})	0.46	0.50	0.77	1.04	1.08	0.74	0.80	0.73	0.89	1.29	1.09	1.07
Al^{+3} (cmol$_c$ dm^{-3})	0.20	0.07	0.02	0.02	0.03	0.00	0.07	0.00	0.00	0.02	0.00	0.00
H^{+}+Al^{+3} (cmol$_c$ dm^{-3})	7.70	6.53	6.22	5.45	5.10	5.87	5.53	5.77	4.55	5.52	5.83	4.53
SB (cmol$_c$ dm^{-3})	1.83	2.18	2.98	4.07	4.32	3.36	3.33	3.30	3.84	5.02	4.92	4.47
t (cmol$_c$ dm^{-3})	2.03	2.25	3.00	4.09	4.35	3.36	3.40	3.30	3.84	5.04	4.92	4.47
T (cmol$_c$ dm^{-3})	9.53	8.71	9.20	9.52	9.42	9.23	8.87	9.06	8.39	10.54	10.76	9.00
V (%)	18.12	24.77	32.68	41.77	44.33	35.97	39.17	35.98	45.03	46.33	45.57	49.40
m (%)	14.02	3.75	0.87	0.67	1.32	0.00	3.00	0.00	0.00	0.75	0.00	0.00
P-Rem (mg L^{-1})	9.57	9.63	6.33	12.43	12.95	6.60	8.23	9.28	7.43	12.48	13.10	8.83
S (mg dm^{-3})	7.72	8.68	6.18	10.87	10.82	6.15	7.37	10.78	7.98	8.28	11.17	6.65
Cu (mg dm^{-3})	0.37	0.22	0.29	0.28	0.26	0.39	0.20	0.22	0.35	0.35	0.26	0.34
Mn (mg dm^{-3})	8.13	5.93	6.23	16.37	11.58	11.93	7.73	5.85	8.53	14.12	14.63	10.72
Fe (mg dm^{-3})	104.43	53.75	52.23	57.62	48.92	84.08	61.35	64.37	67.88	59.43	61.78	59.93
Zn (mg dm^{-3})	3.41	3.01	2.63	12.53	6.94	6.36	3.57	1.94	4.27	11.58	8.64	6.14
Ds (g cm^{-3})	1.41	1.28	1.16	1.32	1.23	1.23	1.25	1.23	1.33	1.22	1.25	1.25
Dp (g cm^{-3})	2.71	2.68	2.68	2.70	2.63	2.68	2.70	2.63	2.69	2.70	2.67	2.72
Pt (cm^{3} cm^{-3})	0.48	0.52	0.56	0.51	0.53	0.54	0.54	0.53	0.51	0.55	0.53	0.54

SF = standard company fertilizer; OF = organic fertiliser; CF = chemical fertiliser; OF+CF = combined organic and chemical fertiliser; TOC = total organic carbon by Walkey-Black (Yeomans & Bremmer,1988); TN = total nitrogen by Kjedhal (Tedesco *et al*., 1995); P and K = extracted by Mehlich 1 and determined by molecular absorption and flame photometry (Defelipo & Ribeiro, 1997); Ca^{2+}, Mg^{2+} and Al^{3+} extracted with KCl 1 mol L^{-1} and determined by atomic absorption and flame photometry (VETTORI, 1969); H+Al extracted with 0.5 mol L^{-1} calcium acetate at pH 7 (EMBRAPA, 2011); SB = sum of exchangeable bases; T = cation exchange capacity at pH 7.0; t = effective cation exchange capacity; V = base saturation index; m = aluminum saturation index (Vettori, 1969); P-rem = extracted with $CaCl_2$ and determined by molecular absorption (Alvarez V. *et al*., 2000); S, Cu, Mn, Fe and Zn extracted by Mehlich 1 and determined by atomic absorption (Defelipo & Ribeiro, 1997); Ds = bulk density, determined by volumetric ring method; Dp = particle density, determined by volumetric balloon method; Pt = total porosity (EMBRAPA, 2011).

2.2.Tree growth in height and diameter and allometric equations

Total tree height (Ht) and circumference at ground level (CGL) and/or at breast height, 1.3 m from the ground (CBH), were measured at 6, 18, 36 and 56 months for all the trees in the experiment. To determine the height, a graduated pole was used for Nat and Ap and an hypsometer (Forest Vertex IV) for Euc. For CGL and CBH, a metric tape was used, with the data subsequently converted into diameter at breast height (DBH).

Selection of the trees for rigorous cubing was done by separation into diametric class at a range of 2 cm, in the plantations at 56 months of age. In the monocrops of A. peregrina and Eucalyptus, three trees were selected for each diametric class, and in the mixed plantation, three trees were cubed for each diametric class and per species. Rigorous cubing of the trees was carried out using the non-destructive method, i.e. the trees were not felled. To do this, the trunk circumference was measured with a tape in height intervals of 0, 0.30, 0.70, 1.00, 1.3 and 2.3 metres. Starting at a height of 2.3 metres, measurements were taken in 1-metre intervals using a Wheeler Pentaprism (Wheeler, 1962), which allows diametrical values to be obtained at different trunk heights up to the diameter limit of the equipment, that is 6.5 cm. The volume of each section was obtained by successive application of Smalian's formula (Campos & Leite, 2013): $V = ((AS_1+AS_2)/2)*L$, where: V is the section volume with bark (m^3), AS_1 and AS_2 are the sectional areas obtained at the ends of the sections (m^2), and L is the length of the section (m). In the case of diameters smaller than 6.5 cm, the rest of the tree was considered as a cone. Dendrometry data allowed the allometric equations to be adjusted based on the Schumacher and Hall (1933) and Spurr (1952) models for each species planted, the choice of the best model being made by parameter consistency, the coefficient of determination (R^2) and the residual standard error (Syx).

Estimates of tree biomass were obtained by multiplying the total volume with bark for each tree, and evaluated by the basic wood density found in the literature (Zanne *et al*., 2009; Oliveira, 2014; Lorenzi, 2008). An estimate of the C stored in the biomass was made by multiplying the estimated biomass by a conversion factor of 0.47 (IPCC, 2006), considering that 47% of biomass consists of C.

Comparisons between the results for increases in height (Ht) and in diameter at ground level (DGL) were made using the respective confidence intervals at 95%

probability. Analysis of variance (ANOVA) was carried out for all results of the variables of volume, biomass and C stock. In the case of a significant effect, Tukey's test was used to compare the mean values, adopting a significance level of up to 10%.

All analyses were performed using the Statistica 7.0 and R (R Core Team 2013) statistical software.

3. RESULTS

3.1. Initial plantation growth

The *A. peregrina* (Ap) trees showed no difference in total height (Ht) when submitted to the different fertilisers at the four ages under study (Figure 2a). However, differences were seen in diameter at ground level (DGL) at 18 months, when the trees submitted to OF+CF (4.83 cm ± 0.25) showed higher values than trees under CF (4.01cm ± 0.03) and SF (4.00 cm ± 0.22). At 36 months the DGL of the trees under SF (7.13 cm ± 0.51) was lower than those under OF+CF (8.34 cm ± 0.48) and under OF (8.17 cm ± 0.30), with no difference to the trees under CF (7.49 cm ± 0.98). At 56 months, the trees under SF (9.27 cm ± 0.49) presented a lower DGL in relation to those under OF (10.24 cm ± 0.25), with no difference to the other fertilisation treatments. It was seen that the greatest increases in Ht (Figure 2c) occurred from 18 to 36 months, with the trees growing on average 49% relative to the total. For DGL, the greatest increase was seen between 6 to 18 and 36 to 56 months, when on average 33% and 42% of the total was seen respectively (Figure 2d).

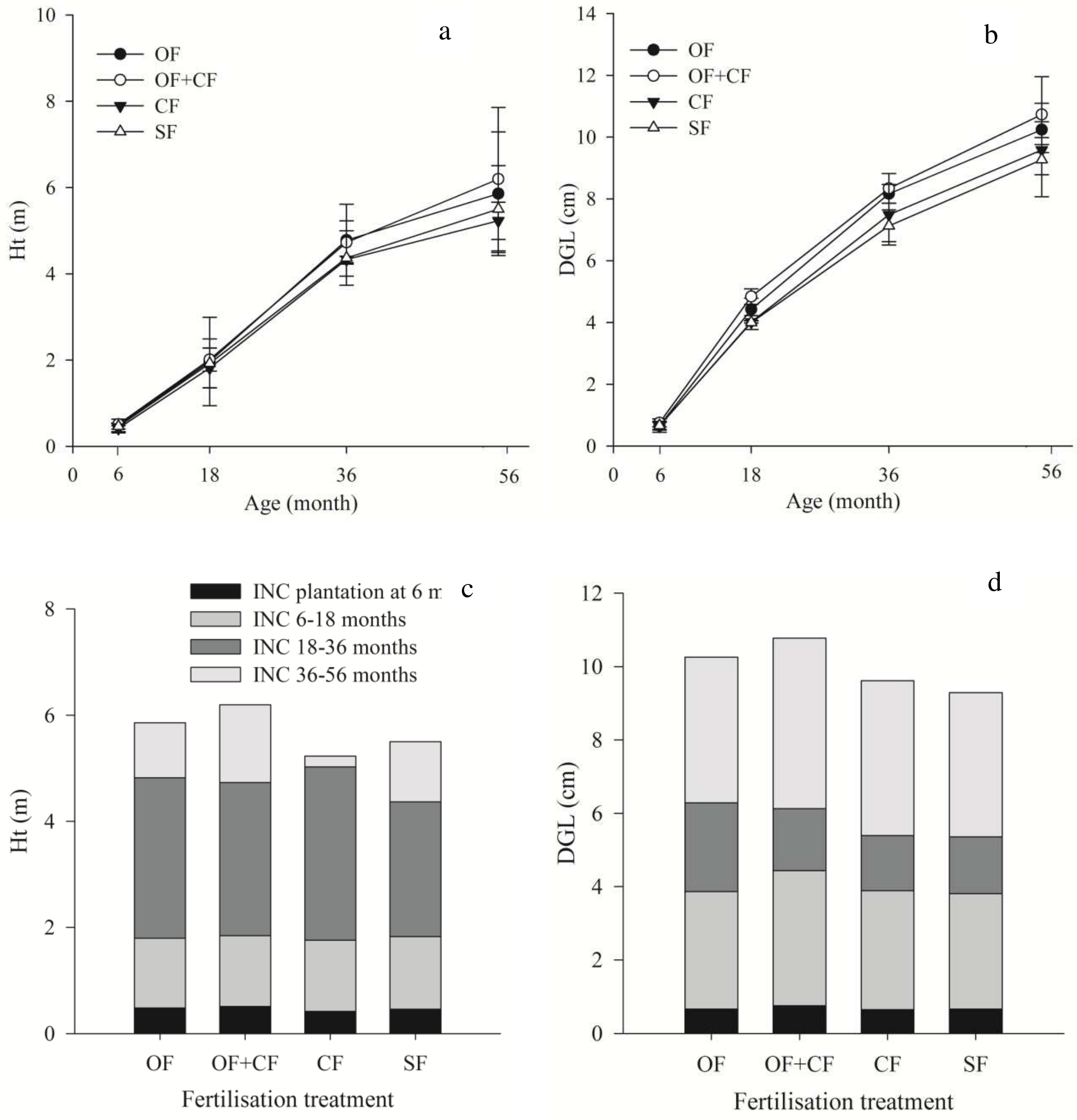

Figure 2 - a) Growth in height (Ht), b) trunk diameter at ground level (DGL), c) increase (INC) in Ht, and d) increase (INC) in DGL in Red Angico (*Anadenanthera peregrina*) at 6, 18, 36 and 56 months of age, submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF) and standard (SF) fertiliser, planted in an area of bauxite mining. Vertical bars represent the confidence interval at 95% probability.

At an age of six months, the Eucalyptus trees (Euc) submitted to OF (1.96 m ± 0.02) showed greater height (Ht) in relation to the trees under SF (1.24 m ± 0.32) and CF (1.51 m ± 0.05), however there was no difference to plants submitted to OF+CF (1.94 m ± 0.42). The different types of fertiliser had no influence on Ht in the Eucalyptus (Euc) at 18 months of age, while at 36 months, only the trees submitted to fertilisation with OF+CF (19.8 ± 0.38) and SF (18.6 ± 0.74) showed a difference. The same as seen at 36 months occurred at 56 months, with values of 22.74 ± 0.57 and 21.33 ± 1.08 respectively.

DGL was influenced for all the ages under study (Figure 3). At an age of six months, the trees submitted to OF (3.51 cm ± 0.096) differed from those under SF (2.58 cm ± 0.53) and CF (2.92 cm ± 0.022), being similar to OF+CF (3.45 cm ± 0.45). At 18 and 36 months, the DGL of plants submitted to OF+CF (12.03 cm ± 0.87 and 17.48 cm ± 0.45 respectively) was greater than that of the trees under SF (10.64 cm ± 0.47 and 15.88 cm ± 0.83 respectively) and under CF (10.88 cm ± 0.20 and 15.86 cm ± 0.85 respectively), and similar to those under OF (11.58 cm ± 0.65). At 56 months, the trees under OF (20.32 cm ± 0.09) were larger than those under SF (18.80 cm ± 1.29) and CF (18.8 cm ± 0.86), however, there was no difference to trees under OF+CF (20.71 cm ± 0.82). The greatest increases in Ht and DGL for Euc were seen from 6 to 18, and 18 to 36 months of age, 33% and 41%, and 28% and 36% respectively (Figure 3c and 3d).

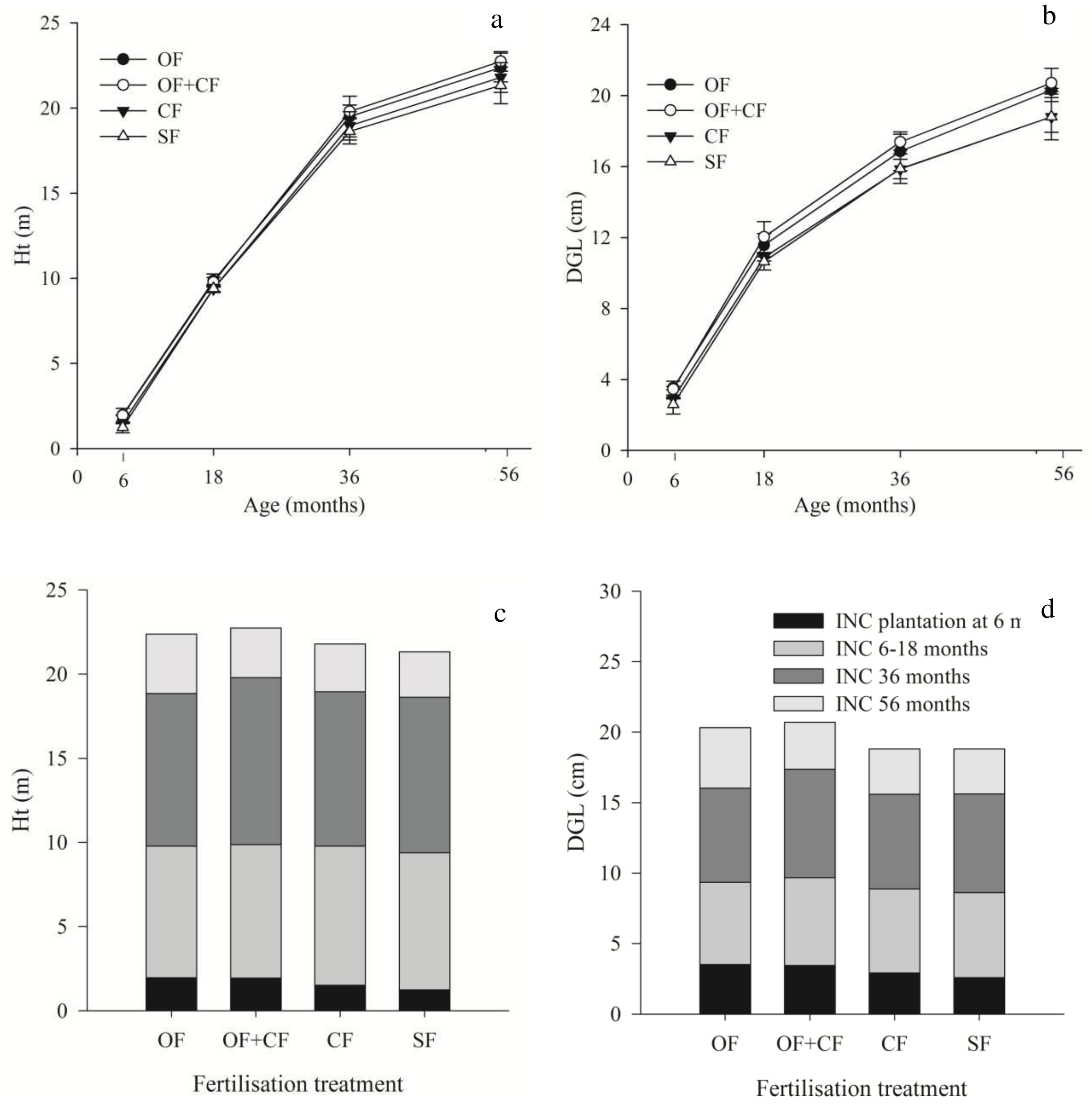

Figure 3 - a) Total growth in height (Ht), b) diameter at ground level (DGL), increase (INC) in Ht, and d) increase in DGL in Eucalyptus (*Eucalyptus urophylla* x *Eucalyptus grandis*) from planting to 6, 18, 36 and 56 months of age, submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF) and standard (SF) fertiliser, planted in an area of bauxite mining. Vertical bars represent the confidence interval at 95% probability.

No effects were seen from the different fertilisers on Ht in the native forest species (Nat) at an age of six months. However, at 18, 36 and 56 months, trees submitted to SF (1.77 m ± 0.13, 4.09 m ± 0.24 and 4.96 m ± 0.43 respectively) had the lowest values for Ht compared to the other fertilisation treatments. At 36 months, the trees under SF maintained the lowest values for Ht in relation to the trees under OF (4.8 m ± 0.40) and CF (4.71 m ± 0.14), while at 56 months of age, the trees under SF had smaller values for Ht only in relation to those under CF (5.60 m ± 0.13), showing no difference to the other fertilisation treatments. The greatest increase in Ht occurred between 18 and 36 months, with an average of 45% in relation to the total (Figure 4c); in general, the DGL of Nat was not influenced by the fertiliser for any of the ages under study. The greatest increases in DGL were obtained from 6 to 18, and 18 to 36 months of age, representing 32% and 37% of the total respectively.

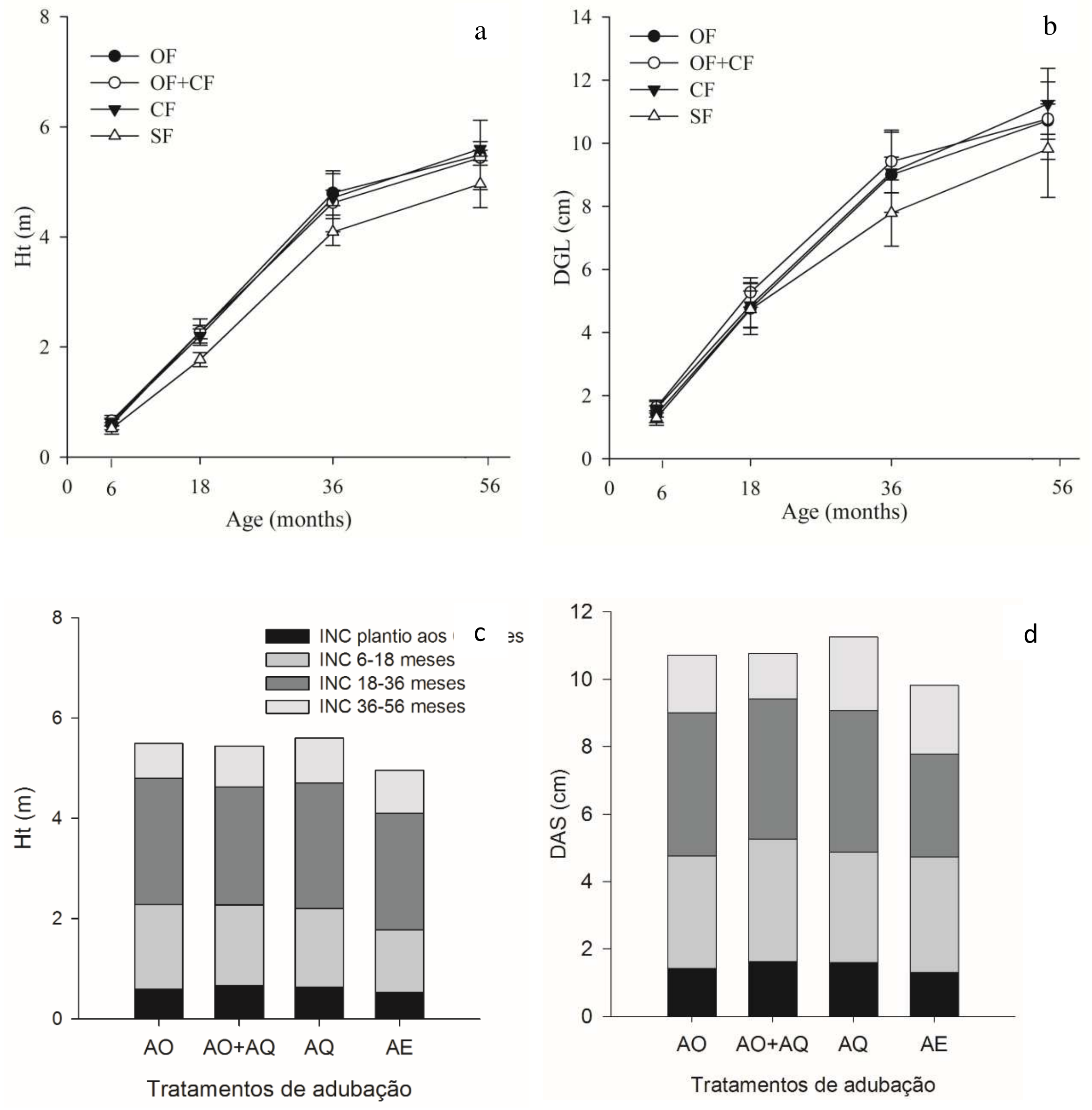

Figure 4 - a) Total growth in height (Ht); b) trunk diameter at ground level (DGL); c) increase (INC) in Ht, and d) increase in DGL in native forest species at 6, 18, 36 and 56 months of age, submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF) and standard (SF) fertiliser, planted in an area of bauxite mining. Vertical bars represent the confidence interval at 95% probability.

The group of pioneer species stood out for Ht, differing from the non-pioneer group at all ages (Figure 5a and 5b). The fertiliser influenced Ht in the pioneer species at 18 months of age only, with the trees submitted to SF (2.11 m ± 0.16) having the lowest values in relation to the trees under OF+CF (2.58 m ± 0.18) and CF (2.62 m ± 0.26). In the non-pioneer group, Ht was influenced by the fertiliser at

18 months and 36 months. At these ages the trees submitted to SF had the smallest values for Ht in relation to the other three fertilisers studied. In the pioneer group, among the species that were most noticeable for height at the end of the evaluation period (56 months of age) were: *Piptadenia gonoacantha* – Jacare (J1), *Enterolobium contortisiliquum* – Monkey Ear (O) and *Ceiba speciosa* – Silk Floss (PA1) (Figure 5). Among the non-pioneers, the species with the greatest growth in height were *Annona squamosa* – Araticum (A1) and *Trichilia s*p - Catigua (C3) (Figure 5). In general, the greatest increase in height was seen from 18 to 36 months of age (Figure 5).

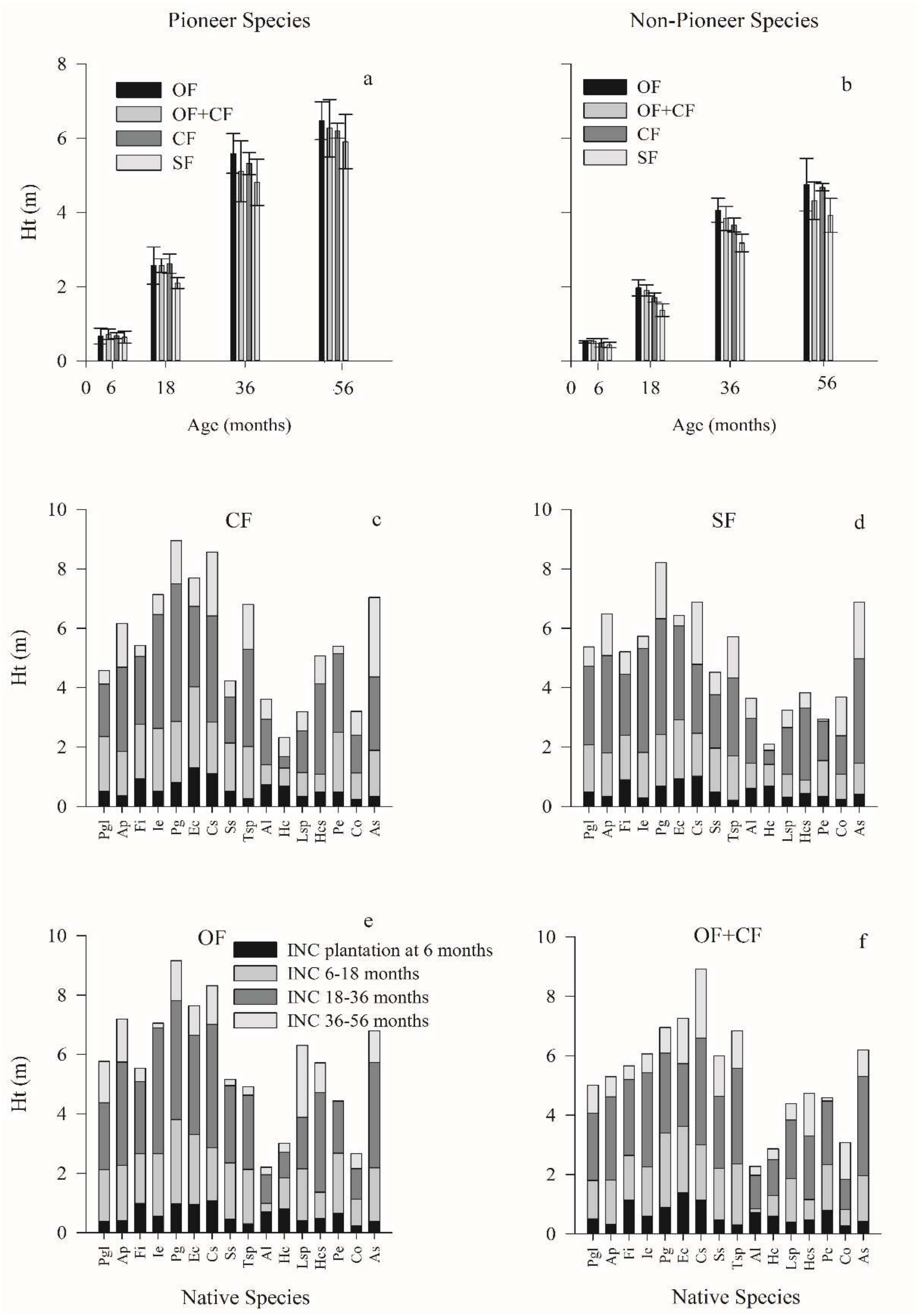

Figure 5 - a) Growth in height (Ht) in native pioneer forest species and b) non-pioneer species, and increase (INC) in Ht of the trees at 6, 18, 36 and 56 months of age, submitted to c) chemical (CF), d) standard (SF), e) organic (OF) and f) combined organic and chemical (OF+CF) fertiliser, planted in an area of bauxite mining. Vertical bars indicate the confidence interval at 95% probability. C2: Tamanqueira; A2: Red Angico; F: Figueira; I1: Inga; J1: Jacare; O: Monkey Ear;

PA1: Silk Floss; S: Soapberry; C3: Catigua; G: Garapa; I2: Golden Trumpet; J2: Jequitiba; J3: Jatoba; PA2: Brazilwood; C1: Camboata; A1: Araticum.

Similarly to growth in height, the pioneer group also displayed the highest values for DGL under all the fertilisers being studied compared to the non-pioneer group (Figure 6). In the pioneer group, the fertilisation treatments influenced DGL at 56 months of age only, when the trees submitted to SF (12.20 cm ± 0.17) displayed lower DGL values in relation to the trees under CF (12.96 cm ± 0.72). Among the non-pioneer species, the same differences in relation to fertiliser were seen as early as 36 months. The largest increases in DGL, as well as in height, were seen at 36 months of age for all the species under study. The pioneer species displayed larger increases in both Ht and DGL than did the non-pioneer species, especially *Ceiba speciosa* (PA1*), Piptadenia gonoacantha* (J1) and *Enterolobium contortisiliquum* (O).

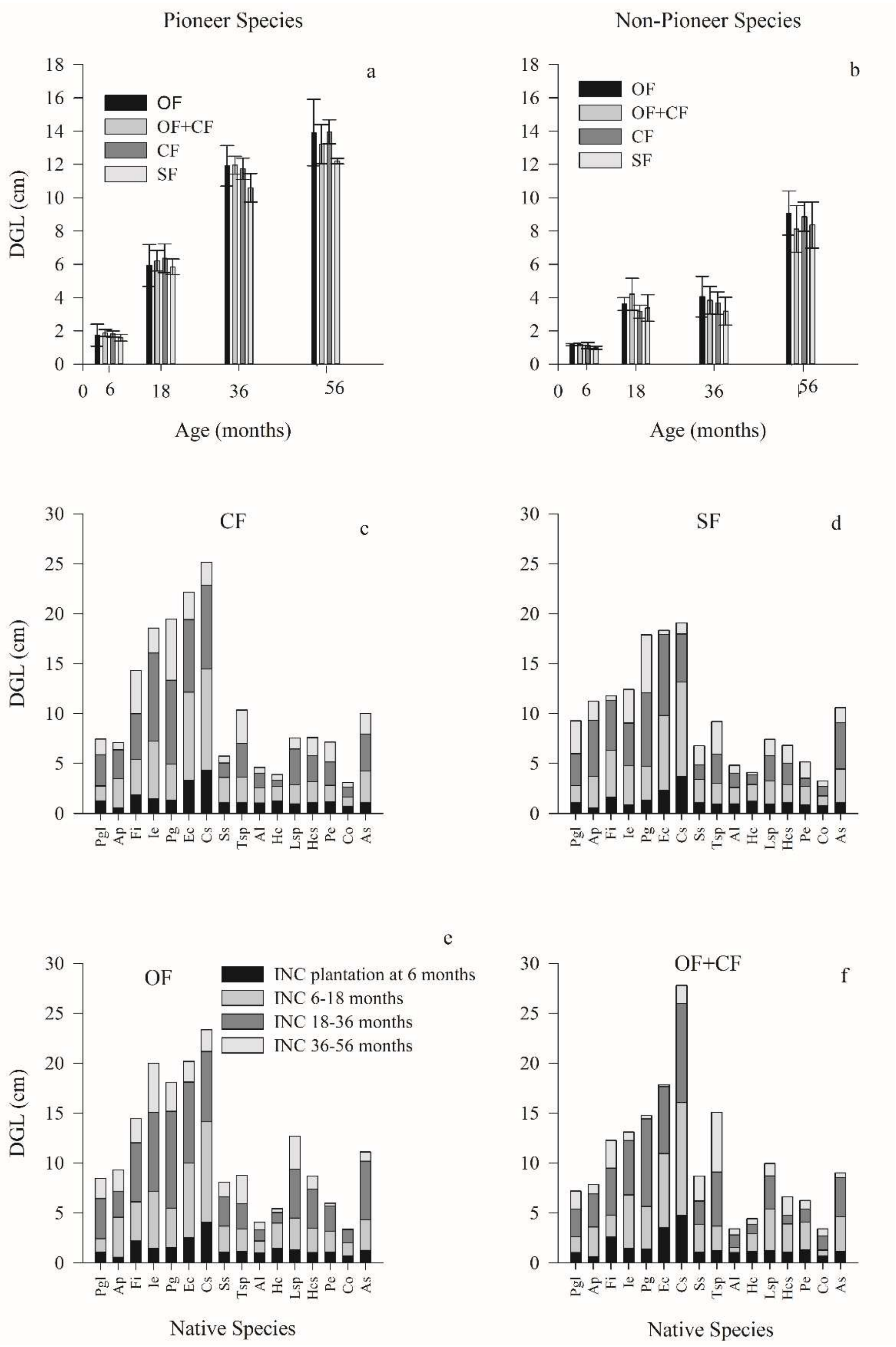

Figure 6 – a) Trunk diameter at ground level (DGL) in native pioneer forest species and b) non-pioneer species planted in an area of bauxite mining, c) increase (INC) in DGL by species at 6, 18, 36 and 56 months of age, submitted to chemical fertiliser (CF), d) standard fertiliser (SF), e) organic (OF) fertiliser and f) combined organic

and chemical fertiliser (OF+CF). Vertical bars indicate the confidence interval at 95% probability. C2: Tamanqueira; A2: Red Angico; F: Figueira; I1: Inga; J1: Jacare; O: Monkey Ear; PA1: Silk Floss; S: Soapberry; C3: Catigua; G: Garapa; I2: Golden Trumpet; J2: Jequitiba; J3: Jatoba; PA2: Brazilwood; C1: Camboata; A1: Araticum.

3.2.Estimating volume, biomass and carbon stocks

The allometric equations obtained by rigorous tree cubing at 56 months of age allowed the trunk volume with bark to be estimated for all the species planted in the experimental area. The values for R^2 were greater than 90% for most of the species (Table 2).

Table 2 – Estimation equations for trunk volume (V) with bark (m^3) in Eucalyptus, Angico and the 16 native forest species at 56 months of age, planted in an area of bauxite mining

Species	Equation	R^2	Syx
Anadenanthera peregrina	$V = 0.0000461*DBH^{2.63300}*Ht^{0.48000}$	95.91	0.0081
Annona squamosa	$V = 0.0000517*DBH^{2.68700}*Ht^{0.38920}$	97.59	0.0049
Ceiba speciosa	$V = 0.0004879*DBH^{1.19835}*Ht^{1.11988}$	90.76	0.0416
Enterolobium contortisiliquum	$V = 0.002877*DBH^{1.361393}*Ht^{0.137388}$	80.94	0.0379
Ficus insipida	$V = 0.002025*DBH^{1.12599}*Ht^{0.200889}$	70.62	0.0063
Inga edulis	$V = 0.000036*DBH^{1.75500}*Ht^{1.60600}$	89.64	0.0085
Piptadenia gonoacantha	$V = 0.000107*DBH^{2.13900}*Ht^{0.71090}$	80.05	0.0278
Sapindus saponaria	$V = 0.0001858*DBH^{1.111359}*Ht^{1.26140}$	94.93	0.0024
Pera glabrata	$V = 0.0003974*DBH^{1.815447}*Ht^{0.15768}$	95.03	0.0016
Apuleia leiocarpa	$V = 0.00007855*(DBH^2*Ht)^{0.95510}$	92.22	0.0014
Caesalpinea equinatha	$V = 0.0008909*DBH^{1.38518}*Ht^{0.075967}$	86.39	0.0009
Lecythis sp	$V = 0.0007675*DBH^{1.59705}*Ht^{0.127039}$	98.29	0.0016
Cupania oblongifolia	$V = 0.0004105*DBH^{1.55291}*Ht^{0.178269}$	96.70	0.0002
Trichilia sp	$V = 0.0004869*DBH^{1.55045}*Ht^{0.35253}$	91.84	0.0021
Handroanthus chrisotricha	$V = 0.0004074*DBH^{1.920903}*Ht^{0.18401}$	91.81	0.0009
Hymenea coubaril	$V = 0.0003974*DBH^{1.815447}*Ht^{0.15768}$	98.00	0.0009
General equation for native species	$V = 0.0007063*DBH^{1.52273}*Ht^{0.522145}$	91.23	0.0248
E. urophylla x E. grandis	$V = 0.000065*DBH^{1.88700}*Ht^{0.98100}$	98.55	0.0197
Anadenanthera peregrina (monocrop)	$V = 0.0001147*DBH^{2.13900}*Ht^{0.59080}$	95.10	0.0195

DBH = trunk diameter at breast height (cm); Ht = total height (m)

R^2 = coefficient of determination; Syx = residual standard error

Among the types of cover planted after the bauxite mining, Euc displayed the greatest values for trunk volume with bark, while Ap and Nat showed no difference to each other (Figure 7). For the fertilisers under study, OF+CF (499.3 m^3 ha^{-1}) gave the highest trunk volume for Euc, showing no difference to the fertilisation with poultry litter (OF) (447.4 m^3), which was statistically similar to SF (402.5 m^3) and CF (419.6 m^3). For Nat and Ap, the fertiliser did not influence trunk volume. The estimate for trunk biomass with bark in *Eucalyptus urophylla* x *grandis*, at 56 months of age, was 250 Mg ha^{-1} under OF+CF. In this case, the trees submitted to SF (205 Mg ha^{-1}) and CF (214.1 Mg ha^{-1}) displayed less biomass than the trees under OF+CF. For Ap and Nat the fertiliser had no influence on the respective biomass. The Euc plantation displayed C stocks of around 119.6 Mg ha^{-1} and 107.2 Mg ha^{-1} in the trunk biomass for OF+CF and OF respectively, while the others ranged from 96.5 Mg ha^{-1} for SF and 110.6 Mg ha^{-1} for CF. Ap (19.9 Mg ha^{-1}) and Nat (24.1 Mg ha^{-1}) did not differ for C stocks, but were well below the values obtained by Euc, irrespective of the fertiliser.

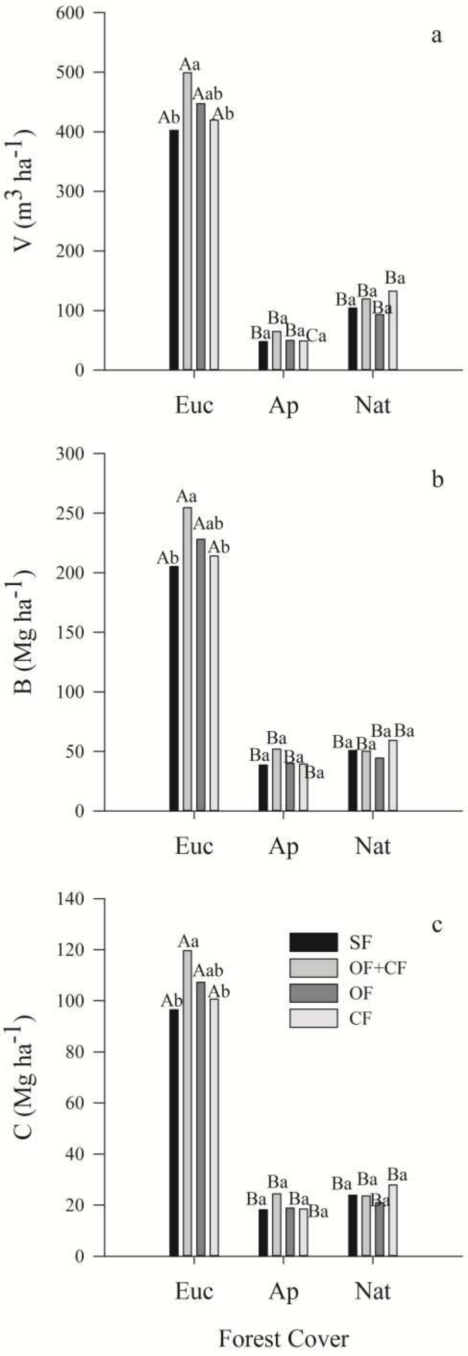

Figure 7 - a) Volume (V) (m^3 ha^{-1}), b) biomass (B) (Mg ha^{-1}) and c) Carbon (C) stocks in the trunk with bark (Mg ha^{-1}) for *Eucalyptus* (Euc), *A peregrina* (Ap) and native species (Nat) at 56 months of age, planted in an area of bauxite mining and submitted to standard (SF), combined organic and chemical (OF+CF), organic (OF) and chemical (CF) fertiliser. Uppercase letters compare the mean values for the different forest covers, while lowercase letters compare the fertilisation treatments within each type of cover and when similar, indicate the lack of significant difference between them by Tukey's test at 10%.

Analysing the native forest species planted in the experimental area (Figure 8), it was found that the pioneer group had the greatest values for volume (197.82 m^3 ha^{-1}), biomass (79.22 Mg ha^{-1}) and C stocks (37.23 Mg ha^{-1}) in relation to the group of native non-pioneer forest species; these showed 26.56 m^3 ha^{-1}, 13.68 Mg ha^{-1} and 6.43 Mg ha^{-1} respectively, with the fertilisation treatments not having any significant effect.

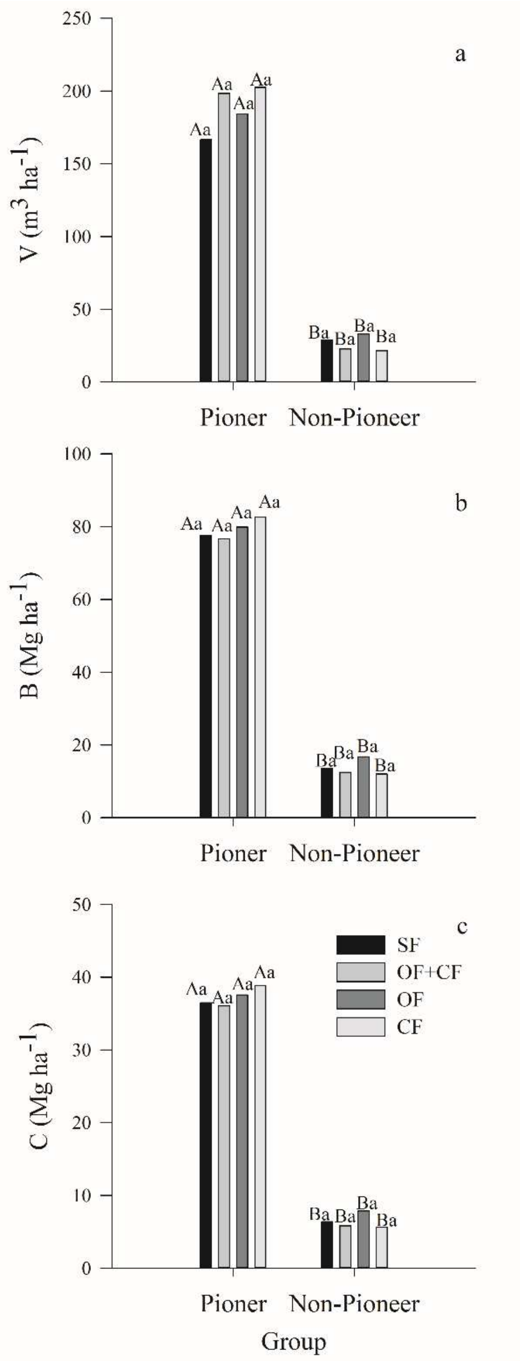

Figure 8 – Volume (V) (m^3 ha^{-1}), biomass (B) (Mg ha^{-1}) and Carbon (C) stocks (Mg ha^{-1}) in native pioneer forest species (Pio) and native non-pioneer forest species at 56 months of age, planted in area of bauxite mining and submitted to standard (SF), combined organic and chemical (OF+CF), organic (OF), and chemical (CF) fertiliser. Uppercase letters compare the mean values for the groups (Pioneers and Non-Pioneers) within the same fertiliser, while lowercase letters compare the fertilisation treatments within the same group, and when similar indicate the lack of significant difference between them by Tukey's test at 10%.

The pioneer forest species Silk Floss (*Ceiba speciosa*), Monkey Ear (*Enterolobium contortisiliquum*) and Jacare (*Piptadenia gonoacantha*) were the species showing the greatest volume at 56 months of age. Monkey Ear and Jacare presented averages of 425 m^3 ha^{-1} and 225 m^3 ha^{-1} respectively irrespective of the type of fertiliser, and Silk Floss, the greatest volumes under OF+CF (773.58 m^3 ha^{-1}) and CF (672.54 m3 ha^{-1}). These three species also stood out from the other pioneer species for biomass production and C stocks. The biomass estimates for Monkey Ear (174.25 Mg ha^{-1}) and Jacare (153.05 Mg ha^{-1}) were the same irrespective of the type of fertiliser, and similar to Silk Floss under OF+CF (193 Mg ha^{-1}) and CF (168.13 Mg ha^{-1}). The C stocks followed the same pattern seen for the biomass.

Among the native non-pioneer forest species, *Annona squamosa* - Araticum had the greatest volume under SF (130.42 m^3) and OF (121.96 m^3). This species also had the greatest biomass under SF (41.7 Mg ha^{-1}) and OF (39.0 Mg ha^{-1}), together with Jequitiba (23.7 Mg ha^{-1}) and Jatoba Mg ha^{-1}). The same behaviour was seen in relation to C stocks. There was no difference between the other species in relation to the accumulation of biomass or C stocks in the trunk.

4. *DISCUSSION*

Angico (Ap) has been used in the revegetation of sites degraded by bauxite mining in south-eastern Brazil due to its good adaptation to soils of low fertility with physical characteristics considered unfavourable to plant growth (Tótola & Borges, 2000). This species develops in different types of soil, whether dry or humid, deep or shallow or even compacted (Lorenzi, 2008); together with the fact that it is a legume associated with N_2-fixing bacteria, this makes it important in the recovery of degraded areas (Santos *et al.*, 2008). Despite being a native pioneer species considered to be relatively fast growing, its nutrient demand is low when compared to Euc, which resulted in the same growth in Ht for the fertilisers under study at all ages. Paiva & Poggiani (2000), evaluating the growth of Ap intercropped with other species, found trees with a height of 0.99 m at 12 months. This value was close to that found in the present study as early as 6 months of age.

Eucalyptus (Euc) is a species of rapid growth, with a large initial spurt and, consequently, a greater demand for nutrients. This condition probably reflected in the growth response in Ht and DGL when the fertilisers were applied. Fertilisation with more nutrients (OF+CF) and the organic fertiliser (OF) improved plant growth in relation to those plants under SF in most of the months under study.

In the early stages of tree growth in the field, fertilisers rich in nitrogen compounds may accelerate the growth rate (Barros *et al.*, 1990), increasing N availability at a stage when the mineralisation rates of this nutrient in soil and plant residue does not meet the high demand of the trees (Jesus *et al.*, 2012). N is a nutrient of low availability in the soil, which coupled with the great demand of plants, makes it one of the most limiting nutrients in productivity for most crops (Barker & Bryson, 2006). The fact that fertilisation with poultry litter (OF) gave similar results to OF+CF, underlines the fact that the growth of the Euc may be a reflection of the low levels of soil organic matter (SOM), a characteristic of soil degraded by mining activities. The low fertility of such soils makes the Eucalyptus more responsive to fertilisation (Ferreira *et al.*, 2015). In degraded environments and soils of low fertility, fertiliser is necessary for the satisfactory development of forest plantations (Florentine & Westbrooke, 2004).

The native pioneer species showed more accelerated growth in height and diameter at ground level than the non-pioneer species (Benvenuti-Ferreira *et al.*, 2009; Carnevali *et al.*, 2016). The growth potential of pioneer species is restricted when grown in poor soils, and they are more responsive to fertilisation in relation to non-pioneer species, in which the growth stimulus provided by fertilisation is less pronounced and sometimes non-existent, a tendency that in part can be attributed to slower growth (Santos *et al.*, 2008). At a more advanced age, non-pioneer species tend to acquire more pronounced growth, unlike pioneer species, as seen by Ferreira *et al.* (2007), 58 months after planting.

Volume and biomass in the Euc were four times greater at 56 months of age compared to the other two forest covers under study. Euc was the only cover that showed a difference in biomass due to the fertilisation treatments. The OF+CF fertiliser (255 Mg ha^{-1}) provided a trunk biomass with bark greater than that found under CF (214 Mg ha^{-1}) and SF (205 Mg ha^{-1}) in the Euc plantation. The results of estimated biomass for Euc at 56 months of age in an area recovering from bauxite mining were higher than those found in unmined areas by some researchers, such as, for example, Santana *et al.* (2008), on the northern coast of the State of Espírito Santo (100.9 Mg ha^{-1}) at 60 months, or Gatto *et al.* (2004), in some regions of the

State of Minas Gerais, such as Cocais (78.5 Mg ha^{-1}), Rio Doce (139.5 Mg ha^{-1}) and Sabinópolis (104.1 Mg ha^{-1}) in plantations at 60 months of age, as well as results found by Stape, Binkley & Ryan (2008), with trunk biomass reaching 140 Mg ha^{-1} in plantations at 5.5 years of age.

The results found in the present study are higher than those found by the above-mentioned authors, however it is important to point out that the results of this study were obtained from experimental plots in the field, where conditions are more homogeneous, i.e. the quality of the sites is similar, mainly due to the high application of nutrients through fertilisation.

The results obtained for trunk biomass with bark in Nat (51 Mg ha^{-1}) and Ap (42.5 Mg ha^{-1}) at 56 months were also higher than those found by Campoe, Stape & Mendes (2010) in plantations composed of 20 forest species native to the Atlantic Forest, at different spacings and under different management activities. According to the authors, the estimated biomass was 18.6 Mg ha^{-1} at an age of 42 months in the treatments that received the greatest fertilisation at spacings of 3 x 2 and 3 x 1 m. In the same area, but at 50 months, Ferez (2010) found a biomass of 33 Mg ha^{-1} in plantations under high-intensity management, but at a lower plant density (1,667 individuals ha^{-1}). Increases in the intensity of silvicultural practices, such as fertilisation and the control of weed-competition, favour tree growth and C sequestration in their biomass (Campoe *et al.*, 2014; Ferez *et al.*, 2015), leading to a positive effect on the restoration of degraded areas. The average value for C stocks found in the present study (24 Mg ha^{-1}) was also higher than that found by Ferez *et al.* (2015) (16 Mg ha^{-1}) at an age of 5 years. In fragments of the Atlantic Forest with an approximate age of 40 years in the northern part of the State of Rio de Janeiro, trunk biomass can reach 158 Mg ha^{-1} (Cunha *et al.*, 2009). Ribeiro *et al.* (2010) found values for trunk biomass with no bark, and for C stocks of 166.67 Mg ha^{-}1 and 84.34 Mg ha^{-}1 respectively in a fragment of Atlantic Forest of at least 100 years of age in Viçosa, Minas Gerais.

The pioneer species in the present study showed better results in terms of growth, biomass and C stocks, as also seen by Campoe *et al.* (2014). Pioneer forest species have the potential for allocating nutritional resources and energy for the rapid growth of their seedlings, thus promoting rapid new ground cover and the formation of forest structure, in addition to increased seed production and availability in relation to non-pioneer species (Souza & Batista, 2004), an important characteristic in recovery programs of degraded areas. Pioneer species probably include the greater allocation of biomass to the aerial part among their survival strategies, guaranteeing light capture in the face of other competing species. Non-pioneer species however, as they naturally occur in more shaded environments, tend to invest more in the root system, while waiting for the appearance of a clearing (Ferez, 2010). Among the pioneer species, Jacaré (*Piptadenica gonoacantha*), Silk Floss (*Ceiba speciosa*) and Monkey Ear (*Enterolobium contortisilicuum*) stood out for growth and biomass estimation. These species are considered fast growing plants and indispensable in recovery programs of degraded areas (Lorenzi, 2008). Silk Floss, despite its low wood density (0.25 g cm^3), stood out in relation to estimations of biomass production, due to its rapid growth and thickening of the trunk, a characteristic feature in species of the genus *Ceiba*.

5. CONCLUSIONS

Fifty-six months after planting the three types of forest cover in an area of bauxite mining, it can be concluded that:

- The applied fertilisers favoured growth in height and diameter in all the forest covers, especially *Eucalyptus urophyll*a x *Eucalyptus grandis*, which showed the greatest growth, mainly under the combined organic+chemical and organic fertilisers;

- The estimation equations for volume developed for all the forest species under study displayed high predictive capacity (given the values for R^2 and Syx) and only depend on variables that are easily measured in the field, such as total height and diameter at breast height (DBH) ;

- Trunk biomass and C stocks in the forest cover under study showed higher values compared to those found in the literature, but it is assumed that this is due to the homogeneity of the site and the increased application of nutrients from the fertilisation carried out in the experimental area.

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SUPORTING INFORMATION

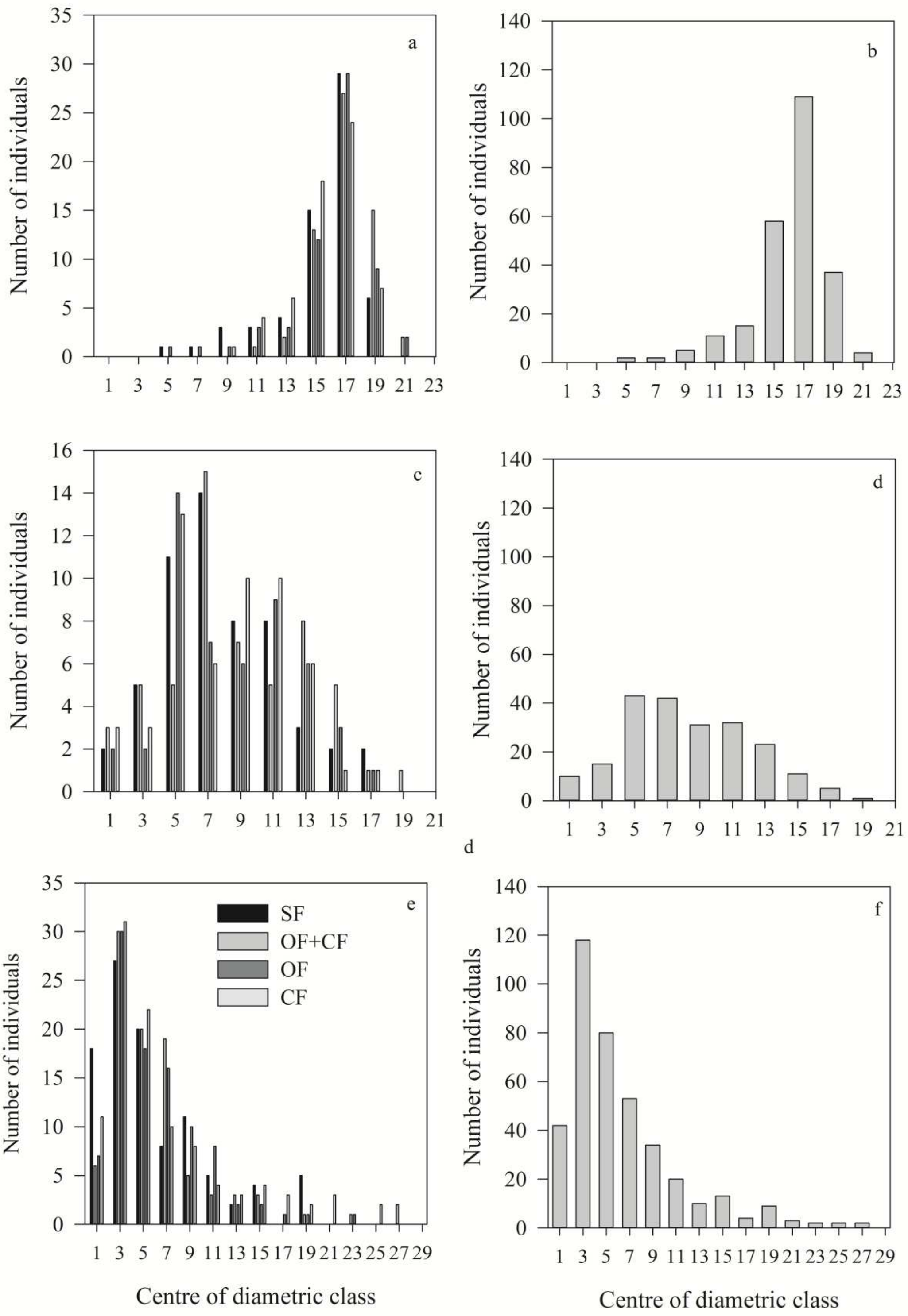

Figure S1 - Distribution of individuals by diametric class in plantations of Eucalyptus (a,b), Angico (c,d) and native species (e,f) at 56 months of age submitted to organic (OF), combined organic and chemical (OF+CF), chemical (CF) and standard (SF) fertiliser, planted in an area of bauxite mining.

Table S1 - Results of analysis of variance (ANOVA) for volume, biomass estimation and C stocks for Eucalyptus (Euc), Angico (Ang) and native species (Nat) at 56 months of age, submitted to four types of fertiliser in an area of bauxite mining in process of recovery

Volume

SV	DF	SS	MS	F	p
Block	2	2372	1186	1.167	0.398772
Forest Cover (FC)	2	1054566	527283	518.847	0.000015**
Error A (Block x FC)	4	4065	1016		
Fertilisation (A)	3	8821	2940	2.783	0.070638**
A x FC	6	10501	1750	1.657	0.189187
Error B	18	19015	1056		
Total	35	1099340			

Biomass

SV	DF	SS	MS	F	p
Block	2	682	341	1.141	0.405482
Forest Cover (FC)	2	255872	127936	428.109	0.000022
Error A (Block x FC)	4	1195	299		
Fertilisation (A)	3	2091	697	2.559	0.087225
A x FC	6	2790	465	1.708	0.176568
Error B	18	4902	272		
Total	35	267532			

C Stocks

SV	DF	SS	MS	F	p
Block	2	151	75	1.141	0.405482
Forest Cover (FC)	2	56522	28261	428.109	0.000022
Error A (Block x FC)	4	264	66		
Fertilisation (A)	3	462	154	2.559	0.087225
A x FC	6	616	103	1.708	0.176568
Error B	18	1083	60		
Total	35	59098			

**significant at 10% probability

Table S2 - Results of analysis of variance (ANOVA) for volume, biomass estimation and C stocks for native pioneer forest species and native non-pioneer forest species at 56 months of age, submitted to four types of fertiliser in an area of bauxite mining in process of recovery

Volume					
SV	DF	SS	MS	F	p
Block	2	695.2	347.6	0.4365	0.696149
Group	1	156214.4	156214.4	196.1684	0.005059**
Error A (Group*Block)	2	1592.7	796.3		
Fertilisation (A)	3	758.8	252.9	0.4961	0.691809
Group*A	3	1895.7	631.9	1.2394	0.338514
Error B	12	6118.3	509.9		
Total	23	167275.0			
Biomass					
SV	DF	SS	MS	F	p
Block	2	256.59	128.30	0.5222	0.656952
Group	1	25770.22	25770.22	104.8886	0.009400**
Error A (Group*Block)	2	491.38	245.69		
Fertilisation (A)	3	51.72	17.24	0.2739	0.843091
Group*A	3	53.26	17.75	0.2821	0.837380
Error B	12	755.26	62.94		
Total	23	27378.43			
C Stocks					
SV	DF	SS	MS	F	p
Block	2	56.68	28.34	0.5222	0.656952
Group	1	5692.64	5692.64	104.8886	0.009400**
Error A (Group*Block)	2	108.55	54.27		
Fertilisation (A)	3	11.42	3.81	0.2739	0.843091
Group*A	3	11.76	3.92	0.2821	0.837380
Error B	12	166.84	13.90		
Total	23	6047.89			

** significant at 10% probability

Table S3 - Basic wood density (g cm^{-3}) of forest species planted in an area of bauxite mining

Species	Basic wood density (g cm^{-3})	Source
Ceiba speciosa	0.25	Zanna *et al*. (2009)
Inga edulis	0.53	Zanna *et al*. (2009)
Ficus insipida	0.39	Zanna *et al*. (2009)
Piptadenia gonoacantha	0.66	Zanna *et al*. (2009)
Enterolobium contortisiliquum	0.41	Zanna *et al*. (2009)
Sapindus saponária	0.60	Zanna *et al*. (2009)
Anadenathera peregrina	0.80	Zanna *et al*. (2009)
Annona squamosa	0.32	Lorenzi (2008)
Cupania oblongifolia	0.67	Lorenzi (2008)
Lecythis sp	0.56	Zanna *et al*. (2009)
Handroanthus chrysotrichia	0.72	Oliveira (2014)
Caesalpinea equinatha	0.86	Oliveira (2014)
Hymenea coubaril	0.8	Oliveira (2014)
Apuleia leiocarpa	0.76	Oliveira (2014)
Trichilia sp	0.5	Oliveira (2014)
Pera glabrata	0.63	Oliveira (2014)

Chapter 2

Production, rate of decomposition and nutrient cycling of litterfall in an area of mining revegetated with forest species

RESUMO

A produção de serapilheira (*litterfall*) por árvores plantadas e sua decomposição em ambientes degradados são importantes para a reativação da ciclagem de nutrientes, podendo serem utilizadas como indicadores da avaliação e monitoramento da recuperação destas áreas degradadas. Objetivou-se determinar a produção e a taxa de decomposição da serapilheira e seus componentes, bem como o estado nutricional do folhedo e galhos de três coberturas florestais (eucalipto - Euc, angico - Ang e plantio misto de 16 espécies nativas - Nat) plantadas em área minerada de bauxita e em recuperação. A produção mensal de serapilheira (*litterfall*) e os seus componentes (folhedo+galhos) nas três coberturas florestais foram avaliados mensalmente durante 30 meses utilizando coletores suspensos. A serapilheira acumulada na superfície do solo (*litter*) também foi avaliada, bem como, seus componentes (folhedo+galhos) duas vezes ao ano (nos finais dos períodos secos e chuvosos). A taxa de decomposição aparente foi estimada pela razão entre o serapilheira coletada (*litterfall*) e a serapilheira acumulada na superfície do solo (*litter*). A determinação dos teores e a estimativa dos conteúdos de Ca, Mg, K, P, S, C e N do folhedo e galhos da serapilheira coletada (*litterfall*) e da serapilheira acumulada na superfície do solo (*litter*) foi realizada a partir de amostras agrupadas por estações (seca e chuvosa). As médias anuais de serapilheira coletadas e acumuladas no solo foram maiores em Euc e Nat. *Eucalyptus* apresentou o maior aporte de galhos coletados (presentes no *litterfall*). As estações do ano não influenciaram o aporte de serapilheira (*litterfall*) para Ang, o que não ocorreu para Euc e Nat, os quais apresentaram, nas estações chuvosa e seca, respectivamente, maiores produções, tanto da serapilheira quanto do folhedo. Em relação ao *litter*, o Ang e Nat apresentaram os maiores valores na estação seca, enquanto para Euc não houve influência da estação. As estações do ano influenciaram a taxa de decomposição aparente de Ang e Nat, sendo os maiores valores observados na chuvosa. O Ang foi a cobertura que apresentou a maior taxa de decomposição aparente na época chuvosa, enquanto que entre Euc e Nat não houve diferenças. Nativas foi a cobertura que apresentou os maiores teores de P, K, Ca e Mg no folhedo, tanto do *litterfall*, como do *litter*, o que repercutiu, também, no maior conteúdo de nutrientes no folhedo. O Euc foi a cobertura com menores teores de P, K, Ca, S e N e maior teor de C, presentes no galhos do *litterfall*, bem como os menores teores de P, K, e S nos galhos do *litter*. A produção de serapilheira (*litterfall*), em especial folhedo, em áreas degradadas é uma importante forma de garantir o retorno de nutrientes ao solo e promover e ativar a ciclagem biogeoquímica nestes ambientes. A escolha de espécies com elevada produção de serapilheira (*litterfall*) e aporte de nutrientes é importante para garantir o sucesso na recuperação de solos degradados.

ABSTRACT

The production of litterfall by planted trees and its decomposition in degraded environments are important for the reactivation of nutrient cycling, and can be used as indicators in the evaluation and monitoring of the recovery of these degraded areas. The aim of this study was to determine the production and rate of decomposition of litterfall and its components, as well as the nutritional status of the leaf and twigs of three types of forest cover (Eucalyptus - Euc, Angico – Ang, and a mixed plantation of 16 native species) planted in an area of bauxite mining in recovery. The monthly production of litterfall and its components (leaf + twigs) in the three types of forest cover were evaluated monthly for 30 months, using suspended collectors. The litter accumulated on the ground was also evaluated, together with its components (leaf + twigs) twice a year (at the end of dry and rainy seasons). The apparent rate of decomposition was estimated from the ratio between the collected litterfall and the litter accumulated on the ground. The levels and estimated content of Ca, Mg, K, P, S, C and N in the leaf and twigs of the collected litterfall was carried out with samples grouped by season (dry and rainy). The annual average values for litterfall collected and accumulated on the ground were higher for Euc and Nat. Eucalyptus showed the greatest contribution of collected twigs (present in the litterfall). The season had no influence on the contribution of litterfall in Ang; this did not occur in Euc and Nat, which presented greater production values for both litterfall and leaf in the rainy and dry seasons respectively. In relation to litter, Ang and Nat showed the highest values during the dry season, while for Euc the season had no influence. The season influenced the apparent rate of decomposition in Ang and Nat, with the highest values seen during the rainy season. The cover with the highest apparent rate of decomposition during the rainy season was Ang, whereas there were no differences between Euc and Nat. The cover of native species presented the highest levels of P, K, Ca and Mg in the leaf , for both litterfall and litter, which also reflected in the higher nutrient content of the leaf. Euc had the lowest levels of P, K, Ca, S and N, and the greatest C content present in the litterfall, as well as the lowest levels of P, K and S in the litter from the twigs. The production of litterfall, especially of leaf , in degraded areas is an important way to ensure nutrient return to the soil, and to promote and activate biogeochemical cycling in these environments. Choosing species with high litterfall production and nutrient contribution is important to ensure the successful recovery of degraded soils.

Keywords: Land reclamation, soil qualiy, forest cover, litter, Eucalyptus, Brazilian Atlantic forest.

1. Introduction

Mining activities are responsible for the degradation of thousands of hectares of land around the world (Machado *et al.*, 2013). The artificial ecosystem formed after mining can be classified as extreme degradation, because the physical, chemical and biological properties of the soil are profoundly altered (Shrestha and Lal, 2011). In these degraded ecosystems, anthropic action is necessary for recovery, since they no longer have efficient mechanisms for the establishment and natural regeneration of plant cover (Celentano *et al.*, 2011; Machado *et al.*, 2013; Shrestha and Lal, 2006). With elimination of the surface layer, the possible natural seed bank is also lost, and the subsoil presents low levels of nutrients and organic matter (Littlefield *et al.*, 2013).

An alternative for improving the soil quality of degraded areas is the establishment of forest cover using native or exotic species that promote the rapid revegetation of the area (Parrotta and Knowles, 1999). Forest species, through the contribution and decomposition of litter, are fundamental for reactivating the biogeochemical cycling of the soil (Barlow *et al.*, 2007; Celentano *et al.*, 2011; Pandey *et al.*, 2007; Tang *et al.*, 2010; Vitousek and Sanford, 1986; Wang *et al.*, 2007), especially in soils that are poorer in nutrients, such as those found in tropical regions (Ge *et al*., 2013; Tang *et al*., 2010; Wang *et al*., 2007). The importance of litterfall production is not only in the activation of nutrient cycling in degraded forest soils, but also in the prevention of erosive processes due to the ground cover, the increase in the soil microbial substrate, and improvement in the chemical and physical properties of the soil, enhancing the productivity and biodiversity of the ecosystem (González-Rodríguez *et al*., 2011). Therefore, quantification of production and decomposition is one of the indicators used in the evaluation and monitoring of restored forests (Arato et al., 2003; Moreira and Silva, 2004).

Some studies have reported that in plantations with greater species diversity there is greater litterfall production than in monocrops (Gama-Rodrigues et al., 2007; Tang *et al*., 2010; Wang *et al*., 2007) with litterfall of better quality (Celentano *et al*., 2011), i.e. with higher levels of N, lower C/N ratios, and low concentrations of phenolic compounds and lignin (Castellano *et al*., 2015), resulting in greater nutrient input to the soil. The quality of litterfall has been mentioned as fundamental in the process of decomposition in different forest ecosystems (Aponte et al., 2012; Zhang *et al*., 2008). The decomposition of litterfall is the main process by which soil organic matter is formed (Cotrufo *et al*., 2013). The most labile components of litterfall and plant compounds resulting from microbiological transformation are the main precursors of more-stable soil organic matter (Cotrufo *et al*., 2015; Haddix et al., 2016), contradicting past studies which reported that more-stable soil organic matter (SOM) was formed from more-recalcitrant compounds (Cotrufo *et al*., 2015).

In the recovery of degraded soils, it is necessary to have knowledge of changes in the litterfall of planted forests, i.e. their production, nutrient content and rate of decomposition, since these characteristics determine the supply of C and N to the soil, reactivating nutrient cycling and increasing the chances of success in the process of recovery of the soil in these areas.

The aim of the present work was to evaluate litterfall production and rate of decomposition, as well as nutrient return to the soil, in three types of forest cover planted in an area of bauxite mining.

2. Material and Methods

2.1. Characterisation of the study area and experimental design

The study was carried out over 30 months under field conditions, in an experiment set up in the town of São Sebastião da Vargem Alegre in the Forest Zone (*Zona da Mata*) of the State of Minas Gerais (MG), Brazil (21°1'58" S and 42°35'8" W), at an altitude of 780 m, in an area of bauxite extraction by The Brazilian Aluminium Company - Votorantim Metais. Following mining activities, the topsoil, stored for approximately one year, was returned to the original area during the process of topographic reconfiguration. Shortly after, the terrain was decompacted using a subsoiler at a depth of 60 cm. The predominant soils in the region are typic dystrophic Red-Yellow Latosols.

According to the Köppen classification, the climate in the region is of type Cwa, with hot and rainy summers, a well-defined dry season, and average annual precipitation and temperatures of 1,287 mm and 20.3ºC respectively (INMET, 2016). Climate data for precipitation and maximum, average and minimum temperatures were obtained from a meteorological station installed in the experimental area (Figure 1).

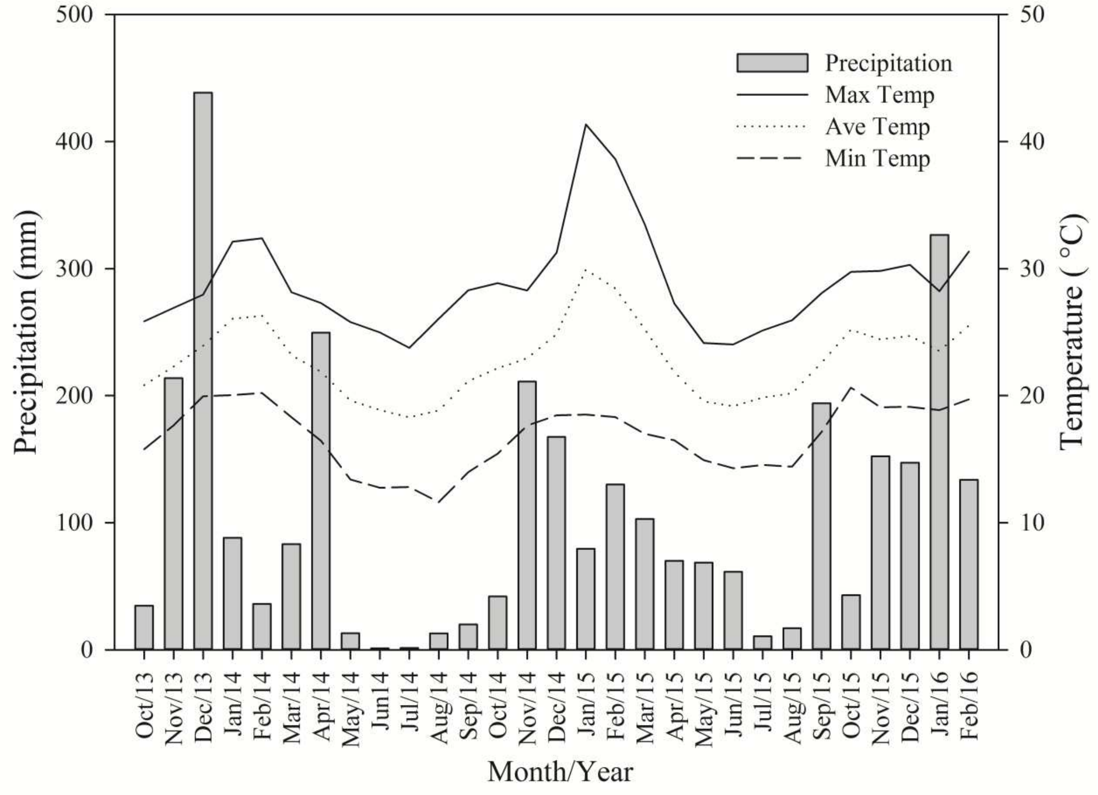

Figure 1 - Cumulative monthly precipitation and mean (Ave Temp), maximum (Max Temp) and minimum (Min Temp) temperatures in an experimental area under different types of forest cover, in recovery after bauxite mining, São Sebastião da Vargem Alegre, MG.

The area was mined for bauxite in 2009 and reconfigured in 2010. The experiment was set up in March 2011 in the area, using a randomised block design with subdivided plots and three replications. The plots, 40 x 18 m in size, comprised the following forest cover: clonal Eucalyptus (a hybrid from a cross between *Eucalyptus urophylla* and *Eucalyptus grandis* - clone AEC144®) (Euc); Red Angico (*Anadenanthera peregrina* (L.) Speg) (Ang); and a mixed plantation (Nat) consisting of 16 native forest species from the region, Red Angico (*Anadenanthera peregrina*

(L.) Speg) - A2, Fig (*Ficus insipida* Willd) - F, Inga cipó (*Inga edulis* Mart.) - I1, Jacare (*Piptadenia gonoacantha* (Mart.) JF Macbr.) - J1, Monkey Ear (*Enterolobium contortisiliquum* (Vell.) Morong.) - O, Silk Floss (*Ceiba speciosa* (A. St.-Hil.) Ravenna) PA1, Soapberry (Sapindus saponaria L.) – S, and Tamanqueira (*Pera glabrata* (Schott) Poepp. Ex Baill.) - C2; forest species considered as pioneers, and the non-pioneer species Catigua (*Trichilia* sp) - C3, Camboata (*Cupania oblongifolia* Mart.) - C1, Garapa (*Apuleia leiocarpa* (Vogel) JF Macbr.) - G, Golden Trumpet (Handroanthus chrysotrichus (Mart. Ex A. DC.) Mattos) – I2, Jatoba (*Hymenaea courbaril* var. *stilbocarpa* (Hayne) YT Lee & Langenh) – J3, Jequitibá (*Lecythis sp*) – J2, Brazilwood (*Paubrasilia echinata* Lam.) - PA2, and Ariticum (*Annona squamosa* L.) – A1. These native species were planted in Quincunx (4 pioneers, with one climax in the centre) at a spacing of 2 x 1.5 m, using seedlings produced from seeds collected in fragments of Atlantic Forest in the second stage of regeneration (Woodland) in the study region. For the Eucalyptus and Angico, the adopted spacing was 3 x 2 m.

The subplots (10 x 18 m) included the standard fertiliser used by the company (SF) in their recovery activities of mined areas and the propositions under study, which considered the SF, but supplemented with organic fertiliser (OF), chemical fertiliser (CF) and a combination of OF+CF. Six months before planting the trees, SF composed of 2.0 t ha^{-1} dolomitic limestone and 30.0 t ha^{-1} poultry litter (*in natura*, with an average of 30% moisture) was applied over the whole area; the OF was composed of SF and 30 t ha^{-1} poultry litter, and the CF included the application of a further 3 t ha^{-1} dolomitic limestone and 0.75 t ha^{-1} Bayovar natural reactive phosphate for Euc and Ang, and 1.5 t ha^{-1} for Nat. The application of OF+CF was a combination of the two supplementary applications (OF and CF). Part of the doses of poultry litter and limestone was applied to the planting hole and part between the rows, incorporated into the 0-15 cm layer 30 days before planting. The treatments with Euc and Ang received 22% of the dose of poultry litter in the planting hole and 78% between the rows, while the treatment with Nat received 44% in the planting hole and 56% between the rows. Similarly, application of the limestone was carried out so that 25% of the total dose was applied to the holes and 75% between the rows for Euc and Ang; for Nat, 50% was applied to the planting hole and the remainder (50%) between the rows. The reactive natural phosphate was applied to the bottom of the planting holes.

In addition to the fertilisation carried out when planting, the areas also received two doses of top-dressing, the first, one month after setting up the experiment, consisting of 10 kg ha^{-1} N, 22 kg ha^{-1} P and 8 kg ha^{-1} K when planting the Eucalyptus and Angico, and 20 kg ha^{-1} N, 44 kg ha^{-1} P and 16 kg ha^{-1} K when planting the multiple native species, enriched with micronutrients (1.7 kg ha-1 B, 0.8 kg ha^{-1} Zn, 0.8 kg ha^{-1} Cu) for the Eucalyptus and Angico, and double this dose for the mixed plantation of native species, and placed (in shallow holes) 20 cm to the side of the plants. The second fertilisation was carried out 10 months after starting the treatments, applying 67 kg ha^{-1} N, 17 kg ha^{-1} P and 67 kg ha^{-1} K to the Eucalyptus and Angico, and 134 kg ha^{-1} N, 34 kg ha^{-1} P and 134 kg ha^{-1} K to the mixed plantation, in grooves 5 cm deep, in the upper part of the canopy projection area. It should be noted that only treatments with CF and OF+CF received the top-dressing, since these were carried out using chemical fertiliser only.

For the present study, only the subplots comprising SF and OF+CF were selected.

The main chemical and physical characteristics of the soil in the experimental area at the end of the evaluation period are shown in Table 1.

Table 1

Chemical and physical properties of a Red-Yellow Latosol in an area of bauxite mining in process of recovery with Eucalyptus (Euc), Angico (Ang) and a mixed plantation of native species (Nat), at 56 months, São Sebastião da Vargem Alegre, MG

Attribute	SF			OF			CF			OF+CF		
	Euc	Ang	Nat	Euc	Ang	Nat	Euc	Ang	Nat	Euc	Ang	Nat
pH	5.28	5.40	5.57	5.78	5.40	5.62	5.57	5.50	5.67	5.48	5.61	5.89
TOC (dag kg^{-1})	2.14	1.98	2.08	2.01	2.01	1.99	2.02	1.95	1.75	2.31	2.23	1.92
TN (dag kg^{-1})	0.14	0.13	0.14	0.15	0.15	0.15	0.13	0.14	0.12	0.17	0.16	0.14
P (mg dm^{-3})	6.40	5.55	5.05	43.07	21.18	11.68	6.12	3.12	15.65	55.95	25.62	16.95
K (mg dm^{-3})	51.50	57.33	39.83	63.00	66.17	56.67	52.17	54.00	71.33	61.33	82.00	72.00
Ca^{+2} (cmol$_c$ dm^{-3})	1.24	1.53	2.11	2.87	3.07	2.48	2.40	2.42	2.77	3.58	3.63	3.22
Mg^{+2} (cmol$_c$ dm^{-3})	0.46	0.50	0.77	1.04	1.08	0.74	0.80	0.73	0.89	1.29	1.09	1.07
Al^{+3} (cmol$_c$ dm^{-3})	0.20	0.07	0.02	0.02	0.03	0.00	0.07	0.00	0.00	0.02	0.00	0.00
H^{+}+Al^{+3} (cmol$_c$ dm^{-3})	7.70	6.53	6.22	5.45	5.10	5.87	5.53	5.77	4.55	5.52	5.83	4.53
SB (cmol$_c$ dm^{-3})	1.83	2.18	2.98	4.07	4.32	3.36	3.33	3.30	3.84	5.02	4.92	4.47
t (cmol$_c$ dm^{-3})	2.03	2.25	3.00	4.09	4.35	3.36	3.40	3.30	3.84	5.04	4.92	4.47
T (cmol$_c$ dm^{-3})	9.53	8.71	9.20	9.52	9.42	9.23	8.87	9.06	8.39	10.54	10.76	9.00
V (%)	18.12	24.77	32.68	41.77	44.33	35.97	39.17	35.98	45.03	46.33	45.57	49.40
m (%)	14.02	3.75	0.87	0.67	1.32	0.00	3.00	0.00	0.00	0.75	0.00	0.00
P-Rem (mg L^{-1})	9.57	9.63	6.33	12.43	12.95	6.60	8.23	9.28	7.43	12.48	13.10	8.83
S (mg dm^{-3})	7.72	8.68	6.18	10.87	10.82	6.15	7.37	10.78	7.98	8.28	11.17	6.65
Cu (mg dm^{-3})	0.37	0.22	0.29	0.28	0.26	0.39	0.20	0.22	0.35	0.35	0.26	0.34
Mn (mg dm^{-3})	8.13	5.93	6.23	16.37	11.58	11.93	7.73	5.85	8.53	14.12	14.63	10.72
Fe (mg dm^{-3})	104.43	53.75	52.23	57.62	48.92	84.08	61.35	64.37	67.88	59.43	61.78	59.93
Zn (mg dm^{-3})	3.41	3.01	2.63	12.53	6.94	6.36	3.57	1.94	4.27	11.58	8.64	6.14
Ds (g cm^{-3})	1.41	1.28	1.16	1.32	1.23	1.23	1.25	1.23	1.33	1.22	1.25	1.25
Dp (g cm^{-3})	2.71	2.68	2.68	2.70	2.63	2.68	2.70	2.63	2.69	2.70	2.67	2.72
Pt (cm^{3} cm^{-3})	0.48	0.52	0.56	0.51	0.53	0.54	0.54	0.53	0.51	0.55	0.53	0.54

SF = standard company fertiliser; OF = organic fertiliser; CF = chemical fertiliser; OF+CF = combined organic and chemical fertiliser; TOC = total organic carbon by Walkey-Black (YEOMANS; BREMMER [1988]); TN = total nitrogen by Kjedhal (TEDESCO *et al*., 1995); P and K = extracted by Mehlich 1 and determined by molecular absorption and flame photometry (DEFELIPO; RIBEIRO, 1997); Ca^{2+}, Mg^{2+} and Al^{3+} extracted with KCl 1 mol L^{-1} and determined by atomic absorption and flame photometry (VETTORI, 1969); H+Al extracted with 0.5 mol L^{-1} calcium acetate at pH 7 (EMBRAPA, 2011); SB = sum of exchangeable bases; T = cation exchange capacity at pH 7.0; t = effective cation exchange capacity; V = base saturation index; m = aluminum saturation index (VETTORI, 1969); P-Rem = extracted with $CaCl_2$ and determined by molecular absorption (ALVAREZ V. *et al*., 2000); S, Cu, Mn, Fe and Zn extracted by Mehlich 1 and determined by atomic absorption (DEFELIPO; RIBEIRO, 1997); Ds = bulk density, determined by volumetric ring method; Dp = particle density, determined by volumetric balloon method; Pt = total porosity (EMBRAPA, 2011).

2.2. *Monthly production and litter accumulation on the ground*

Monthly interception of the collected litterfall in Euc, Ang and Nat was carried out using collectors made of nylon (1 mm mesh), 8 x 0.5 m in size (4 m^2), suspended 0.5 m above the ground, and began when the plantation was at an age of 31 months. These collectors were distributed in triplicate between the planting rows, taking care that all the species planted in Nat were represented in the collectors. The litterfall intercepted by the collectors was evaluated monthly over 30 months by weighing. For each collection, one sample was selected and separated into leaves, twigs and reproductive structures. Each component was weighed before and after oven drying at 65°C for 48 hours to determine the dry weight, and then stored for chemical characterisation.

The remaining litter on the ground was estimated twice a year: at the end of the dry season (September 2014 and September 2015) and the rainy season (March 2014, March 2015 and March 2016). The samples were collected using a 0.5 m x 0.5 m template, thrown randomly in the subplots, and repeated five times. The collected samples were weighed and separated into leaves, twigs and reproductive structures. The components were weighed before and after oven drying at 65°C for 48 hours to determine the dry matter weight, and then stored for chemical characterisation.

In the present study, the terms leaf litterfall and 'leaf litter' were used to characterise the total amount of leaves and reproductive structures in both the litterfall (intercepted by the collectors) and the litter (accumulated on the ground), respectively.

2.3. Estimation of the apparent rate of decomposition

The rate of decomposition of the litter and its components (leaf litter and twigs) was estimated at the end of the dry and rainy seasons, according to the equation proposed by Olson (1963), $k = \frac{\Sigma Mt}{Mr}$, where k is the rate of decomposition year^{-1}; Mt is the sum of the average monthly weight, in kg ha^{-1} of litterfall collected in the collectors during the dry or rainy season; and Mr is the average weight, in kg ha^{-1} of litter remaining on the ground at the end of the dry or rainy season.

2.4. Chemical characterisation of the leaf and twigs

For chemical characterisation of the leaf and twigs added monthly to the collectors, i.e. the litterfall components, the samples were grouped according to season, either dry or rainy. To make up the composite sample, the monthly weight (kg ha^{-1}) of the added leaf litterfall or twigs was considered, where the most productive months were most represented in the composite sample. The leaf litter and twigs present in the litter that accumulated on the ground, i.e. the litter components, were analysed after each collection. The samples were ground in a Wiley-type mill and then submitted to nitric-perchloric digestion to determine the levels of K (flame photometry); P (colourimetry, by the vitamin C method, modified by Braga and Defelipo, 1974); and Ca, Mg and S (atomic absorption spectroscopy).

The nutrient content of the leaf and twigs in the litterfall and litter were estimated using the average production of leaf and twigs for the time of year (kg ha^{-1}) multiplied by the nutrient concentration in the respective litterfall and litter components (kg kg^{-1}) (TANG *et al*., 2010; VITOUSEK; SANFORD, 1986).

2.5. Statistical analysis

Data for the production and decomposition of the litterfall and its components (leaf litter and twigs), as well as the levels and content of nutrients in the leaf litter and twigs, were submitted to analysis of variance, and the mean values compared by Tukey's test at 10% probability.

3. Results

3.1. Monthly production and litter accumulation on the ground

In general, the interaction between the sources of variation, types of fertiliser (SF and OF+CF) and types of forest cover planted in the mined area, showed no significant effects ($p > 0.1$) in relation to the litterfall collected in the collectors, the litter accumulated on the ground or the apparent rate of decomposition (ANNEX); this led to the use of the mean values obtained in the treatments submitted to SF and OF+CF.

The average annual production of litterfall for Ang, Euc and Nat was 3,950±593; 8,324±1,979 and 6,322±608 kg ha^{-1} year^{-1} respectively. The cover with the lowest contribution of litterfall was Ang, differing significantly from the other two types of cover under study ($p < 0.1$) (Fig 2a). Evaluating the litterfall components, it was found that the leaf represented 77, 67 and 84% of the total production of litterfall for Ang, Euc and Nat respectively, following a pattern similar to the contribution of litterfall throughout the studied months. Twig production was far lower, with Euc (33%) presenting the highest annual contribution of twigs, and differing from the other types of cover (Ang 23% and Nat 16%) (Fig 2b and 2c).

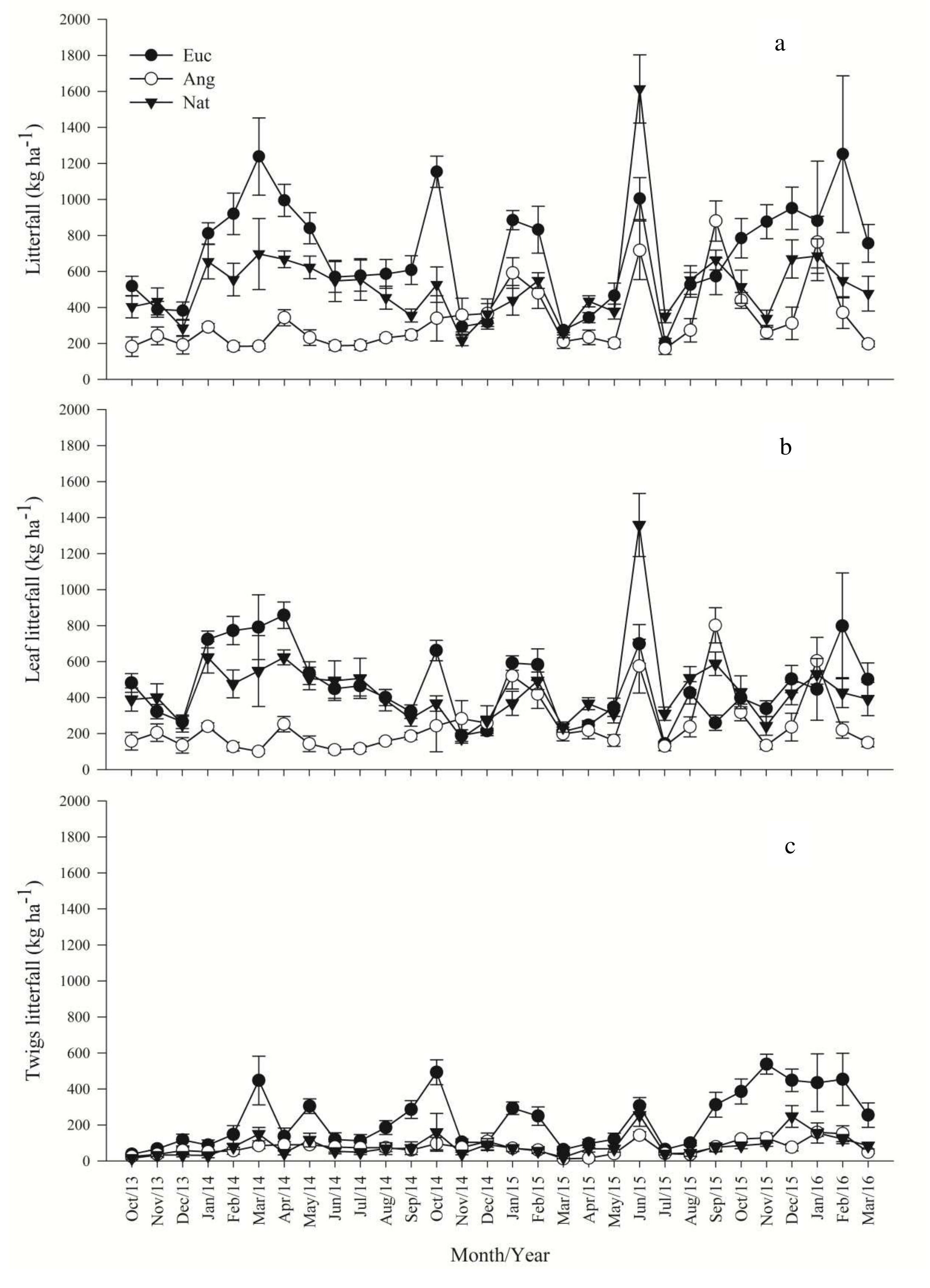

Figure 2 - Total monthly contribution (kg ha^{-1}) of (a) litterfall, (b) leaf litterfall and (c) twigs in an area of bauxite mining in process of recovery with Eucalyptus (Euc), Angico (Ang) and a mixed plantation of native species (Nat), during 30 months of evaluation. (Bars indicate the standard error of the mean, n = 6).

The annual average for litter accumulated on the ground for Ang (5,717.12±811.37 kg ha^{-1} $year^{-1}$) was also significantly lower ($p < 0.1$) than seen for Euc (15,658.46±3209.51 kg ha^{-1} $year^{-1}$) and Nat (12,508.69±721.57 kg ha^{-1} $year^{-1}$) (Fig. 3a). There were no differences between these last two types of cover for annual average litter accumulated on the ground. Among the studied litter components, leaf was found to represent about 62, 50 and 79% for Ang, Euc and Nat respectively in relation to the total, presenting a pattern similar to the litter (Fig 3a and 3b). The Eucalyptus cover had the greatest accumulation of twigs on the ground (49%) throughout the collections (Fig 3c).

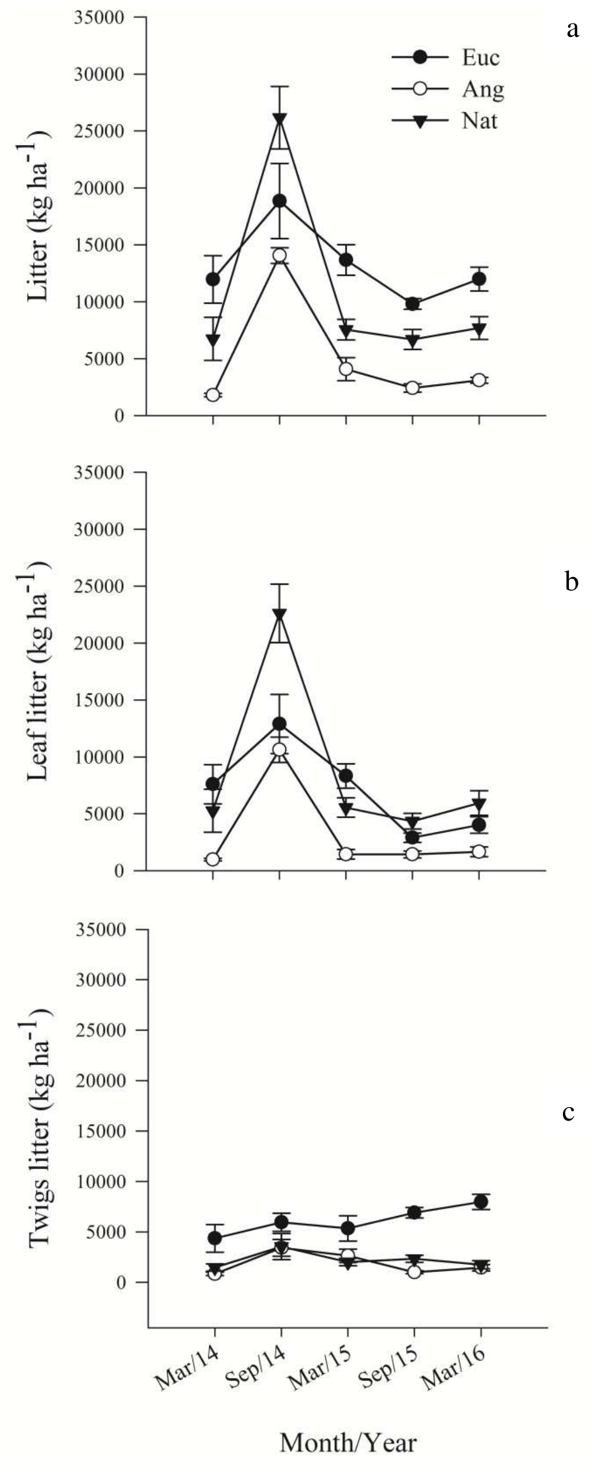

Figure 3 - Litter (kg ha^{-1}) (a), leaf (b) and (c) twigs accumulated on the ground at the end of the dry and rainy seasons in an area of bauxite mining in process of recovery with Eucalyptus (Euc), Angico (Nat) and a mixed plantation of native species, during 30 months of evaluation. (Bars indicate the standard error of the mean, n = 6.)

3.2. Seasonal variation in the production and accumulation of litterfall and its components

The time of year influenced litterfall production in Euc and Nat, but this did not happen in Ang. The cover of Eucalyptus (Euc) presented the largest contribution of litterfall during the rainy season, while in Nat, the greatest production was seen during the dry season, showing no difference from Euc for that season (Figure 4). The leaf in the collectors during the dry and rainy seasons followed a pattern similar to that seen for litterfall, with Ang having the lowest values in both the dry and rainy seasons. The native species and Euc displayed the same changes in leaf-litter contribution during the rainy and dry seasons. The Eucalyptus cover contributed the most twigs during both the rainy and dry seasons, except that the greatest contribution of branches for this cover was seen during the former. Angico and Nat did not differ as regards the contribution of twigs.

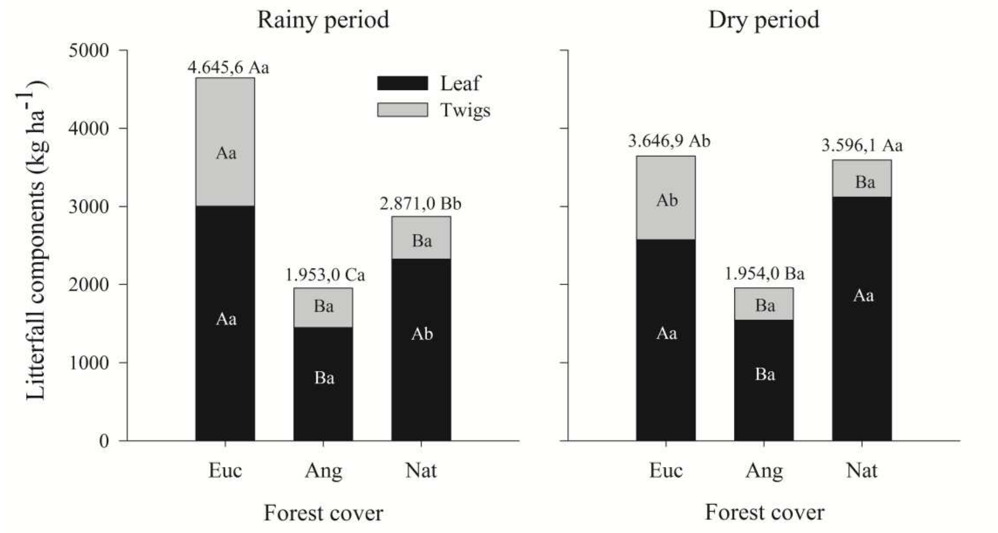

Figure 4 - Litterfall components (leaf and twigs) (kg ha^{-1}) at the end of the dry and rainy seasons in an area of bauxite mining in process of recovery with Eucalyptus (Euc), Angico (Ang) and a mixed plantation of native species (Nat), for 30 months of

evaluation. Uppercase letters compare between the different types of cover for each of the seasons (dry or rainy), while lowercase letters compare each type of forest cover between the dry and rainy seasons, and when similar, indicate no significant differences by Tukey's test at 10%. Values above the bars indicate litterfall.

Euc showed no differences for time of year in relation to litter accumulated on the ground (Fig. 5). Ang and Nat presented higher values during the dry season. During the rainy season, it was seen that Euc had the greatest accumulation of litter on the ground, followed by Nat and Ang; during the dry season, Euc did not differ from Nat. Ang was the forest cover with the smallest accumulation of litter on the ground, irrespective of the time of year. The dry season was responsible for the greatest accumulation of leaf litter on the ground in Ang and Nat; however for Euc, the time of year did not influence the accumulation of leaf litter on the ground. Ang had the least accumulation of leaf litter on the ground compared to Euc and Nat. In relation to the twigs that accumulated on the ground, Euc had the highest values, differing from Ang and Nat in both seasons.

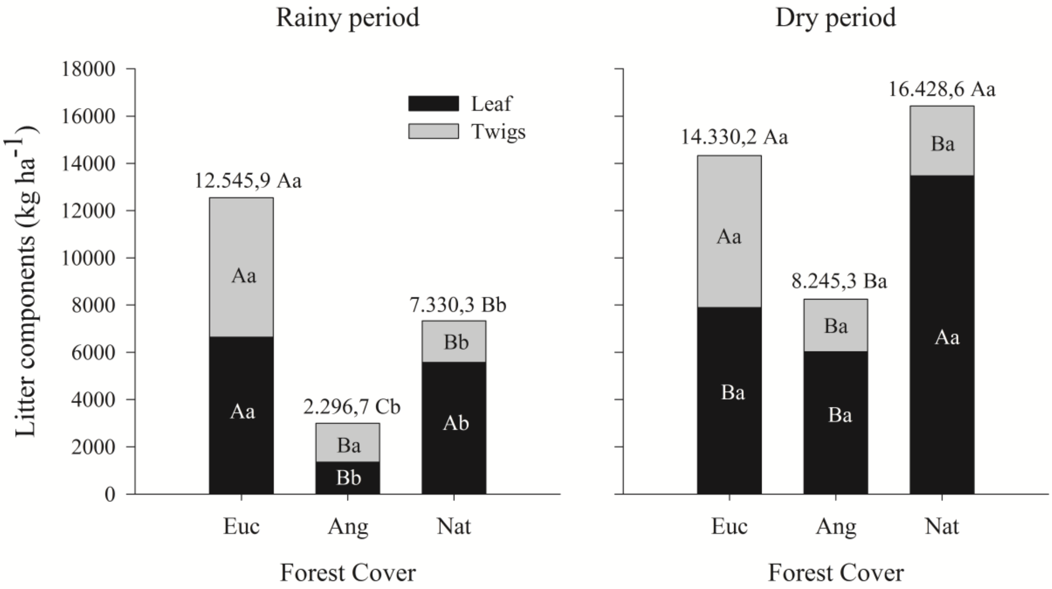

Figure 5 - Litter components (leaf litter and twigs) accumulated on the ground (kg ha^{-1}) at the end of the dry and rainy seasons in an area of bauxite mining in process of recovery with Eucalyptus (Euc), Angico (Ang) and a mixed plantation of native species (Nat), for 30 months of evaluation. Uppercase letters compare between the different types of cover for each of the seasons (dry or rainy), while lowercase letters compare each type of forest cover between the dry and rainy seasons, and when similar, indicate no significant differences by Tukey's test at 10%. Values above the bars indicate total litter.

3.3. *Apparent decomposition of the litter and its components*

Ang and Nat showed differences in the apparent rate of decomposition (k) for the time of year, with the highest rates seen during the rainy season (Fig 6), and the highest rate of decomposition being associated with Ang (0.7 year^{-1}). During the dry season, there were no differences in relation to the other types of cover. The rate of litter and leaf decomposition in Euc did not vary between seasons. The leaf in Ang presented a rate of decomposition around three times higher than the other species studied during the rainy season. The rate of decomposition of the twigs did not vary for type of forest cover, with a higher rate being seen during the rainy season.

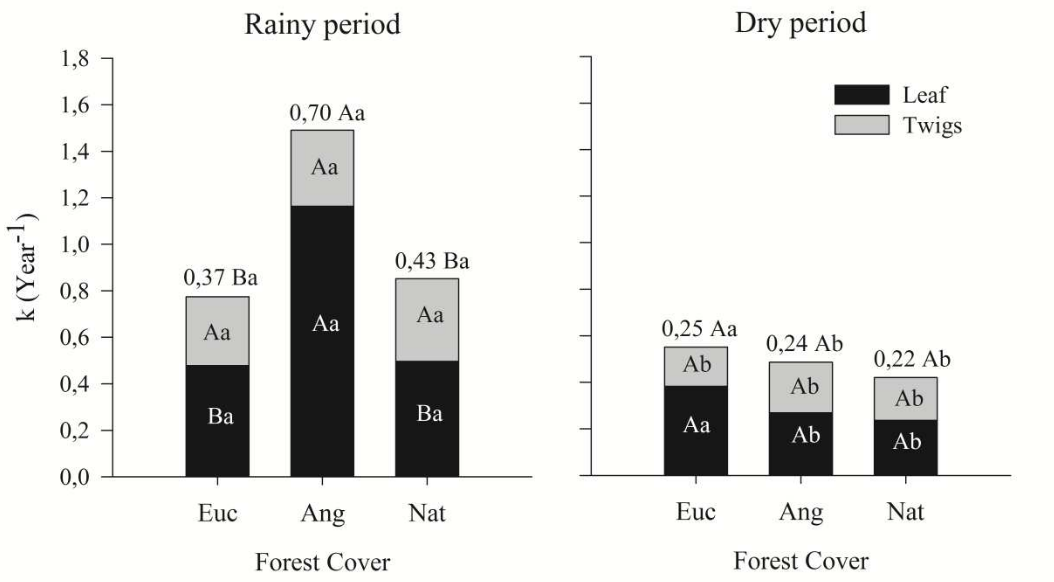

Figure 6 - (a) Apparent rate of decomposition for litter (year^{-1}), (b) leaf and (c) twigs at the end of the dry and rainy seasons in an area of bauxite mining in process of recovery with Eucalyptus (Euc), Angico (Ang) and a mixed plantation of native species (Nat), for 30 months of evaluation. Uppercase letters compare between the different types of cover for each of the seasons (dry or rainy), while lowercase letters compare each type of forest cover between the dry and rainy seasons, and when similar, indicate no significant differences by Tukey's test at 10%. Values above the bars indicate the total rate of decomposition.

3.4. *Mineral content of the leaf and twigs*

Among the types of forest cover under study, Nat presented the highest levels of P, K, Ca and Mg contributed by the leaf in the litterfall (Table 2). The highest levels of P for Ang and Nat were found during the rainy season and of K for Nat during the dry season. The levels of Ca and Mg did not differ for the time of year for Nat; this cover displayed the lowest levels of C, with Ang displaying the highest, whereas for N, Ang had the highest levels and Euc the lowest, which resulted in a greater leaf-litter C/N ratio for Euc and a lower ratio for Ang. For the nutrients in the twigs of the litterfall, Euc displayed the lowest levels of P, K, Ca, S, and N. The highest C content was seen in the twigs from Euc, which also presented the highest C/N ratio in comparison to the other types of cover.

In relation to the nutrients in the leaf accumulated on the ground (present in the litter) at the end of the dry and rainy seasons (Table 2), Nat was seen to have the highest levels of P during the dry season, and also the highest levels of Ca, Mg and S irrespective of the time of year. Angico and Euc did not differ in relation to these nutrients. The highest levels of K were seen during the dry season for Ang and Nat. The leaf litter in Euc displayed the highest and lowest levels of C and N respectively, and consequently, the highest C/N ratios.

In Euc, the levels of P, K and S in the twigs remaining on the ground were lower in relation to those of Ang and Nat, irrespective of the time of year. Ang had the highest levels of Ca, showing no difference to Nat (Table 3). The levels of C in the twigs remaining on the ground were influenced by the time of the year, with Euc having the highest levels during the rainy season and Nat during the dry season. The lowest C/N ratio for the twigs was seen in Ang.

Table 2
Nutrient content (g kg^{-1}) of the leaf and twigs contributed in the collectors (litterfall) and remaining on the ground (litter) in Angico (Ang), Eucalyptus (Euc) and a mixed plantation of native species (Nat) at the end of the rainy and dry seasons in an area of bauxite mining in the process of recovery, for 30 months of collection

Forest Cover	Season	P	K	Ca	Mg	S	C	N	C/N
		Leaf (g kg^{-1}) – Contibuted in the collectors (*Litterfall*)							
Ang	Rainy	1.2 Aa	5.4 Ba	8.4 Ba	1.4 Ba	1.1 Aa	477.5 Aa	27.8 Aa	17.2 Ca
	Dry	0.8 Bb	5.6 Ba	10.7 Ba	1.5 Ba	1. Aa	469.9 Ab	23.9 Aa	19.7 Ca
Euc	Rainy	0.7 Ba	4.2 Ca	7.7 Ba	1.5 Ba	0.6 Ba	464.3 Ba	8.4 Ca	55.3 Aa
	Dry	0.6 Ca	4.4 Ca	9.1 Ba	1.6 Ba	0.6 Ba	462.9 Ba	8.8 Ca	52.6 Ab
Nat	Rainy	1.1 Aa	6.5 Ab	13.6 Aa	2.6 Aa	1.2 Aa	434.9 Ca	17.8 Ba	24.4 Ba
	Dry	1.0 Ab	7.7 Aa	14.5 Aa	2.6 Aa	1.2 Aa	432.8 Ca	18.6 Ba	23.3 Ba
		Twigs (g kg^{-1}) - Contibuted in the collectors (*Litterfall*)							
Ang	Rainy	0.8 Aa	6.6 Ab	15.5 Aa	1.4 Ba	0.8 Aa	436.6 Ba	15.3 Aa	30.7 Ba
	Dry	0.5 Ab	4.8 Ba	18.6 Aa	1.3 Ba	0.8 Ba	434.3 Aa	16.7 Aa	26.5 Ca
Euc	Rainy	0.3 Ca	3.3 Ba	9.1 Ba	1.2 Ba	0.4 Ba	440.2 A a	3.9 Ca	112.6 Aa
	Dry	0.2 Ba	2.9 Ca	9.1 Ba	1.3 Ba	0.4 Ca	438.1 Aa	4.4 Ca	101.9 Ab
Nat	Rainy	0.6 Ba	5.7 Ab	15.4 Aa	2.6 Aa	0.9 Ab	422.4 Ba	12.6 Ba	38.2 Ba
	Dry	0.5 Ab	7.7 Aa	12.8 Ba	2.2 Ab	1.1 Aa	420.8 Ba	11.6 Ba	40.1 Ba
		Leaf (g kg^{-1}) – Remaining on the ground (*Litter*)							
Ang	Rainy	0.6 Aa	2.9 Ab	14.4 Ba	1.3 Ba	0.9 Ba	389.9 Bb	18.0 Ba	21.6 Ba
	Dry	0.5 Ba	4.7 Aa	15.8 Ba	1.6 Ba	0.86 Ba	420.9 Aa	17.8 Ba	23.6 Ba
Euc	Rainy	0.6 Aa	1.0 Ba	11.0 Ba	1.6 Ba	0.9 Ba	445.2 Aa	12.0 Ca	37.1 Ab
	Dry	0.6 Ba	1.7 Ca	10.4 Ba	1.5 Ba	0.6 Bb	442.9 Aa	9.9 Ca	44.7 Aa
Nat	Rainy	0.7 Aa	2.3 Ab	17.8 Aa	2.1 Aa	1.2 Aa	406.8 Bb	22.2 Aa	18.3 Ba
	Dry	0.7 Aa	3.2 Ba	21.9 Aa	2.2 Aa	1.3Aa	446.8 Aa	21.7 Aa	20.6 Ba
		Twigs (g kg^{-1}) - Remaining on the ground (*Litter*)							
Ang	Rainy	0.42 Aa	2.8 Ab	17.4 Aa	1.4 Ba	0.7 Aa	406.6 Bb	16.2 Aa	25.1 Ba
	Dry	0.49 Aa	4.1 Aa	22.4 Aa	1.6 Ba	0.7 Aa	431.3 Ba	17.9 Aa	24.1 Ba
Euc	Rainy	0.17 Ba	1.3 Ba	9.5 Ba	1.2 Ba	0.3 Ba	429.9 Aa	13.5 Aa	31.8 Ab
	Dry	0.16 Ba	1.4 Ba	12.4 Ba	1.2 Ba	0.3 Ba	422.6 Ba	6.0 Bb	70.4 Aa
Nat	Rainy	0.34 Ab	2.8 Ab	12.4 ABb	1.8 Aa	0.8 Aa	398.4 Bb	13.7 Aa	29.1 ABa
	Dry	0.50 Aa	3.7 Aa	18.5 ABa	2.1 Aa	0.9 Aa	461.6 Aa	12.8 ABa	36.1 Ba

Upper case letters in a column compare between the different types of forest cover for each of the seasons, while lowercase letters compare each type of cover between the dry and rainy seasons, and when similar indicate no significant differences by Tukey's test at 10%.

3.5. Contributed and remaining nutrient content of the leaf and twigs

The nutrient content of the leaf contributed in the collectors (litterfall) at the end of the dry and rainy seasons was higher in Nat (Table 3) for P, K, Ca, Mg, S and N, with the dry season being responsible for the greatest input of nutrients to soil. Ang and Euc showed no difference in nutrient content for most of the nutrients under study, with the exception of C, that presented a higher content in Euc. The highest C/N ratio for the leaf contributed to the soil was seen in Euc and the lowest in Ang. In relation to the nutrient content contributed to the soil by the twigs, Euc showed the highest values for Ca, Mg and N during the rainy season, and the highest C content irrespective of the time of year. The C/N ratio in the twigs did not vary for type of cover during the rainy season, however during the dry season, Euc showed the highest ratios.

The nutrient content of the leaf accumulated on the ground (litter) during the dry season was higher in Nat for all the studied nutrients. Euc and Nat showed no difference for nutrient content of the leaf during the rainy season; the highest C/N ratio in the leaf was seen in Euc (Table 3). In relation to the nutrient content of the twigs remaining on the ground, the types of forest cover did not differ for P or K irrespective of the time of year, nor did they differ for Ca during the rainy season. The twigs in Euc showed the highest C content. The C/N ratio of the twigs did not vary for type of forest cover during the rainy season, but during the dry season, Euc displayed the highest C/N ratios.

Table 3
Nutrient content (g kg^{-1}) of the leaf and twigs contributed in the collectors (litterfall) and accumulated on the ground (litter) in Angico (Ang), Eucalyptus (Euc) and native species (Nat) at the end of the rainy and dry seasons in an area of bauxite mining in the process of recovery, for 30 months of collection

Forest Cover	Season	P	K	Ca	Mg	S	C	N	C/N
Leaf (g kg^{-1}) – Contibuted in the collectors (*Litterfall)*									
Ang	Rainy	1.8 Ba	8.0 Ba	12.5 Ba	2.1 Ca	1.6 Bb	693.4 Ca	34.8 Ba	19.9 Ca
	Dry	1.3 Bb	8.4 Ba	17.0 Ba	2.0 Ba	1.9 Ba	724.8 Ba	37.1 Ba	20.5Ca
Euc	Rainy	2.0 Ba	12.2 Aa	22.9 ABa	4.6 Ba	1.7 Ba	1394.2 Aa	25.2 Ca	55.1 Aa
	Dry	1.5 Bb	11.1 Ba	23.4 Ba	3.1 Bb	1.6 Ca	1193.0 Ab	22.7 Ca	52.6 Ab
Nat	Rainy	2.6 Ab	15.3 Ab	31.6 Ab	6.0 Aa	2.9 Ab	1011.0 Bb	42.6 Ab	26.6 Ba
	Dry	3.0 Aa	24.4 Aa	45.4 Aa	5.0 Ab	3.6 Aa	1348.6 Aa	60.1 Aa	24.8 Ba
Twigs (g kg^{-1}) - Contibuted in the collectors (*Litterfall)*									
Ang	Rainy	0.2 ABa	1.4 Aa	8.6 Ba	0.7 Ba	0.4 Ba	204.0 Ba	8.2 Ba	29.6 Aa
	Dry	0.2 Aa	1.8 Aa	9.2 Aa	0.7 Ba	0.3 Ba	177.4 Ba	7.5 Aa	24.4 Ba
Euc	Rainy	0.3 Aa	2.0 Aa	16.1 Aa	1.9 Aa	0.5 Aa	707.6 Aa	21.9 Aa	32.4 Ab
	Dry	0.2 Ab	1.5 Ab	13.3 Aa	1.3 Ab	0.3 ABb	451.9 Ab	5.8 Ab	90.7 Aa
Nat	Rainy	0.2 Ba	1.6 Aa	7.6 Ba	1.0 Ba	0.4 ABa	219.5 Ba	7.4 Ba	29.6 Aa
	Dry	0.2 Aa	1.8 Aa	8.8 Aa	1.0 ABa	0.4 Aa	217.2 Ba	6.2 Aa	37.5 Ba
Leaf (g kg^{-1}) – Remaining on the ground (*Litter)*									
Ang	Rainy	0.7 Bb	3.1 Bb	16.2 Bb	1.8 Bb	1.2 Bb	548.6 Bb	28.8 Bb	19.1 Bb
	Dry	3.1 Ba	28.9 Ba	97.2 Ba	8.3 Ba	4.9 Ba	3532.5 Ba	106.6 Ba	24.2 Ba
Euc	Rainy	3.7 Aa	7.3 ABb	57.3 Aa	8.5 Aa	5.8 Aa	2995.6 Aa	91.3 Aa	33.1 Ab
	Dry	4.3 Ba	14.2 Ca	83.2 Ba	12.7 Ba	4.9 Ba	2582.6 Ba	80.2 Ba	45.2 Aa
Nat	Rainy	3.5 Ab	13.1 Ab	61.2 Ab	9.9 Ab	6.8 Ab	2273.8 Ab	121.9 Ab	18.6 Ba
	Dry	9.1 Aa	48.5 Aa	198.1 Aa	27.1 Aa	17.9 Aa	6000.4 Aa	292.9 Aa	20.6 Ba
Twigs (g kg^{-1}) – Remaining on the ground (*Litter)*									
Ang	Rainy	0.7 Aa	4.6 Ab	27.9 Aa	2.2 Ba	1.2 Ba	663.7 Ba	27.1 Ba	25.6 Aa
	Dry	1.1 Aa	8.8 Aa	50.6 Ba	3.3 Ba	1.5 Ba	955.7 Ba	39.5 Aa	24.4 Ba
Euc	Rainy	1.0 Aa	7.3 Aa	54.3 Ab	7.0 Aa	2.0 Aa	2543.0 Aa	80.4 Aa	32.4 Ab
	Dry	1.1 Aa	9.0 Aa	83.4 Aa	8.2 Aa	2.1 ABa	2721.8 Aa	39.4 Ab	90.7 Aa
Nat	Rainy	0.6 Ab	4.9 Ab	24.0 Ab	3.2 Bb	1.4 ABb	708.1 Bb	23.1 Ba	29.6 Aa
	Dry	1.5 Aa	10.9 Aa	53.8 ABa	6.2 Ba	2.7 Aa	1353.8 Ba	35.7 Aa	37.5 Ba

Upper case letters in a column compare between the different types of forest cover for each of the seasons, while lowercase letters compare each type of cover between the dry and rainy seasons, and when similar indicate no significant differences by Tukey's test at 10%.

4. Discussion

4.1. Litterfall production and litter accumulated under ground by the types of forest cover

Of the types of forest cover under study, Euc (8,324.30 kg ha^{-1} year^{-1}) and Nat (6,322.06 kg ha^{-1} year^{-1}) had the highest annual contributions of litterfall, contradicting the results found by some authors who report that plantations with greater species diversity, such as Nat, tend to present the greatest litterfall production (Gama-Rodrigues et al., 2007; Tang *et al.*, 2010; Wang *et al.*, 2007). The results obtained in Nat agree with those found by Miranda Neto *et al.* (2015), who studied litterfall production in a mining area in recovery in Minas Gerais, Brazil, with native forest species nine years of age, and found an annual litterfall production of 6772±1940 kg ha^{-1}. Other authors also found similar values for litterfall production in areas of tropical regions degraded by other activities and in recovery with forest species, such as Celestano *et al.* (2011) (6,290.0 kg ha^{-1}), Machado, Piña-Rodrigues and Pereira (2008) (5,810-8,980 kg ha^{-1}), and Moreira e Silva (2004) (6,636.0 kg ha^{-1}). Pinto *et al.* (2008) found an annual litterfall production of 6,310.0 and 8,810.0 kg ha^{-1} respectively in forests in the early stages of succession and in a mature forest. Gama-Rodrigues and Barros (2002) found a total of 9,400 kg ha^{-1} for a native forest in secondary regeneration.

Eucalyptus is a fast-growing species, and which probably provided the greatest contribution of organic material during the season under evaluation. As seen by Wang *et al.* (2007), the growth rate and productivity of forests influence the production of litterfall. Souza and Davide (2001), evaluating litterfall production in 12-year old *Eucalyptus saligna* in an area of bauxite mining in the Poços de Caldas region of Minas Gerais, found an annual production of 7,100 kg ha^{-1}, lower than that of the present study. Schumacher *et al.* (2013) found a production of 7,400 kg ha^{-1} in plantations of *Eucalyptus urophylla* x *Eucalyptus globulus maidenii* of between six and seven years of age in an unmined area, a similar amount (7,000,0 kg ha^{-1}) to that seen by Gama-Rodrigues and Barros (2002) in plantations of *Eucalyptus grandis* x *Eucalyptus urophylla*.

However, Angico is a species that has little foliar mass due to the reduced size of its folioles (Jaramillo-Botero *et al.*, 2008), which probably led to the smaller contribution of litterfall. Schumacher *et al.* (2011) found an average annual litterfall production of 1,000 kg ha^{-1} in *Parapiptadenia rigida*, another species of Angico in southern Brazil, far lower values than found in the present study (3,950 kg ha^{-1}).

Euc demonstrated the greatest litterfall contribution during the rainy season, a different pattern from the cover of native forest species used in this study (Figure 4). These results agree with those found by Souza and Davide (2001) for *Eucalyptus saligna* in a mined area in Poços de Caldas, Minas Gerais. Barlow *et al.* (2007) saw greater litterfall production during the rainy season for *Eucalyptus urophylla* in an unmined area, compared to native forests in the Amazon, as did Cunha, Gama-Rodrigues and Costa (2005) for *Eucalyptus grandis*. This is probably due to the greater availability of water, which leads to more vegetative growth, and consequently the discarding of old leaves and a larger contribution of plant material. This high litterfall production in eucalyptus is important in degraded areas, since rapid revegetation of the ground can prevent erosive processes and promote biogeochemical cycling.

During the dry season, Nat displayed the opposite behaviour to that seen in Euc, i.e. the greatest production of litterfall (Figure 4), which was also seen by

Miranda Neto *et al.* (2005) in an area of bauxite mining in the process of recovery with native Atlantic Forest species, and also in other studies of litterfall production in tropical forests in Brazil (Smith et al., 1998; Barlow *et al.*, 2007; Jaramillo-Botero *et al.*, 2008; Gomes *et al.*, 2010) and in other parts of the world (Tang *et al.*, 2010; Zhang *et al.*, 2014).

Precipitation and radiation are also limiting factors in regulating litterfall production in tropical regions. During the dry season, leaf abscission occurs as a mechanism of plant adaptation to water stress, increasing average litterfall production at this time of year (Jha and Mohapatra, 2010). Some authors report that litterfall production by forest species may be related to the perennial or deciduous behaviour of the trees, and not only to climate factors (Arato et al., 2003; Machado et al., 2008). In the mixed plantation of forest species (Nat), mixed deciduous and semi-deciduous species that lose their leaves during the dry season predominate, which may explain the greater production of litterfall/leaf litter during that season.

Eucalyptus (Euc) was the forest cover that most accumulated litter on the ground during the rainy season (12,545 kg ha^{-1}), since it also produced more litterfall at that time of year. Souza and Davide (2001) found an accumulation of around 63,320 kg ha^{-1} in plantations of *Eucalyptus saligna* in an area of bauxite mining, values much higher than those found in the present study, but in plantations 12 years of age. However, other authors, studying the litter accumulated on the ground in Eucalyptus plantations in an unmined area, found values close to the present study (13,500 kg ha^{-1}) (Gama-Rodrigues and Barros, 2002).

4.2. *Apparent rate of decomposition and seasonality*

With the exception of Euc, the types of forest cover under study displayed higher rates of decomposition during the rainy season (Figure 10). These results were also seen by Miranda Neto *et al.* (2015), in mining areas in recovery with native forest species in Minas Gerais. At this time of year, favourable conditions of temperature and humidity stimulate soil microbial activity and consequently, an increase in the rate of decomposition (Pandey *et al.*, 2007; Aponte et al., 2012).

The higher rate of decomposition of the leaf in Ang in relation to the other types of cover (Figure 6) may be related to the very small folioles, which facilitate the process of decomposition by soil microorganisms, especially during the rainy season when the microbial community tends to be larger and more active, with a consequent reduction in the litterfall remaining on the ground. Another factor may be related to the lower C/N ratio of the leaf litter in Ang in relation to the other types of cover, which may have contributed to an increase in the rate of decomposition.

Schumacher *et al.* (2013) found a rate of decomposition of 0.54 year^{-1} for *E. urophylla* x *E. globulus maidenii*, and Zaia and Gama-Rodrigues (2004) found rates of decomposition of 0.51, 0.59 and 1.0 year^{-1} for *E. pelita*, *E. camaldulensis* and *E. grandis* respectively in plantations six years of age. These values were higher than found for Euc in the present study (0.48 year^{-1}), but in an unmined area. Whereas Souza and Davide (2001) found a lower rate of decomposition (0.11 year^{-1}) than that of the present study for a eucalyptus plantation in an area of mining. The low N content in the leaf from Eucalyptus is perhaps the main factor that limits its decomposition, generating high values for the C/N ratios (55.3 and 52.6 in the rainy and dry seasons respectively, for the present study) (Gama –Rodrigues and Barros, 2002).

Despite the greater species diversity in Nat, no differences were seen in decomposition rate between this forest cover and Euc (Figure 6). The rate of decomposition is more influenced by the litterfall quality of the species used and to a lesser extent by the diversity of those species (Meier and Bowman, 2008; *tang et al.*, 2010; Cizungu *et al.*, 2014). The lignin content, and the C/N and C/P ratios in the plant tissue are strongly related to their recalcitrance and consequently, to higher or lower rates of decomposition (Barlow *et al.*, 2007; Cizungu *et al.*, 2014; Duarte *et al.*, 2013). Moreover, the process of decomposition can be influenced by the interactions of the physicochemical conditions of the environment, such as the composition of the decomposing community where the plantation is located (Gama-Rodrigues *et al.*, 2003; Yang *et al.*, 2014), and the soil structure, especially in mining areas where it is greatly modified (Miranda Neto *et al.*, 2015).

4.3. Nutrient input via the contributed and remaining leaf and twigs

Nat was the forest cover with the highest nutrient content in the leaf litterfall contributed to the soil for almost all the nutrients under study (Table 2), and was also the cover that provided the highest nutrient return to the soil via the leaf litter, compared to the other types of forest cover studied (Table 3). Differences in composition of the species making up Nat may have been responsible for the higher nutrient content of the leaf produced and contributed to the soil in comparison to the two studied monocrops, as also seen in other studies (Celentano *et al.*, 2011; Cizungu *et al.*, 2014). In general, Eucalyptus produces litterfall with lower nutrient concentrations due to its efficient biochemical cycling (Gama-Rodrigues and Barros, 2002). However, even if the contribution of nutrients to the soil by this species were lower, in soils of degraded areas the litterfall can constitute an important source of nutrients and protection to the soil surface. Values for nutrient return to the soil via leaf litter in Euc were much lower than found by Souza and Davide (2001) in an area with *Eucalyptus saligna* at 12 years of age in the process of recovery after bauxite mining in Poços de Caldas. Those authors found a return of 11 kg ha^{-1} P, 11.4 kg ha^{-1} K, 194 kg ha^{-1} Ca, and 25 kg ha^{-1} Mg. Gama-Rodrigues and Barros (2002) in plantations of *Eucalyptus grandis* x *Eucalyptus urophylla* at 16 years of age in an unmined area, found values for these nutrients closer to those of the present study.

Nutrient return to the soil via litterfall is the most important pathway of the biogeochemical cycle, becoming even more important in degraded soils of low fertility (Cunha et al., 2005; Pandey *et al*., 2007; Tang *et al*., 2010), such as mined soils.

5. Conclusions

The types of forest cover studied showed differences in annual litterfall production, with the mixed plantation of native species (Nat) and Eucalyptus (Euc) having the highest annual production in areas of bauxite mining in recovery.

The time of year provides variation in the rate of decomposition, with rainfall being responsible for the highest rates, especially in a monocrop of Angico.

Planting forest cover is important for the contribution of nutrients to the soil by litterfall, the mixed plantation (Nat) producing leaf of better nutritional status in relation to P, K, Ca, Mg and S, and contributing the most nutrients to the soil surface via the leaf litter.

Eucalyptus (Euc), Ang and Nat, presented good litterfall production, accumulated litter and nutrient return to the soil under the conditions studied, and are efficient in the recovery process of areas degraded by bauxite mining, since they presented values similar to unmined areas, whether of natural regeneration or planted.

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APPENDICES

Table A.1

Results of the analysis of variance (ANOVA) for the contribution of litterfall at the end of the dry and rainy seasons for Eucalyptus (Euc), Angico (Ang) and native species (Nat) submitted to standard fertiliser and supplemental fertiliser in an area of bauxite mining in the process of recovery, for 30 months of collection

SV	DF	SS	MS	F	p
Block	2	5151642	2575821	2.885	0.167631
Forest Cover (FC)	2	26930845	13465422	15.081	0.01371
Error A	4	3571490	892872		
Fertiliser (A)	1	1559221	1559221	1.520	0.263795^{ns}
A x FC	2	806949	403475	0.393	0.691087^{ns}
Error B	6	3212280	1026112		
Season	1	28435	28435	0.044	0.852791
Error (Season x Block)	2	1283728	641864		
Season x FC	2	3764746	1882373	12.125	0.002122
Season x A	1	61	61	0.000	0.984574^{ns}
Season x FC x A	2	692323	346161	2.230	0.158209^{ns}
Error B	10	1552461	155246		
Corrected total	35	48554181			

ns = not significant at 10% probability;

Table A.2

Results of the analysis of variance (ANOVA) for litterfall remaining on the ground at the end of the dry and rainy seasons for Eucalyptus (Euc), Angico (Ang) and native species (Nat) submitted to standard fertiliser and supplemental fertiliser in an area of bauxite mining in the process of recovery, for 30 months of collection

SV	DF	SS	MS	F	p
Block	2	37556578	18778289	1.553	0.316907
Forest Cover (FC)	2	410816073	205408037	16.985	0.011098
Error A	4	48374483	12093621		
Fertiliser (A)	1	16262	16262	0.002	0.966423^{ns}
A x FC	2	3729374	1864687	0.221	0.808116^{ns}
Error B	6	28152594	8445232		
Season	1	260213924	260213924	57.006	0.017094
Error (Season x Block)	2	9129421	4564711		
Season x FC	2	80314546	40157273	7.159	0.01176
Season x A	1	2090963	2090963	0.373	0.55513^{ns}
Season x FC x A	2	13256462	6628231	1.182	0.346216^{ns}
Error B	10	56095656	5609566		
Corrected total	35	949746337			

ns = not significant at 10% probability;

Table A.3

Results of the analysis of variance (ANOVA) for rate of litterfall decomposition at the end of the dry and rainy seasons for Eucalyptus (Euc), Angico (Ang) and native species (Nat) submitted to standard fertiliser and supplemental fertiliser in an area of bauxite mining in the process of recovery, for 30 months of collection

SV	DF	SS	MS	F	p
Block	2	0.000256	0.000128	0.003	0.996904
Forest Cover (FC)	2	0.199715	0.099858	2.422	0.204598
Error A	4	0.164945	0.041236		
Fertiliser (A)	1	0.028727	0.028727	0.630	0.45747^{ns}
A x FC	2	0.009342	0.004671	0.102	0.904133^{ns}
Error B	6	0.129388	0.045573		
Season	1	0.631574	0.631574	116.345	0.008486
Error (Season x Block)	2	0.010857	0.005428		
Season x FC	2	0.214035	0.107018	5.109	0.029606
Season x A	1	0.007141	0.007141	0.341	0.572249^{ns}
Season x FC x A	2	0.013949	0.006975	0.333	0.724464^{ns}
Error B	10	0.209483	0.020948		
Corrected total	35	1.619411			

ns = not significant at 10% probability.

Chapter 3

Autotrophic and heterotrophic contribution to soil gas flow in a mining area in recovery with different forest species

Resumo

Alterações nos teores da matéria orgânica do solo (MOS) e na atividade microbiológica são muito comuns em áreas mineradas, tendo influência significativa no fluxo de CO_2 do solo. A utilização de espécies arbóreas na recuperação destas áreas visa aumentar os estoques de C no solo, porém, a dinâmica do fluxo de CO_2 é pouco conhecida. Objetivou-se determinar o fluxo de CO_2 e CH_4 de solo minerado e revegetado com espécies arbóreas, a contribuição da respiração heterotrófica e autotrófica e a influência de variáveis bióticas e abióticas no fluxo de CO_2. O estudo foi realizado em uma área minerada de bauxita, revegetada com eucalipto (Euc) e angico (Ang) em monocultivo, um plantio misto de 16 espécies florestais nativas (Nat) e duas áreas referências, sendo uma minerada sem qualquer tipo de cobertura (Sem Cob) e outra não minerada com vegetação nativa de regeneração secundária (Mata). Nas três coberturas florestais implantadas, o fluxo de CO_2 e CH_4 do solo foi avaliado em presença e ausência de serapilheira. Os tratamentos foram dispostos em blocos casualizados com parcelas subdivididas e três repetições. O fluxo de CO_2 do solo foi avaliado bimestralmente entre setembro de 2014 e julho de 2015 e a temperatura e umidade do solo determinadas em todas as avaliações. O efluxo de CO_2 do solo aumentou com o aumento da cobertura vegetal por espécies florestais, sendo maior em área de vegetação natural (Mata) e menor nas áreas sem qualquer tipo de cobertura (Sem Cob), tanto nos meses de menor umidade do solo como nos de maior. Entre as espécies plantadas (eucalipto, angico e o plantio misto de espécies nativas), o efluxo de CO_2 não variou significativamente em cada período, porém constatou-se o aumento significativo nos meses de menor umidade do solo para os de maior. A respiração heterotrófica do solo foi a que mais contribuiu para o efluxo total de CO_2 do solo, no caso, associada à decomposição da serapilheira. Entre as variáveis abióticas, o aumento da umidade do solo foi o que mais influenciou no efluxo de CO_2, contribuindo para o seu aumento. O fluxo de CH_4 foi negativo em todas as coletas realizadas.

Summary

Changes in the levels of soil organic matter (SOM) and microbiological activity are very common in mining areas, and have a significant influence on soil CO_2 flux. The use of tree species in the recovery of these areas seeks to increase C stocks in the soil, but the dynamics of CO_2 flux is little known. The aims of this study were to determine the CO_2 and CH_4 flux in mined soil revegetated with tree species, the contribution of heterotrophic and autotrophic respiration, and the influence of biotic and abiotic variables on CO_2 flux. The study was carried out in an area of bauxite mining, revegetated with eucalyptus (Euc) and angico (Ang) grown in monoculture; in a mixed plantation of 16 native forest species (Nat); and in two reference areas, one mined with no ground cover (NCov), and the other unmined, of native vegetation in secondary regeneration (Woodland). In the three areas of forest cover, soil CO_2 and CH_4 flux was evaluated in the presence and absence of litter. The treatments were arranged in randomised blocks with subdivided plots and three replications. Soil CO_2 flux was evaluated every two months between September 2014 and July 2015, with soil temperature and moisture determined for all evaluations. Soil CO_2 efflux increased with increasing plant cover by forest species, being higher in the area of natural vegetation (Woodland) and lower in areas with no type of cover (NCov), in months of both the lowest and the highest soil moisture. There was no significant change in CO_2 efflux during each period among the planted species (eucalyptus, angico and a mixed plantation of native species), however a significant increase was found between the months with the lowest soil moisture and those with the highest. Heterotrophic soil respiration contributed the most to total soil CO_2 efflux, in this case associated with litter decomposition. Among the abiotic variables, increases in soil moisture had the most influence on CO_2 efflux, contributing to its increase. CH_4 flow was negative in all samples.

Highligths

- Flow of greenhouse gases in areas of Atlantic forest
- Partitioning of CO2 fluxes in areas of Atlantic forest in recovery after mining
- Heterotrophic soil respiration contributed the most to total soil CO_2 efflux
- In dry seasons, the CO2 flux of areas in recovery with forest species does not differ from non-mining area

1. Introduction

The increase in atmospheric CO_2 caused by the burning of fossil fuels and changes in land use has worried researchers due to its potential role in global warming (Köchy *et al.*, 2015; Shrestha & Lal, 2006). Terrestrial ecosystems play an important part in the regulation of C flux, and the soil is considered to be the largest C reservoir, containing about twice as much C as the atmosphere (Kuzyakov & Cheng, 2001) and three times as much as the vegetation (Granier *et al.*, 2000).

Mining is an anthropic activity that causes drastic disturbances in the soil, so the recovery of areas degraded by the activity plays an important role in C dynamics and soil conservation (Shrestha & Lal, 2006; Tripathi *et al.*, 2014). In the State of Minas Gerais in Brazil, a recent disaster in a mining area has reiterated the need for efficient recovery strategies that would minimise the environmental impact of mining (Massante, 2015; Oliveira *et al.*, 2017).

Soils drastically disturbed by mining activity suffer changes in plant cover, with large volumes of soil removed, turned, and stored for long periods, which can lead to an increase in CO_2 in the atmosphere (Lorenz & Lal, 2007; Shrestha & Lal, 2006). These changes affect the input of organic material, the levels of soil organic matter (SOM), nutrient availability, and the biomass and activity of the microbiological community, significantly influencing nutrient cycling and, as a consequence, soil CO_2 flux (Han *et al.*, 2014).

The recovery process for these soils aims at restoring the organic matter content and introducing plant cover that can provide good C assimilation through photosynthesis (Shrestha & Lal, 2006) and the efficient allocation of this C to the shoots and roots of the plants, which is of great importance in reactivating nutrient cycling, and in the renewal of the C stock in the soil. The measurement of soil CO_2 efflux has become an important tool in the investigation of SOM cycling (Kuzyakov & Cheng, 2001). However, the magnitude of the temporal variations and the factors that influence these processes of C loss due to the efflux of CO_2 from the soil are still not well understood, especially in the soils of mining areas in process of recovery.

In tropical regions, conditions of high temperature and humidity influence the productivity of ecosystems, favour the development of soil microorganisms, increase the rate of SOM decomposition and consequently increase total soil respiration (Peng *et al.*, 2009). Soil respiration is a combination of root respiration and mycorrhizal association (autotrophic respiration) and the respiration of microorganisms during the decomposition process of both soil organic matter and litter (heterotrophic respiration) (Fontaine *et al.*, 2003; Hanson *et al.*, 2000; Millard *et al.*, 2010). Knowledge of the origin of this CO_2 can help in understanding the C cycle in mining areas in the process of recovery.

Soil temperature and moisture are cited in the literature as the main factors controlling the process of soil CO_2 efflux (Davidson *et al.*, 2000; Han *et al.*, 2007; Wang *et al.*, 2008; Wu *et al.*, 2010). Besides these factors, the chemical and physical characteristics of the soil can affect the efflux of CO_2.

The levels of total soil organic C (TOC) affect soil CO_2 flux, as it is a substrate for the development of microorganisms, just as the density and porosity of the soil can affect root growth and CO_2 diffusion to the soil surface. Plant cover is another factor that can influence the soil CO_2 efflux, as it controls the microclimate of the soil, the amount and quality of the input residue and consequently the activity of soil microorganisms and the rate of root respiration (Han *et al.*, 2014; Raich & Tufekciogul, 2000).

Strategies for the recovery of degraded areas that aim to increase CO_2 sequestration from the atmosphere can be achieved through the implantation of forest cover that would promote a greater assimilation of C-CO_2 in its biomass and the formation of SOM that is more stable and resistant to microbial decomposition (Shrestha & Lal, 2006). The study of CO_2 flux under field conditions can generate important information about changes in land use and management, however there is a large gap in such studies for forest ecosystems in tropical regions (Wei *et al.*, 2010), especially in mining areas in the process of recovery. This study therefore aimed to determine (i) the CO_2 flux during the dry and rainy months in an area of bauxite mining revegetated with forest species, (ii) the contribution of heterotrophic and autotrophic respiration in relation to total soil respiration, and (iii) the influence of biotic and abiotic variables on soil CO_2 flux.

2. Material and Methods

2.1. Characterisation of the study area and experimental design

The study was carried out under field conditions on a property located in the town of São Sebastião da Vargem Alegre, in the Forest Zone (*Zona da Mata*) of the State of Minas Gerais in Brazil (21°1'58" S and 42°35'8" W), at an altitude of 780 m, in an area of bauxite extraction by The Brazilian Aluminium Company - Votorantim Metais. Following mining activities, the surface layer (0-20 cm), stored for approximately one year, was returned to the original area during the process of topographic reconfiguration. Shortly after, the terrain was decompacted using a subsoiler at a depth of 60 cm. The predominant soils in the region are typic dystrophic Red-Yellow Latosols.

According to the Köppen classification, the climate in the region is of type Cwa, with hot and rainy summers and a well-defined dry season, and average annual precipitation and temperatures of 1,287 mm and 20.3ºC respectively (INMET, 2016). Climate data for precipitation and maximum, average and minimum temperatures were obtained from a meteorological station installed in the experimental area (Figure 1).

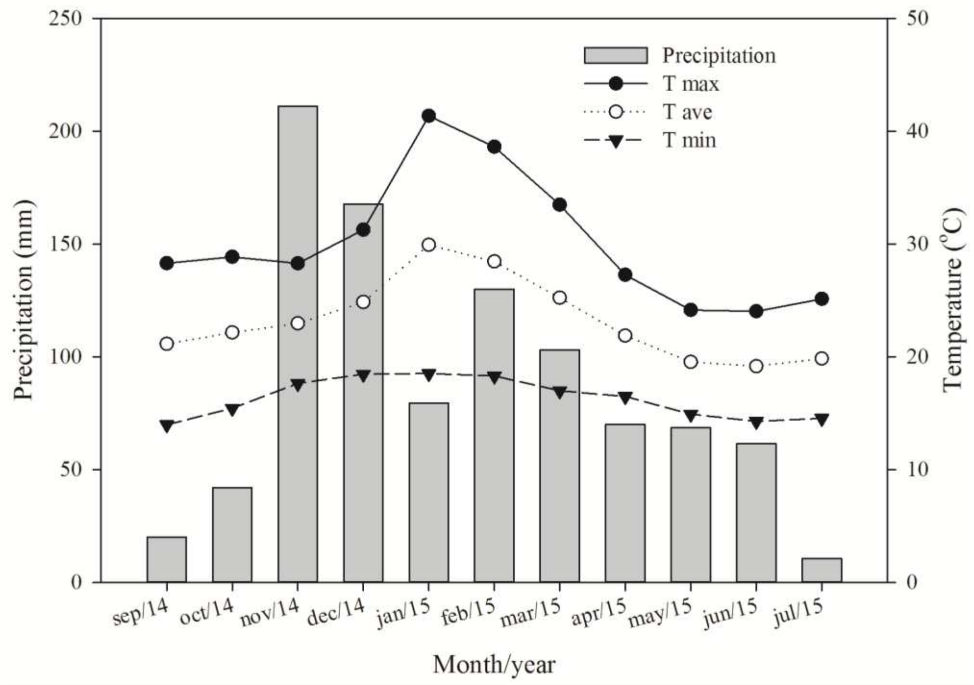


Figure 1 - Monthly precipitation, and average (T ave), maximum (T max) and minimum (T min) temperatures in an experimental area with different forest cover, and in recovery after bauxite mining, São Sebastião da Vargem Alegre, Minas Gerais**.**

The area was mined for bauxite in 2009 and reconfigured in 2010. The experiment was set up in the area in March 2011, using a randomised block design with subdivided plots and three replications. The plots, 40 x 18 m in size, comprised the following forest cover: clonal eucalyptus (a hybrid from a cross between *Eucalyptus urophylla* and *Eucalyptus grandis* - clone AEC144®) (Euc); Red Angico (*Anadenanthera peregrina* (L.) Speg) (Ang); and a mixed plantation (Nat) consisting of 16 native forest species from the region, Red Angico (*Anadenanthera peregrina* (L.) Speg) - A2, The fig (*Ficus insipida* Willd) - F, *Inga edulis* Mart. - I1, *Piptadenia gonoacantha* (Mart.) JF Macbr.) - J1, *Enterolobium contortisiliquum* (Vell.) Morong.) - O, Silk Floss (*Ceiba speciosa* (A. St.-Hil.) Ravenna) PA1, Soapberrya (Sapindus saponaria L.) – S, and *Pera glabrata* (Schott) Poepp. Ex Baill. - C2; forest species considered as pioneers, and the non-pioneer species *Trichilia* sp - C3, *Cupania oblongifolia* Mart. - C1, *Apuleia leiocarpa* (Vogel) JF Macbr. - G, Golden Trumpet (Handroanthus chrysotrichus (Mart. Ex A. DC.) Mattos) – I2, *Hymenaea courbaril* var. *stilbocarpa* (Hayne) YT Lee & Langenh – J3, *Lecythis sp* – J2, Brazilwood (*Paubrasilia echinata* Lam.) - PA2, and *Annona squamosa* L. – A1. These native species were planted in Quincunx (4 pioneers, with one climax in the centre) at a spacing of 2 x 1,5 m, using seedlings produced from seeds collected in fragments of Atlantic Forest in the second stage of regeneration (Woodland) in the study region. For the eucalyptus and angico, the adopted spacing was 3 x 2 m.

The subplots (10 x 18 m) included the standard fertilisation used by the company (SF) in their recovery activities of the mined areas, with the study propositions, which considered SF, but supplemented with organic fertilisation (OF), chemical fertilisation (CF), and a combination of OF+CF. Six months before planting the trees, SF was applied over the whole area, composed of 2.0 t ha^{-1} dolomitic limestone and 30.0 t ha^{-1} poultry litter (*in natura*, with an average of 30% moisture); the OF was composed of SF and 30 t ha^{-1} poultry litter, and the CF included the application of a further 3 t ha^{-1} dolomitic limestone and 0.75 t ha^{-1} Bayóvar natural reactive phosphate for Euc and Ang, and 1.5 t ha^{-1} for Nat. The two supplementary applications (OF and CF) included a combination of OF+CF. Part of the poultry litter and limestone doses was applied to the planting hole and part between the rows, incorporated into the 0-15 cm layer 30 days before planting, in order for all the plants to receive the same dose of fertiliser. The treatments with Euc and Ang received 22% of the dose of poultry litter in the planting hole and 78% between the rows, while the treatment with Nat received 44% in the planting hole and 56% between the rows. Similarly, application of the limestone was carried out so that 25% of the total dosage was applied to the holes and 75% between the rows for Euc and Ang; for Nat, 50% was applied to the planting hole and the remainder (50%) between the rows. The reactive natural phosphate was applied to the bottom of the planting holes.

In addition to the fertilisation carried out when planting, the areas also received two doses of top-dressing, the first, one month after setting up the experiment, consisting of 10 kg ha^{-1} N, 22 kg ha^{-1} P, and 8 kg ha^{-1} K when planting the eucalyptus and angico, and 20 kg ha^{-1} N, 44 kg ha^{-1} P and 16 kg ha^{-1} K when planting the multiple native trees, enriched with micronutrients (1.7 kg ha-1 B, 0.8 kg ha^{-1} Zn, 0.8 kg ha^{-1} Cu) for the eucalyptus and angico and double this dose for the multiple plantation, placed (in small holes) 20 cm to the side of the plants. The second fertilisation was carried out 10 months after starting the treatments, applying 67 kg ha^{-1} N, 17 kg ha^{-1} P, and 67 kg ha^{-1} K to the eucalyptus and angico, and 134 kg ha^{-1} N, 34 kg ha^{-1} P, and 134 kg ha^{-1} K to the multiple native-tree plantation, in grooves 5 cm deep, in the upper part of the canopy projection area. It should be noted that only treatments with CF and OF+CF received the top-dressing, since this was carried out using chemical fertiliser only.

In the present study, only those subplots consisting of SF and OF+CF were selected.

The main chemical, biological and physical characteristics of the soil at the end of the evaluation period are shown in Table 1.

Table 1 - Physical, chemical and biological properties of the soil in an area of bauxite mining in process of recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), native forest in the second stage of regeneration (Woodland), and an area with no ground cover (NCov). Mean values are followed by the standard deviation (n = 6)

Ground cover	Soil layer (cm)	TC^1	TN^1	LC^3	C-MB^4	N-MB^3	Ds^5	Dp^6	Pr^7	DRsm^8 < 2mm	DRgr^8 > 2mm
		dag kg^{-1}	dag kg^{-1}	g kg^{-1}	µg g^{-1}	µg g^{-1}	g cm^{-3}	g cm^{-3}	m^3 m^{-3}	g m^{-3}	g m^{-3}
NCov	0-10	1.44±0.05	0.11±0.00	1.16±0.17	62.16±1.75	18.20±3.17	1.13±0.19	2.73±0.03	0.59±0.07	-	-
	10-20	1.25±0.14	0.09±0.02	0.78±0.26	-	-					
Euc	0-10	2.37±0.32	0.17±0.04	1.75±0.64	174.69±46.63	25.84±14.18	1.32±0.14	2.70±0.09	0.51±0.04	266.68±89.2	253.6±107.1
	10-20	2.24±0.23	0.15±0.03	1.42±0.29	-	-					
Ang	0-10	2.45±0.61	0.18±0.05	2.08±0.56	153.33±59.62	28.58±8.81	1.26±0.10	2.68±0.05	0.53±0.03	437.46±11.2	236.2±49.7
	10-20	1.94±0.38	0.13±0.03	1.47±0.39	-	-					
Nat	0-10	2.10±0.31	0.14±0.02	1.82±0.24	157.98±55.08	23.70±12.32	1.21±0.10	2.70±0.04	0.55±0.04	939.36±275.1	741.9±248.
	10-20	2.04±0.22	0.13±0.02	1.49±0.26	-	-					
Woodland	0-10	5.03±0.51	0.36±0.04	4.54±0.20	705.77±28.26	68.65±6.82	0.97±0.09	2.54±0.03	0.62±0.04	2061.41±739.4	1543.7±375.6
	10-20	4.23±1.20	0.28±0.07	2.58±0.14	-	-					

(1)TOC = total organic carbon (Yeomans & Bremer, 1988); (2)TN = total nitrogen (Tedesco *et al.*, 1995); (3) LC = labile C, determined by oxidation with KMnO4 0.33 mol L^{-1} (Blair *et al.*, 1995) modified by Weil *et al.*, 2003); (4) CMB and NMB = C and N of the microbial biomass, determined by the irradiation-extraction method (Islam & Weil, 1998); (5)Ds = bulk density, determined by the volumetric ring method; (6) Dp = particle density, determined by the volumetric balloon method, (7) Pr = total porosity estimated by the formula: 1 - (Ds/Dp), as per EMBRAPA (2011); (8) DRsm and DRgr = root density smaller and greater than 2 mm in the 0-20 layer respectively, determined by the ratio of root dry mass to soil volume.

2.2.Evaluation of soil CO_2 and CH_4 flux

To evaluate soil CO_2 flux, chloro-polyvinyl (PVC) chambers were installed, 0.20 m in height by 0.30 m in diameter, with fixed bases and movable lids equipped with rubber septa on the top to enable gas collection. These chambers were installed in triplicate 42 months after planting the eucalyptus, angico and native trees, as well as in unmined areas of native forest in the secondary stage of regeneration (Woodland), and a mining area with no forest cover (NCov). In the areas of eucalyptus, angico and native trees, the chambers were installed beneath and outside the litter collectors, i.e. with and without the input of litter from the aerial part of the trees to the soil, both in and between the planting rows.

The emitted gases were collected by means of 60 mL syringes equipped with three-channel valves 0, 10, 20 and 40 minutes after closing the chambers, using two syringes each time. The emitted CO_2 was analysed in the same syringe used for collection at the Stable Isotope Laboratory of the Department of Soils of the Federal University of Viçosa, for reading and quantification in a cavity resonance spectrometer (CRDS - cavity ring-down spectroscopy, G2131-i, Picarro, Sunnyvale, CA). Collections were made every two months between September 2014 and July 2015.

The CO_2 and CH_4 flux was calculated as per the equation: $\text{Flux} = (\Delta Q/\Delta T) \times M \times (PV/TR) \times 1/A$, where Flux: CO_2 or CH_4 flux (mg m^{-2} h^{-1}); $\Delta Q/\Delta t$: the angular coefficient of the adjusted straight line (ppm/s) obtained by readjustment of the gas concentrations during the time (t) of collection; M: the molar mass of CO_2 or CH_4 (g mol^{-1}); P: internal pressure of the chamber, assumed to be 1 atmosphere (atm); V: volume of the chamber (L); R: universal gas constant (0.08205 L atm K^{-1} mol^{-1}); T: soil temperature (K); A: base area of the chamber (m^2).

The soil temperature was determined by means of a digital thermometer inserted at a depth of 5 cm, and the moisture by the gravimetric method, after drying in an oven at 105°C to constant weight. These determinations were made for each gas collection.

2.3.Soil CO_2 flux partitioning

CO_2 flux partitioning into autotrophic respiration (AR) and heterotrophic respiration (HR) was carried out in Euc, Ang and Nat. Total soil respiration (TR) was considered as the weighted mean values of the CO_2 flux obtained in and between the planting rows with the presence of litter ($TR_{withlitter}$). The differences between the CO_2 flux obtained in the treatments with no litter ($TR_{nolitter}$) and the area with no ground cover (TR_{NCov}), i.e. with no plants, was considered autotrophic respiration (AR). The HR was obtained from the difference between the total respiration (TR) and the autotrophic respiration (AR).

The relative contribution of soil microbiota respiration (HR) under the influence of litter and on SOM, to heterotrophic respiration through partitioning was determined. To do this, heterotrophic respiration (HR) was partitioned into HR from litter (HR_{litter}) and HR from SOM (HR_{SOM}). The HR under the influence of litter (HR_{litter}) was obtained by the difference in total respiration of the treatments with the contribution of litter ($TR_{withlitter}$) and with no litter ($TR_{nolitter}$). The contribution of SOM to HR was obtained from the difference between the HR and the contribution of litter respiration (HRlitter).

There follows a summary of the equations used in the CO_2 flux partitioning: $TR = AR+HR$; $AR = TR_{nolitter} - TR_{Ncover}$; $HR = TR-AR$; $HR = HR_{litter} + HR_{SOM}$; $HR_{litter} = TR_{withlitter} - TR_{nolitter}$; $HR_{SOM} = HR_{total} - HR_{litter}$.

2.4. Statistical analysis

The data for CO_2 and CH_4 flux during the period of evaluation were submitted to analysis of variance (ANOVA) and the mean values compared by Tukey's test at a significance level of 10%, using the Statistica 7.0 software. The influence of biotic and abiotic variables on the CO_2 flux was evaluated by means of multivariate regression analysis, with the CO_2 flux considered a dependent variable and the physical, chemical and biological characteristics of the soil considered independent variables. For this analysis, the R software was used (R Development Core Team, 2014).

3. Results

3.1. Variations in soil temperature and moisture

In general, the effects of the interaction between the types of fertilisation (SF and OF+CF) and the forest cover (Euc, Ang and Nat) were not significant ($p > 0.1$) for the gas fluxes under study. This situation led to the use of mean values obtained with these treatments, thereby allowing inclusion of the area with no cover (NCov) and of Woodland in the set of treatments as sources of variation in the statistical analysis.

The soil presented the highest moisture content during November 2014, and March and May 2015 for most of the types of cover under study, while the highest soil temperatures occurred in September 2014, and January and March 2015 (Figure 2), all at a depth of 0-5 cm. Among the types of ground cover under study, Woodland showed the greatest moisture and NCov the highest soil temperature for most of the months studied.

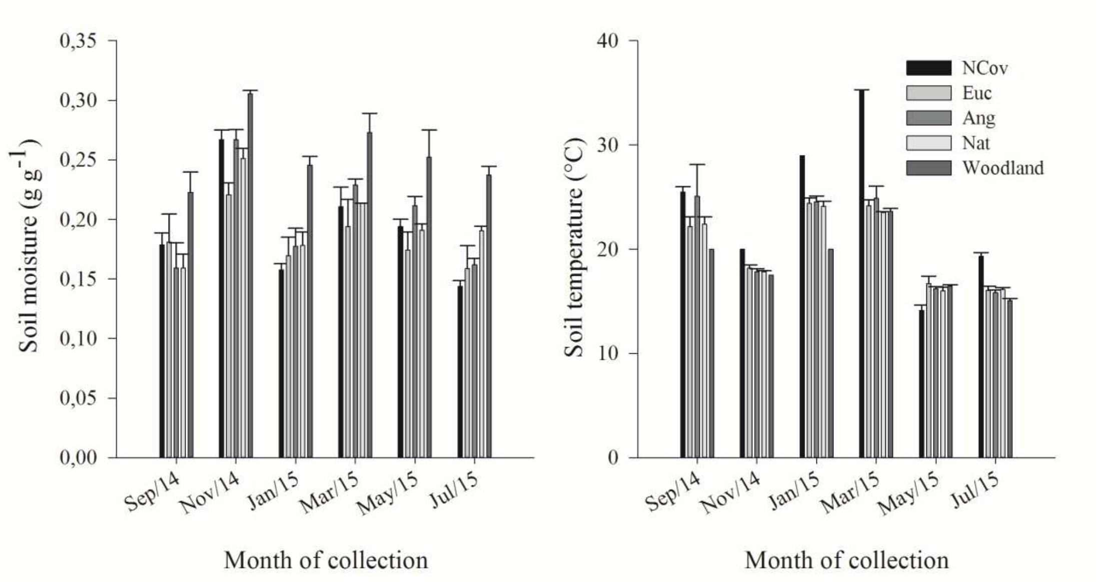
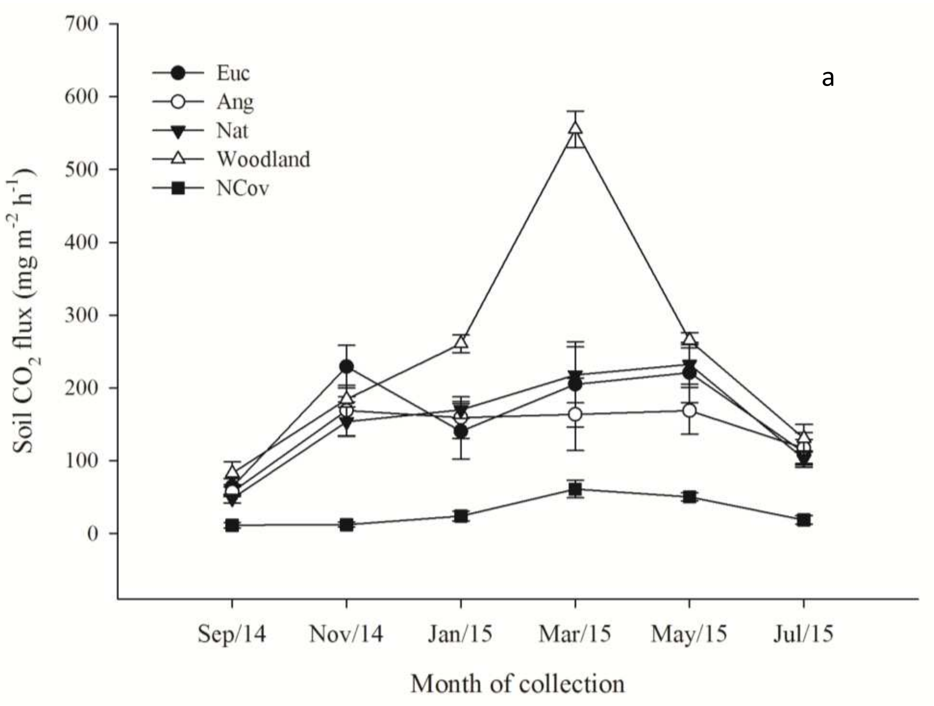


Figure 2 - Variations in soil moisture (a) and temperature (b) in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), native forest in the second stage of regeneration (Woodland), and an area with no ground cover (NCov). (Bars indicate the standard error around the mean, n=6).

3.2. Soil CO_2 flux

In general, the five types of ground cover under study showed differences in relation to CO_2 flux ($p < 0.1$) (Figure 3). The area of NCov showed the lowest values for CO_2 efflux in all collections. In contrast, Woodland presented the greatest values for CO_2 efflux during January and March 2015, differing from the other treatments with Euc, Ang and Nat, which presented the same values for CO_2 efflux for most of the months under study. It was found that Euc and Nat had a similar efflux pattern, with a tendency for greater CO_2 efflux during November, March and May. CO_2 efflux from the soil in Ang was more uniform over time. The process of recovery of the CO_2 flux in the areas planted with Euc, Ang and Nat showed high percentage values in relation to Woodland for all collections, except in May 2015, when the CO_2 efflux for the three types of cover under study presented the lowest percentages, less than 33% in relation to Woodland (Figure 3a). The month with the greatest approximation of the values for CO_2 efflux under forest cover in relation to Woodland was November 2014, when the percentages exceeded 90%.



b

Situation	Relative proportions (%) of CO_2 efflux					
	Month of collection					
	Sep/14	Nov/14	Jan/15	Mar/15	May/15	Jul/15
Euc	76,08 Ab	125,98 Aa	49,16 Ac	29,51 Ac	79,93 ABb	82,73 Ab
Ang	64,12 ABbc	91,07 ABa	57,13 Ac	21,22 Ad	56,45 Bc	87,98 Aab
Nat	51,34 Bbc	91,07 ABa	61,59 Aab	32,13 Ac	85,02 Aa	74,78 Aab

Figure 3 - (a) Variation in soil CO_2 efflux in an area of bauxite mining in process of recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), forest in secondary stage regeneration (Woodland), and an area with no ground cover (NCov) during the six months of collection. (Bars indicate the standard error around the mean, n = 6). (b) Relative proportions (%) of CO_2 efflux = (CO_2 efflux with forest cover - CO_2 efflux NCov)/(CO_2 efflux Woodland - CO_2 efflux NCov)*100.

3.2.Temporal variation in CO_2 flux

The highest values for CO_2 efflux were recorded in the months of greater soil moisture (Figure 4), i.e. November 2014, and March and May 2015. During these months, Woodland had the highest values for efflux and NCov had the lowest. Despite Euc showing a tendency towards greater CO_2 efflux during the months of higher soil moisture when compared to Ang and Nat, there were no significant differences between the three types of cover. In the driest months (September 2014, January and July 2015) Woodland, Euc, Ang and Nat showed no differences for CO_2 efflux, differing only in relation to NCov.

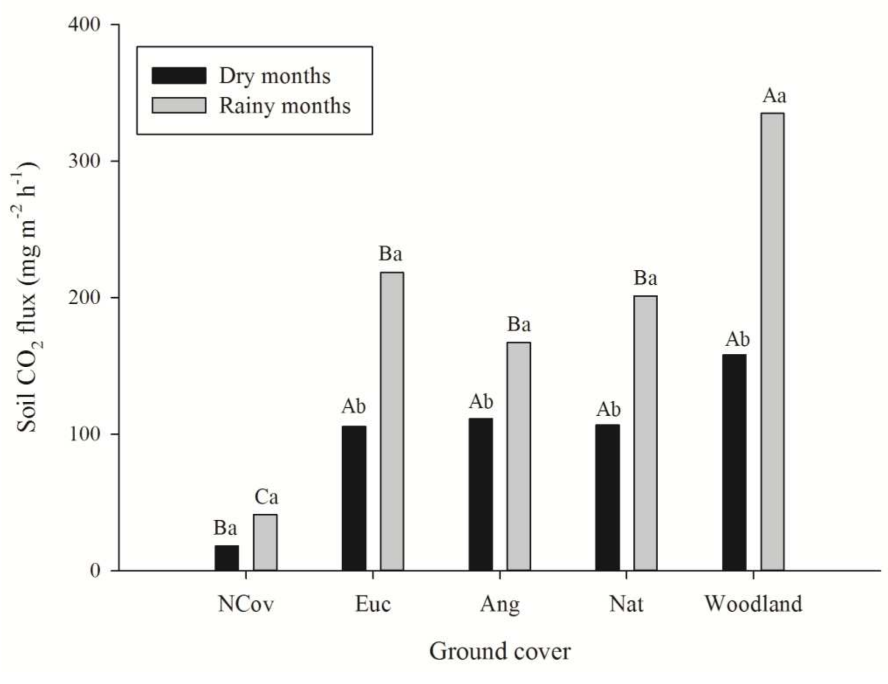


Figure 4 - Soil CO_2 efflux in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), forest in secondary stage regeneration (Woodland), and an area with no ground cover (NCov) during the wet and dry months. Uppercase letters compare between soil CO_2 efflux for the different types of forest cover for each month, while lowercase letters

compare each type of cover between the dry and rainy months, and when similar, indicate the lack of significant difference between them by Tukey's test at 10% probability.

In the drier months (September 2014, January and July 2015), all ground cover showed similar soil moisture, except Woodland, which had the greatest moisture among the types of cover under study. In the months of most rain (November 2014, March and May 2015), the lowest soil moisture was seen for Euc and the highest for Woodland. Soil temperature was similar for Euc, Ang and Nat in the months of lowest soil moisture, the lowest and the highest soil temperature being seen for Woodland and NCov respectively. In the rainiest months, the highest soil temperature was seen for NCov.

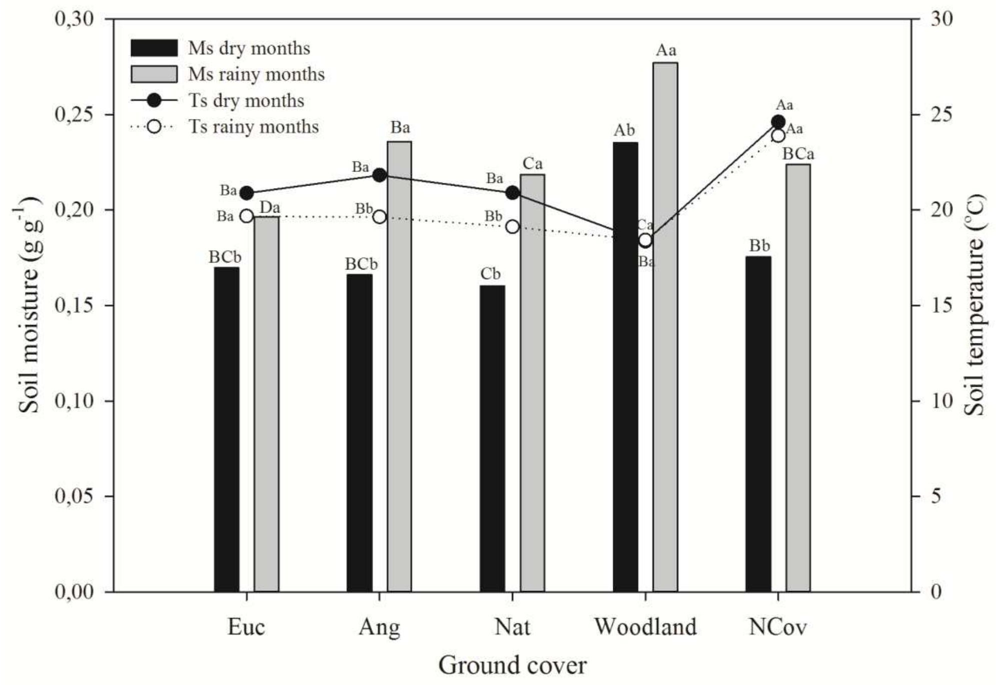


Figure 5 – Variation in soil Moisture (Ms) and soil temperature (Ts) in the driest and wettest months, during the evaluation of soil CO_2 efflux in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), forest in secondary stage regeneration (Woodland), and an area with no ground cover (NCov). Uppercase letters above the columns or above the lines compare soil moisture or soil temperature respectively for the different types of forest cover for each month, while lowercase letters compare each type of cover between the dry and rainy months, and when similar, indicate the absence of significant difference between them by Tukey's test at 10% probability.

3.4.Soil CO_2 flux partitioning

Analysing the results of partitioning total soil respiration (TR) into autotrophic (AR) and heterotrophic (HR) respiration (Figure 6), significant differences were seen in the contributions of AR and HR to soil TR over the months of the study ($p < 0.1$), with HR having the greatest contribution. These differences can be seen in November 2014, and March and May of 2015, when HR contributed more to TR than did AR. In September 2014, and January and July 2015, there was no difference between the contributions of AR and HR to soil TR. AR and HR did not differ in the areas of Euc, Ang or Nat.

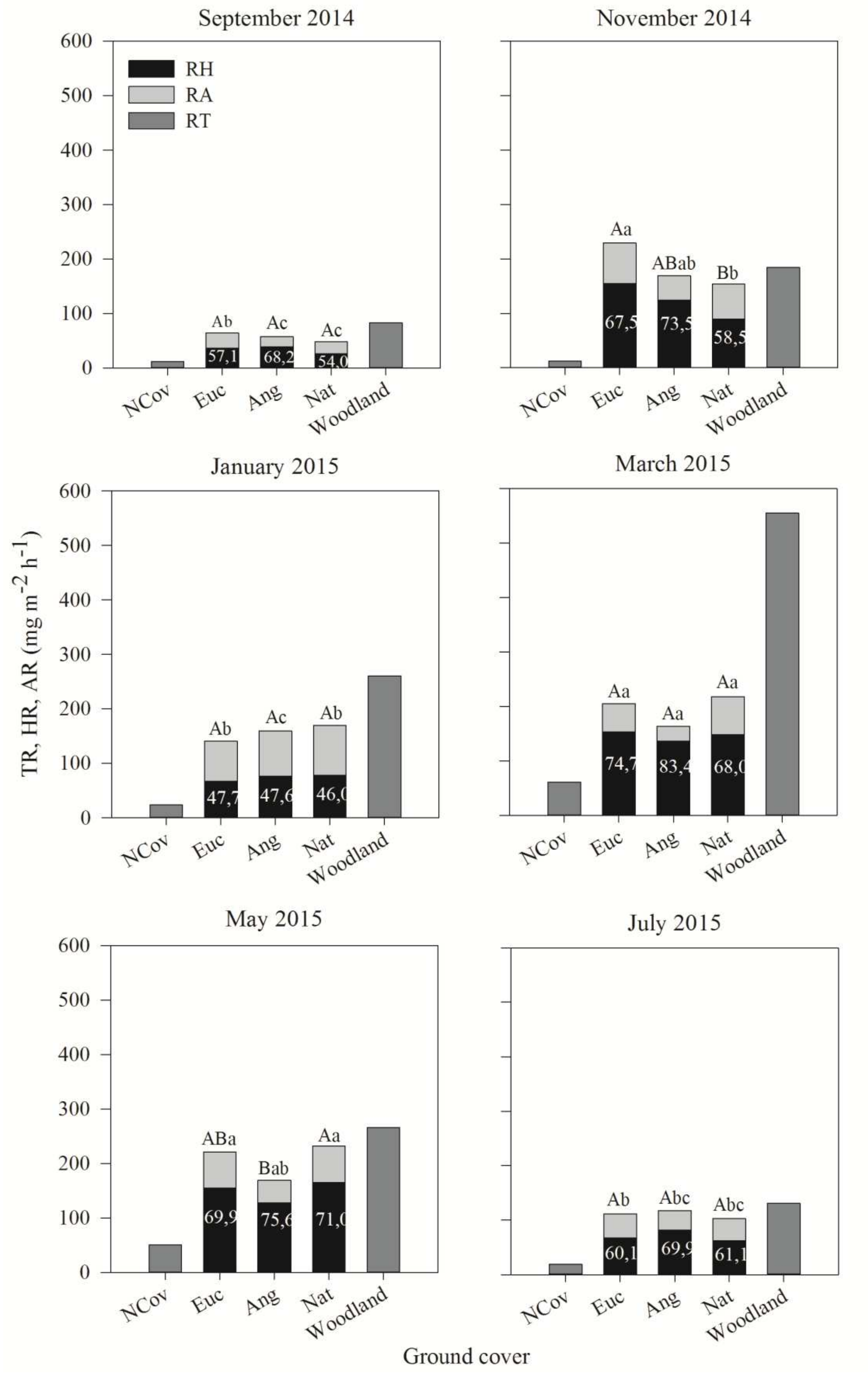


Figure 6 - Total (TR), autotrophic (RA) and heterotrophic (RH) soil respiration in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), forest in secondary stage regeneration (Woodland), and an area with no ground cover (NCov) for the six evaluations.

Values within the columns represent percentage HR in relation to TR. Uppercase letters compare between the HR of the different types of forest cover for each month, while lowercase letters compare each type of cover over the months, and when similar, indicate the lack of significant difference between them by Tukey's test at 10% probability.

Grouping the values for AR and HR during the months of greatest and least soil moisture, i.e. in the months of the greatest and least precipitation, for the moments prior to gas collection it was seen that during the drier months there was no difference between the contributions of AR and HR to TR, with HR accounting for around 55% of TR; whereas, during the wettest months, HR contributed more to TR (71%). The forest plantations did not differ during the dry months, and during the rainy months differences were only seen between Ang and Nat for AR.

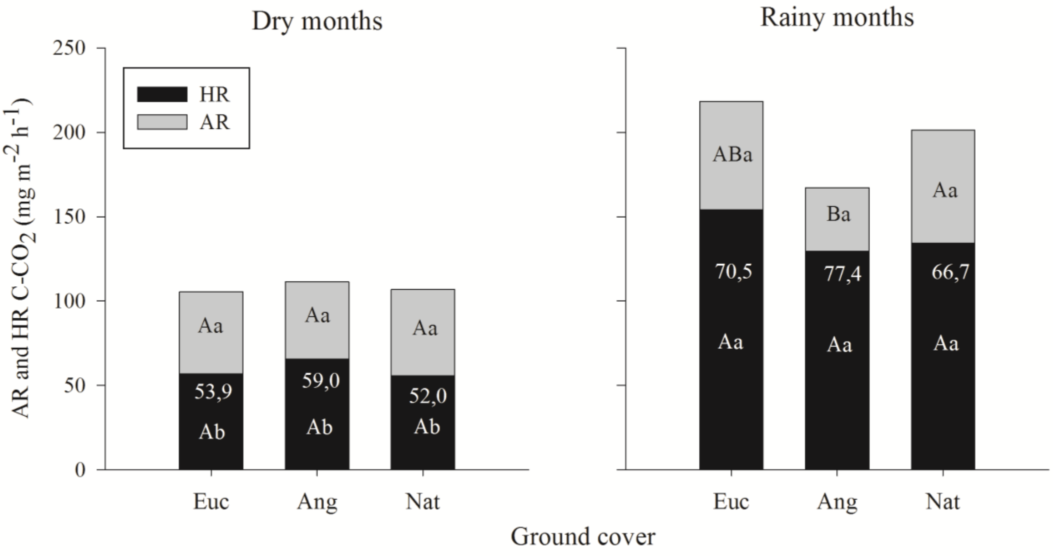


Figure 7 - Partitioning of total soil respiration (TR) into autotrophic (AR) and heterotrophic (HR) respiration in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat),

during the dry and rainy months. Capital letters compare HR and AR in the different types of forest cover for each month, while the lowercase letters compare each type of cover between the dry and rainy months, and when similar, indicate the lack of significant difference between them by Tukey's test at 10 % probability.

3.5. Contribution of litter to heterotrophic soil respiration

The contribution of the soil and litter to soil HR throughout the period under study can be seen in Figure 8. It should be noted that the litter contributed significantly more than the soil to HR for the types of ground cover studied ($p < 0.1$). The greatest contribution to HR by the litter was seen in November 2014 for the three types of forest cover under study. Between the types of forest cover, Euc, Ang and Nat, it could be seen that the contribution of litter to HR does not differ between species in most of the months being studied, except for November 2015, when Euc was superior to Nat.

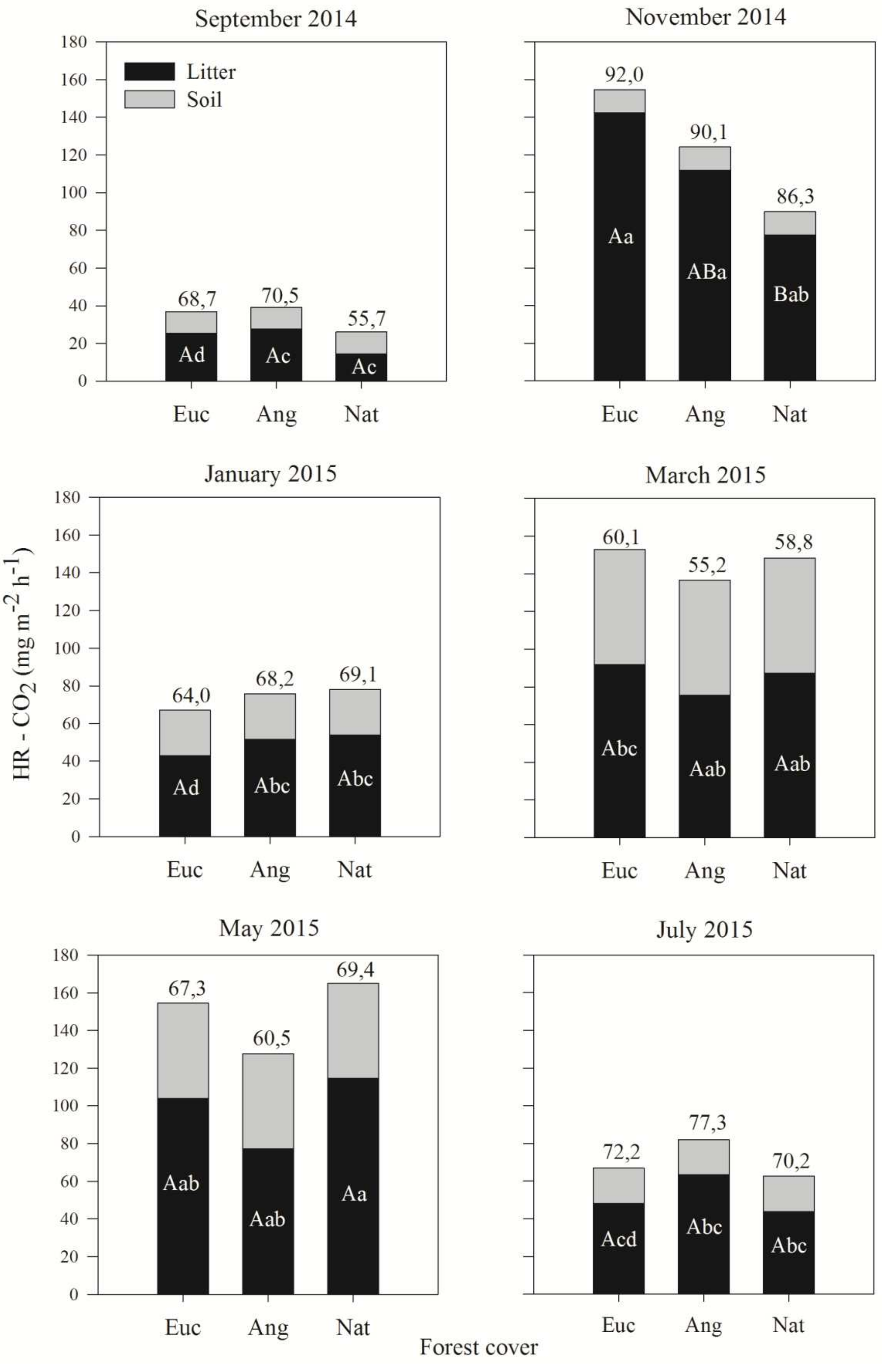


Figure 8 – The contribution of litter and soil to heterotrophic soil respiration in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), during the six months of collection. Mean values above the bars represent the percentage of litter contribution to soil HR. Uppercase

letters compare the contribution of litter between the different types of forest cover during each month, while lowercase letters compare each type of cover over the months, and when similar, indicate the lack of significant differences between them by Tukey's test at 10 % probability.

3.6.Principal component analysis

A multivariate model with two principal components (PC) explained 70.7% of the information contained in the data set: PC1 (60.3%) and PC2 (10.1%). The variables TC, CMB and LC together contributed 43.4% to the model, TN and NMB contributed 25.9%, and DRsm and DRgr contributed 19.7%. Figure 9a shows how the variables were distributed in the multivariate space defined by scatter plot PC2 as a function of PC1. It can be seen that the variables TC, C-MB, LC, TN and N-MB are closer together, reflecting the greater association between the forms of C and N studied in this work. DRsm and DRgr, near to each other, are closer to the above-mentioned variables of C and N compared to the other variables, namely, TR, Ms and Ts, the last with a very small contribution to the model, being more distant from all the other variables studied, especially TR, showing it has little influence on soil CO_2 efflux (TR) under the conditions of this study. Principal component analysis with the results of all the variables split the treatments into three groups, in which NCov and Woodland were at the two extremes of the scatter plot and the others allocated between them (Figure 9). In general, CO_2 efflux (TR) was positively correlated with soil moisture (Ms) and the levels of total C (TC), total N (TN) and C of the microbial biomass (C-MB), with Ms being in closer proximity to TR.

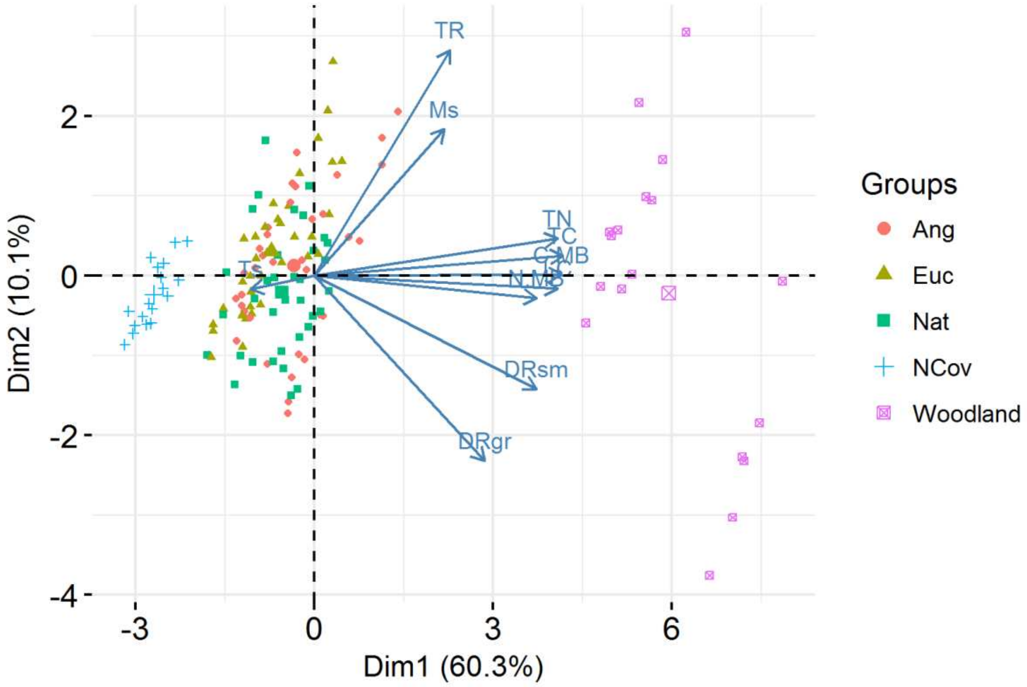


Figure 9 - Dispersion of the properties of the soil and of the areas of eucalyptus (Euc), angico (Ang) and the mixed planting of native species (Nat) in an area of bauxite mining in recovery, forest in secondary stage regeneration (Woodland) and an area with no ground cover (NCov) (a) into principal components 1 and 2 (Dim1 and Dim2). TR = total soil respiration; Ms = soil moisture; Ts = soil temperature; DRsm and DRgr = root density smaller and greater than 2 mm in the 0-20 layer respectively; TC0-10, TN0-10 and LC0-10 = total organic C, total N, and labile C in the 0-10 cm layer respectively; C-MB and N-MB = microbial biomass C and N respectively.

3.7.Methane flux

In general, with each gas collection it was seen that the soil of the types of forest cover under study behaved as a methane sink, with all the flux negative. Woodland presented the highest values for methane influx in four of the six collections, with the greatest influx seen in March 2015.

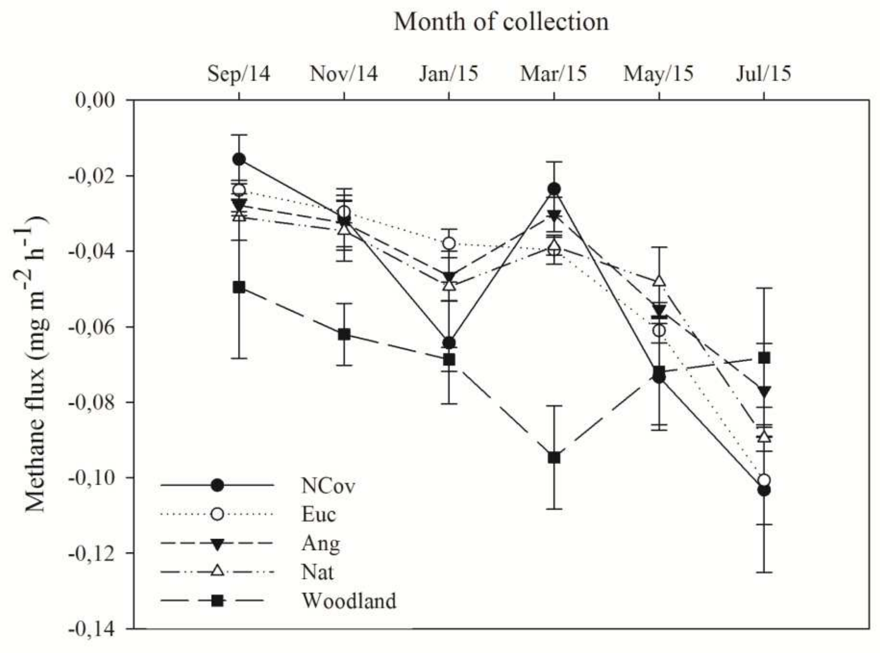


Figure 10 - Variation in methane flux (CH4) of the soil in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang), a mixed plantation of native species (Nat), forest in secondary stage regeneration (Woodland), and area with no ground cover (NCov). (Bars indicate the standard error around the mean, n = 6).

4. Discussion

4.1. Plant cover vs CO_2 and CH_4 flux

The type of plant cover has a great influence on soil CO_2 flux (Raich & Tufekciogul, 2000). The removal of native forests and changes in land use (Polglase *et al.*, 2000) seen in mining activities, accelerates the reduction in soil C stocks (Lorenz & Lal, 2007), with a possible increase in the loss of this C by increases in CO_2 efflux. One of the most effective activities in recovering soil C stocks from degraded areas is tree planting (Moghiseh *et al.,* 2013).

Greater diversity in plant species, together with favourable climate conditions, may result in greater activity, abundance and diversity of the soil microbiological community (Lange *et al.*, 2015), thereby affecting the decomposition of tree residue and SOM, and consequently, the production of CO_2 in the soil. The present study identified that CO_2 efflux showed a tendency to increase with the planting of forest cover (Figure 3).

Soils from mining areas place a limitation on plant growth and if not well managed, tend to have low values for CO_2 efflux (Shanhun *et al.*, 2012; Song *et al.*, 2012), as SOM content is greatly reduced, as seen in the treatment with no plants (Figure 3). Planting the types of forest cover under study led to an increase in CO_2 efflux due to the benefits of such cover in increasing SOM. Analysing the recovery of CO_2 efflux from the forest cover planted after bauxite mining in relation to the Woodland, a high percentage was seen in those types of cover, suggesting that the area is well on the way to recovery in relation to the area of unmined Woodland. Planting forest species favours microbiological activity in the soil by contributing organic material from the shoots and roots that contributes to nutrient cycling, speeding up recovery of the ecosystem (Shrestha & Lal, 2006), and which may reflect in the increase in soil CO_2 efflux.

The treatments with Euc, Ang and Nat showed higher values for CO_2 efflux in relation to NCov, due to the influence of these types of cover on the chemical and biological properties of the soil, which in turn are influenced by the input and composition of organic material from the trees (litter and roots), leading to an increase in SOM, and an increase in biomass and greater biological activity in the soil (Table 1). Studies have shown that different species contribute organic material of different quality (Craine & Gelderman, 2011; Martin *et al.*, 2009), which may affect the microbiological activity of the soil (Barreto *et al.*, 2008) and the increase in SOM. Moreover, differences in root biomass, soil organic matter content, and even the spatial arrangement of the trees, may contribute to variations in the CO_2 efflux (Katayama *et al.*, 2009; Gomes *et al.*, 2016).

Good moisture and temperature (Figure 5) conditions of the soil, together with higher values for TC, TN, LC, C-MB, N-MB and root density (Table 1), may explain the greater values for CO_2 efflux seen in Woodland (Figure 3). Given favourable conditions of temperature and moisture, soil microorganisms act more intensely, thereby producing more CO_2. In addition, the plants release CO_2 by root respiration, and it is possible that the higher the root density, the greater the release of CO_2 for the same climate conditions. Tree roots are responsible for a large flow of C and nutrients to the soil, with respiration accounting for a third or more of the total CO_2 efflux in the soils of tropical forests (Högberg & Read, 2006). In addition to root density and the activity and composition of the microbial community, the amount and quality of available C and photosynthetic activity also influence CO_2 concentrations in the soil and consequently its efflux (Kuzyakov & Cheng, 2001). It can therefore be said that an increase in the diversity of forest species, and the time of planting, favour the development of microorganisms and roots in the soil, resulting in an increase in CO_2 efflux.

The methane influx shows that the soil under study behaves as a methane sink. The ability of the soil to act as both a source of methane or a sink depends on the methanogenic and methanotrophic activity and the soil conditions that regulate them. In general, forest soils function as a sink of atmospheric CH4, especially under natural conditions (Shrestha *et al.*, 2004), which confirms the results of a greater methane influx to the soils of Woodland and the other forest areas studied in this work. Sousa Neto *et al.* (2011) also found negative methane flux in the Atlantic Forest biome. Among the principal factors influencing the emission or capture of CH_4 by the soil are the organic carbon content of the soil, quality of the substrate, temperature, moisture and microbiological activity (Yan *et al.*, 2008). In addition to these factors, soil fertilisation, with emphasis on organic fertilisation via animal waste rich in nitrogenous compounds, influences the dynamics of soil methane flux, and may alter the condition of the soil from methane sink to methane source (Shrestha *et al.*, 2004). Since in the present study fertilisation with poultry litter was applied 42 months before evaluating gas emissions, the methane flux was not affected.

4.2. Autotrophic and heterotrophic respiration

The relative contributions of heterotrophic and autotrophic respiration vary greatly according to the study site (Hanson *et al.*, 2000), and are strongly influenced by such environmental conditions as soil temperature and moisture, which are fundamental for the activity of soil microorganisms and the rate of decomposition of the SOM (Liu *et al.*, 2009), and by intrinsic plant factors, such as the allocation of photoassimilates to the roots (Blair *et al.*, 1995; Epron *et al.*, 2011; Högberg & Read, 2006).

The results of the present study confirm this, since the contribution of soil heterotrophic respiration increased by an average of 55% in the forest species during the driest period, and by 72% during the wettest period (Figure 4). Among the treatments during the rainy season, the ground cover of angico (Ang) showed a tendency towards the highest values for the relative contribution of HR (77.4%), which may be related to the high rate of decomposition of the leaflets from this type of forest cover in relation to the others under study (Gama-Rodrigues *et al.*, 1997) (Figure 5). Wei, Weille and Shaopeng (2010), analysing global data in forest ecosystems, also found positive responses in HR with increased rainfall. Soil microbiota respond more quickly to changes in soil moisture than does the AR, reflecting in a greater contribution of HR to the soil TR (Carbone *et al.*, 2011). In general, variations in AR are more dependent on the photosynthetic activity of the plants (Gomes *et al.*, 2016), responding more slowly to variations in soil temperature and soil moisture when compared to HR (Bond-Lamberty *et al.*, 2004; Högberg *et al.*, 2008, 2009).

The results of partitioning the heterotrophic respiration showed that the CO_2 produced in the soil originates mainly from the mineralisation of plant residue (Figure 8). This is possibly due to the microorganisms having greater ease of access to this material, relatively easier to be degraded compared to the SOM, that is protected and has already undergone some type of biological degradation. For areas in recovery, it is common to see a preference for microorganisms to use the most recently added forms of C, especially where the process of recovery is recent (Novara *et al.*, 2014).

High values for soil moisture can also negatively affect soil CO_2 efflux, preventing diffusion of CO_2 to the surface (Melling *et al.*, 2005). This may explain the high values for litter contribution (90%) in relation to that of the soil, for HR during November 2014, which had the highest values for soil moisture (Figure 1) and consequently may have contributed to greater obstruction of the soil pores.

4.3. Influence of biotic and abiotic factors on CO_2 flux

The separation of the study areas given by the principal component analysis, where the planted forests were placed between NCov and Woodland, follow the same trend seen for soil CO_2 efflux (Figure 3). This indicates that the planted forests are improving the properties of the soil in relation to the treatment with no ground cover and in relation to these properties, and are on the way to becoming native forest in secondary regeneration.

Soil CO_2 efflux is a complex process, and one which is dependent on biotic and abiotic factors. The abiotic factors that most influence this process are soil temperature and moisture (Fenn *et al.*, 2010; Wu *et al.*, 2010), and these factors have a direct influence on the biotic factors, such as soil microorganisms and plant cover.

An increase in soil temperature leads to an increase in the activity of microorganisms (Atkin *et al.*, 2000) and in root respiration (Schindlbacher *et al.*, 2011), causing an increase in soil CO_2 efflux. However, in the present study, soil temperature did not vary much during the evaluations (Figure 2) and therefore did not greatly influence soil CO_2 efflux (Figures 9 and 10). Plant cover with tree species creates a microclimate beneath the canopy that reduces variations in soil temperature, and therefore their influence on soil CO_2 efflux (Gomes *et al.*, 2016).

Soil moisture is a very important factor in the maintenance and development of microbial activity (Liu *et al.*, 2009). The results demonstrated that soil moisture was the variable with the most influence, generally positive, on soil CO_2 efflux. When the soil presented low values for moisture, the microbial activity tended to reduce, and this can be seen from the values for efflux found during September 2014 (Figure 3), which is at the end of the dry season. With the start of the rainy season (November 2014), there was a significant increase in these values, which again decreased with the end of the rainy season (July 2015) (Figure 6), mainly a result of the positive effect on microbial activity of the increase in soil moisture during the wet season.

5. Conclusions

Planting forest cover increases total CO_2 efflux in soils of mining areas, compared to those with no ground cover.

Total soil CO_2 efflux in the areas of eucalyptus and the mixed plantation of native forest species has a pattern of annual variation similar to that seen in Woodland.

In the forest cover under study, heterotrophic respiration contributes more to total soil respiration, with litter decomposition being responsible for greater CO_2 efflux.

The variation in moisture is the main factor responsible for the changes in soil CO_2 efflux in the types of forest cover studied.

The plantations of Euc, Ang and Nat forest cover were efficient in recovering the mined soils, bringing CO_2 efflux in this type of cover closer to that of Atlantic Forest remnants.

Methane flux was negative (inflow) in all the collections carried out for each of the types of ground cover under study.

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Supporting information

Table 1 - Summary of variance analysis (ANOVA) for soil CO_2 efflux in an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang) and a mixed plantation of native species (Nat), submitted to the standard fertilisation used by the company (SF) and supplemental fertilisation (OF+CF) during the six months of collection, obtained relative to the Woodland reference

SV	DF	SS	MS	F	p
Block	2	5.92294	2.96147	35.359	0.002866
Ground cover (GC)	2	0.25171	0.12585	1.503	0.326035
Error A	4	0.33502	0.08375		
Fertilisation (F)	1	0.00015	0.00015	0.001	0.979982
F x GC	2	0.11384	0.05692	0.268	0.773756
Error B	6	1.27534	0.21256		
Time	5	5.43405	1.08681	24.662	0.000025
Error C (Time x Block)	10	0.44068	0.04407		
Time x GC	10	0.99564	0.09956	3.453	0.001664
Time x F	5	0.04252	0.00850	0.295	0.913512
Time x GC x F	10	0.42821	0.04282	1.485	0.172975
Error D	50	1.44187	0.02884		
Corrected total	107	16.68195			

Table 2 - Descriptive statistics of the principal component analysis, identifying the most explanatory variables with the matrix of soil-variable loadings for an area of bauxite mining in recovery with eucalyptus (Euc), angico (Ang), and a mixed plantation of native species (Nat), in addition to an unmined area of native forest in the second stage of regeneration (Woodland) and a mining area with no forest cover (NCov)

Variable	PC1	PC2	CP3	CP4	CP5	CP6	CP7	CP8	CP9	PC10
	Factor loading coefficient									
TR	-0.5214	0.6479	-0.0127	-0.0978	-0.5386	-0.0835	-0.0203	0.0347	-0.0067	-0.0007
Ms	-0.4995	0.4206	0.0531	0.7212	0.2061	0.0813	0.0165	-0.0327	-0.0124	0.0000
Ts	0.2445	-0.0389	-0.9604	0.1121	-0.0598	0.0114	-0.0072	-0.0100	-0.0002	-0.0002
TC	-0.9555	0.0574	-0.0644	-0.2029	0.0806	0.0900	0.0918	-0.1021	0.0479	-0.0524
TN	-0.9343	0.1076	-0.0776	-0.2416	0.1023	0.0479	0.1323	-0.1356	0.0179	0.0462
LC	-0.9351	-0.0368	-0.0740	-0.1430	0.0957	0.2010	0.0226	0.1357	-0.1724	-0.0006
NMB	-0.8548	-0.0648	-0.0661	0.0173	0.1949	-0.4675	-0.0264	0.0038	-0.0565	-0.0044
CMB	-0.9513	0.0029	-0.0735	-0.0394	0.1512	0.0346	-0.0916	0.1665	0.1670	0.0081
DRsm	-0.8545	-0.3257	0.0396	0.1005	-0.1967	0.0831	-0.3074	-0.1076	-0.0199	0.0033
DRgr	-0.6538	-0.5314	0.0628	0.3185	-0.3687	-0.0265	0.2151	0.0357	0.0228	0.0015
Eigenvalue	6.03	1.01	0.96	0.78	0.60	0.29	0.18	0.09	0.06	0.005
Explained variance (%)	60.3	10.1	9.6	7.8	6.0	2.9	1.8	0.9	0.6	0.05
Cumulative explained variance (%)	60.3	70.4	80.0	87.7	93.7	96.6	98.4	99.3	100.0	100.0

Capítulo 4

ESTOQUES DE C E N NO SOLO EM ÁREA MINERADA DE BAUXITA EM RECUPERAÇÃO COM ESPÉCIES FLORESTAIS

RESUMO: A recuperação do conteúdo da matéria orgânica do solo é primordial em programas de reabilitação das alterações drásticas dos atributos físicos, químicos e biológicos do solo promovidos pela mineração. Objetivou-se com este estudo avaliar os estoques de C e N em frações da matéria orgânica do solo em área minerada de bauxita em processo de reabilitação com espécies florestais nativas e exótica após 56 meses de plantio. As coberturas florestais avaliadas foram o eucalipto (Euc), o angico vermelho (Ang) e um plantio misto composto por 16 espécies florestais nativas (Nat), além de área sem cobertura florestal (Sem Cob) e de mata nativa em área não minerada em estágio secundário de regeneração (Mata). Foram determinados os teores de C e N totais, lábil (CL), da matéria orgânica particulada (MOP), da matéria orgânica associada aos minerais (MAM), a relação C/N, bem como, o índice de manejo de carbono (IMC) nas camadas de 0-10, 10-20, 20-40 e 40-60 cm de profundidade e C e N da biomassa microbiana na camada de 0-10 cm. O efeito da presença e ausência do litter também foi testado para as três coberturas florestais (Euc, Ang e Nat) em duas adubações (AE e AO+AQ). De maneira geral os estoques de C e N totais não apresentaram diferenças entre as coberturas florestais estudadas, exceto a Mata que apresentou os maiores estoques. O CL e o C da biomassa microbiana foram os atributos que mais sinalizaram mudanças em decorrência das aplicações dos tratamentos após mineração de bauxita. O IMC das coberturas florestais implantadas foi maior que a área Sem Cob na camada de 0-60 cm. A atividade de mineração de bauxita provoca acentuada queda nos atributos orgânicos do solo, porém, a implantação de coberturas florestais resulta em aumento nos estoques de COT, CL e IMC no perfil de solo (0-60 cm).

ABSTRACT: The recovery of soil organic matter content is essential in rehabilitation programs for drastic changes in soil physical, chemical and biological attributes promoted by mining. The objective of this study was to evaluate the C and N stocks in organic matter fractions of the soil in a bauxite mining area in the process of rehabilitation with native and exotic forest species after 56 months of planting. The forest cover was eucalyptus (Euc), Angico Vermelho (Ang) and a mixed plantation composed of 16 native forest species (Nat), and an area without forest cover (Sem Cob) and native forest in secondary regeneration stage (Mata). The values of C and N total, labile (CL), particulate organic matter (MOP), organic matter associated with minerals (MAM), C/N ratio, as well as the carbon management index (IMC) in the 0-10, 10-20, 20-40 and 40-60 cm depth and C and N of the microbial biomass in the 0-10 cm layer. The effect of presence and absence of litter was also tested for the three forest coverages (Euc, Ang and Nat) in two fertilizations (AE and AO+AQ). In general, the total C and N stocks did not show differences between the forest cover studied, except for Mata that had the largest stocks. The CL and C of the microbial biomass were the attributes that most signaled changes due to the applications of the treatments after bauxite mining. The IMC of the forest cover implanted was greater than the Sem Cob area in the 0-60 cm layer. The bauxite mining activity causes a significant drop in the organic attributes of the soil, however, the implantation of forest cover results in an increase in the COT, CL and IMC stocks in the soil profile (0-60 cm).

1. *Introdução*

A mineração é uma das atividades antrópicas que mais impactam o solo, causando grandes interferências em suas propriedades físicas, químicas e biológicas. A recuperação destas áreas mineradas é motivo de esforços por parte das empresas do setor, órgãos ambientais, universidades e institutos de pesquisa que buscam procedimentos eficazes para restabelecer os processos essenciais do solo e ecossistemas degradados (CARNEIRO et al., 2008). O solo é componente fundamental por meio do qual muitos organismos obtém nutrientes e energia, portanto, o sucesso nos programas de recuperação de áreas degradadas é altamente dependente da manutenção da qualidade do solo (STAHL et al., 2002).

As atividades de mineração provocam elevada perda da matéria orgânica do solo (MOS) devido, principalmente, ao aumento da mineralização como resultado da quebra de agregados durante o procedimento de remoção e estocagem da camada superficial, erosão, lixiviação, redução ou ausência de biomassa que retorna ao solo

(LORENZ; LAL, 2007; SHRESTHA; LAL, 2006; TRIPATHI; SINGH; NATHANAIL, 2014) e mistura de camadas superficiais e subsuperficiais nestes solos minerados (SCHWENKE;, MULLIGAN;BELL, 1999; WARD, 2000). Diante disto, a MOS pode ser considerada um bom indicador da qualidade do solo destas áreas.

A matéria orgânica do solo (MOS) é um dos principais agentes de formação e estabilização de agregados do solo e, portanto, alterações no uso do solo e a adoção de práticas de manejo que promovam a quebra de agregados levam a exposição da MOS e consequente degradação microbiológica. Tais condições resultam em diminuição do C orgânico do solo (MATOS et al., 2008), principalmente das frações mais lábeis da MOS, caracterizadas por serem mais acessíveis à ação microbiana, ou seja, mais dinâmicas, respondendo mais rapidamente aos impactos da mudança proporcionada pelo uso e manejo do solo (HAYNES, 2000; PASSOS et al., 2007).

Entre as frações da MOS, o C orgânico lábil (CL) (BLAIR; LEFROY; LISLE, 1995) e da matéria orgânica particulada (MOP) (CAMBARDELLA; ELLIOTT, 1992; LEHMANN; CRAVO; ZECH, 2001) têm sido utilizados como indicadores sensíveis da qualidade do solo, permitindo a detecção de alterações causadas pelo uso, principalmente, em curto período de tempo. Também os estoques de C e N da biomassa microbiana podem ser bons indicadores, pois são facilmente alterados por mudanças no uso do solo. Segundo Barreto et al. (2008), a biomassa microbiana representa a fração lábil da MOS, de natureza dinâmica e facilmente alterada por fatores bióticos e abióticos. Apesar de representar pequena parte do C orgânico do solo, as propriedades microbiológicas do solo também têm sido consideradas indicadores sensíveis de alterações provocadas pelos diferentes sistemas de uso e manejo do solo (ARAÚJO et al, 2013; GAMA-RODRIGUES et al., 2008; HUANG et al., 2014; SILVA et al., 2010).

Desta maneira os programas de reabilitação de solos minerados envolvendo as coberturas florestais visam melhorar os atributos físicos, químicos e biológicos do solo, por meio da manutenção ou aumento da matéria orgânica, fixação biológica de N, a exploração de nutrientes em profundidades maiores, o aumento da infiltração e armazenamento de água, a redução da perda de nutrientes por erosão ou lixiviação (SINGH; RAGHUBANSHI; SINGH, 2004).

Apesar da importância dos estoques de COT, NT e suas frações no solo já ser bastante reconhecida, são escassos os estudos desenvolvidos sobre estes atributos em áreas mineradas e reabilitadas, principalmente, quando exploradas por bauxita (CARNEIRO et al., 2008). Nesse contexto, objetivou-se, neste estudo, avaliar os estoques de C e N em frações da matéria orgânica do solo de área minerada de bauxita em processo de reabilitação com o uso de espécies florestais nativas e exótica.

2. Material e Métodos

2.1. Caracterização da área de estudo e desenho experimental

O estudo foi conduzido no município de São Sebastião da Vargem Alegre, Zona da Mata de Minas Gerais, Brasil (21°1´58´´S e 42°35´8´´W), a 780 m de altitude, em área onde houve a extração de bauxita pela Companhia Brasileira de Alumínio – Votorantim Metais. Após as atividades de mineração, o *topsoil*, estocado por aproximadamente um ano, foi retornado a área original durante o processo de reconfiguração topográfica. Logo depois, o terreno foi descompactado com subsolador a 60 cm de profundidade. O solo predominante na região é o Latossolo Vermelho-Amarelo distrófico típico.

O clima da região é do tipo Cwa, segundo a classificação do Köppen, com verões quentes e chuvosos e estação seca bem definida, com precipitação e temperaturas médias anuais de 1.287 mm e 20,3 ºC, respectivamente (INMET, 2016).

A área foi minerada com bauxita e reconfigurada nos anos de 2009 e 2010, respectivamente. O experimento foi instalado em março de 2011 nesta área utilizando o delineamento em blocos casualizados com parcelas subdivididas e com três repetições. As parcelas, nas dimensões de 40 x 18 m foram compostas pelas coberturas florestais: eucalipto clonal (híbrido oriundo do cruzamento entre *Eucalyptus urophylla* x *Eucalyptus grandis;* clone AEC144$^{®}$) (Euc), angico vermelho (*Anadenanthera peregrina* (L.) Speg) (Ang) e plantio misto (Nat) composto por 16 espécies florestais nativas da região, sendo o Angico vermelho (*Anadenanthera peregrina* (L.) Speg) – Ap, Figueira (*Ficus insipida* Willd) - Fi, Ingá cipó (*Inga edulis* Mart.) – Ie, Jacaré (*Piptadenia gonoacantha* (Mart.) JF Macbr.) – Pg, Orelha de negro (*Enterolobium contortisiliquum* (Vell.) Morong.) - Ec, Paineira

(*Ceiba speciosa* (A. St. –Hil.) Ravenna) – Cs, Saboneteira (*Sapindus saponaria* L.) - Ss e Tamanqueira (*Pera glabrata* (Schott) Poepp. Ex Baill.) – Pg, espécies florestais consideradas pioneiras. Como espécies não pioneiras tem-se: catiguá (*Trichilia sp*) – Tsp, Camboatá (*Cupania oblongifolia* Mart.) – Co, Garapa (*Apuleia leiocarpa* (Vogel) JF Macbr.) - Al, Ipê tabaco (*Handroanthus chrysotrichus* (Mart. Ex A. DC.) Mattos) – Hc, Jatobá (*Hymenaea courbaril* var. *stilbocarpa* (Hayne) YT Lee & Langenh) – Hcs, Jequitibá (*Lecythis sp*) – J2, Pau brasil (*Paubrasilia echinata* Lam.) – Pe e Araticum (*Annona squamosa* L.) – As. Essas espécies nativas foram plantadas seguindo o modelo Quinquôncio (4 pioneiras e uma clímax no centro), espaçamento 2 x 1,5 m utilizando mudas produzidas a partir de sementes coletadas em fragmentos de Mata Atlântica próximos a região do estudo. O espaçamento adotado para o eucalipto e angico em monocultivo foi 3 x 2 m.

As subparcelas (10 x 18 m) foram compostas pela adubação padrão adotada pela empresa (AE) nas suas atividades de recuperação de áreas mineradas e pelas proposições de estudo que consideravam AE, porém suplementadas com adubação orgânica (AO), adubação química (AQ) e a combinação de AO+AQ. A AE foi realizada na área total, seis meses antes do plantio das árvores, e foi composta por 2,0 t ha^{-1} de calcário dolomítico e 30,0 t ha^{-1} de cama de aviário (*in natura,* com média de 30% de umidade). A AO foi composta por AE mais 30 t ha^{-1} de cama de aviário e a AQ pela aplicação de mais 3 t ha^{-1} de calcário dolomítico e 0,75 t ha^{-1} de fosfato natural reativo Bayóvar para o Euc e Ang e 1,5 t ha^{-1} para o Nat. A AO+AQ foi a combinação das duas aplicações suplementares (AO e AQ). Parte da dose da cama de aviário e do calcário foram aplicados na cova e parte nas entrelinhas de plantio, neste caso, incorporados na camada 0-15 cm, 30 dias antes do plantio, de forma a permitir que todas as plantas recebessem a mesma dose dos referidos adubos. Eucalipto e Angico receberam 22% da dose da cama de aviário na cova e 78% nas entrelinhas de plantio, enquanto Nat 44% e 56%, respectivamente. A aplicação do calcário também foi realizada de modo que 25% da dosagem total fosse aplicada nas covas e 75% nas entrelinhas de plantio para Euc e Ang, enquanto que em Nat, 50% foi aplicado na cova e o restante (50%) nas entrelinhas de plantio. O fosfato natural reativo foi aplicado no fundo das covas de plantio.

Além das adubações realizadas na implantação, as áreas ainda receberam duas adubações de cobertura, sendo a primeira um mês após a implantação do experimento, consistindo em 10 kg ha^{-1} de N, 22 kg ha^{-1} de P e 8 kg ha^{-1} de K para o plantio de eucalipto e angico e 20 kg ha^{-1} de N, 44 kg ha^{-1} de P e 16 kg ha^{-1} de K para o plantio múltiplo de nativas, enriquecido com micronutrientes (1,7 kg ha^{-1} de B, 0,8 kg ha^{-1} de Zn de 0,8 kg ha^{-1} de Cu para eucalipto e angico e o dobro destas doses para o plantio múltiplo de nativas), de forma localizada (covetas) lateralmente a 20 cm das plantas. A segunda adubação foi realizada 10 meses após a implantação dos tratamentos, sendo aplicados 67 kg ha^{-1} de N, 17 kg ha^{-1} de P e 67 kg ha^{-1} de K para o plantio de eucalipto e angico e 134 kg ha^{-1} de N, 34 kg ha^{-1} de P e 134 kg ha^{-1} de K para o plantio múltiplo de nativas, em sulcos de 5 cm de profundidade na parte superior da projeção da copa. Cabe ressaltar que apenas os tratamentos com adubação AQ e AO+AQ receberam estas adubações de cobertura, uma vez que esta foi realizada apenas com adubo químico. As principais características químicas e físicas do solo na área experimental no final do período de avaliação podem ser observadas em anexo (Tabela 1).

2.2. Análise dos atributos orgânicos do solo

Amostras de solos de cada subparcela citada acima, nas camadas de 0-10, 10-20, 20-40 e 40-60 cm, foram retiradas e trituradas em almofariz e passadas em peneira de 60 mesh (0,250 mm) para análise dos atributos orgânicos abaixo.

O carbono orgânico total (COT) foi quantificado por oxidação da matéria orgânica via úmida com $K_2Cr_2O_7$ 0,167 mol L^{-1} em meio sulfúrico, empregando-se como fonte de energia o calor desprendido pelo H_2SO_4 e fonte externa de aquecimento (YEOMANS; BREMNER, 1988). O nitrogênio total (NT) foi determinado pelo método Kjeldahl, modificado por Tedesco (1985), empregando-se digestão sulfúrica, destilação e quantificação por titulação com HCl 0,02 mol L^{-1}.

O carbono orgânico lábil (CL) foi extraído por oxidação em $KMnO_4$ 0,33 mol L^{-1} e quantificado por espectrofotometria de absorção molecular com leitura da absorvância a 565 nm (Blair et al.,1995 modificada por Weil et al., 2003).

O fracionamento físico da matéria orgânica do solo foi realizado em solo, previamente passado em peneiras de 2 mm, dispersos com hexametafosfato de sódio (5 g L^{-1}) e agitação horizontal a 120 rpm. Posteriormente, amostras foram passadas em peneiras com malha de 53 μm (170 mesh), originando duas frações: a retida (matéria orgânica particulada - MOP) e a que passou pela peneira (a matéria orgânica associada aos minerais - MAM). Estas duas frações foram secas em estufa a 60 ºC, pesadas e passadas em peneiras de 0,149 mm (100 mesh) para avaliação dos teores de COT e NT, já descritas (CAMBARDELLA; ELLIOTT, 1992).

O carbono e nitrogênio da biomassa microbiana (CBM e NBM, respectivamente) do solo foram determinados somente em 0-10 cm tendo sido acondicionadas em frascos plásticos com tampas, incubadas por 10 dias a 25 °C, com a umidade correspondente a 80 % do equivalente de umidade, visando restabelecer a comunidade microbiana. Após incubação, deterrminaram os teores de CBM e NBM pelo método da irradiação-extração (ISLAM; WEIL, 1998), utilizando forno micro-ondas. Após a irradiação, as amostras foram submetidas ao extrator K_2SO_4 0,5 mol L^{-1} e o C nos extratos quantificado por meio de oxidação úmida sem aquecimento externo e o N por meio de digestão sulfúrica, seguida da destilação e titulação com solução de HCl (TEDESCO et al., 1985).

O índice de manejo de carbono do solo (IMC) (BLAIR et al., 1995) foi calculado a partir dos dados de COT, CL e CNL (carbono orgânico não lábil, calculado pela diferença entre COT e CL), utilizando os valores obtidos na área de Mata como referência, por meio da seguinte equação: $IMA = ((COT_1/COT_{Mata})*((CL_1/CNL_1)/(CL_{Mata}/CNL_{Mata}))*100$, sendo COT_1: carbono orgânico total da área de Euc, Ang, Nat ou Sem Cob; CL_1 e CNL_1: C lábil e não lábil, respectivamente, da área de Euc, Ang, Nat ou Sem Cob.

Para este trabalho, além dos tratamentos descritos foi avaliada a influência do *litter* das árvores nos estoques de C e N do solo e suas frações considerando a presença e ausência de *litter* provenientes das coberturas florestais Euc, Ang e Nat, submetidas as adubações AE e AO+AQ. Coletaram-se amostram embaixo dos coletores de litter instalados na área para estimativa de biomassa aportada ao solo (dados não considerados neste estudo, porém, apresentados no capítulo 1 e 2 desta tese).

Os estoques de C e N das frações da MOS, nas diferentes camadas do solo, foram calculados multiplicando-se os teores de C ou N pelo volume de solo em cada camada de solo e pela densidade do solo sob a Mata nas diferentes profundidades (PULROLNIK et al., 2009).

2.3. Análises estatísticas

Os dados obtidos foram submetidos à análise de variância e os tratamentos comparados pelo teste de Tukey a 10% de probabilidade utilizando o programa estatístico Statistica 7.0. Considerou-se também as probabilidades de 15 % e 20 % para discussão das tendências apresentadas pelos tratamentos estudados.

3. Resultados

De maneira geral, a interação entre as fontes de variação tipos de adubação e coberturas florestais implantadas na área minerada após 56 meses de plantio não apresentaram efeitos significativos ($p>0,1$) sobre os atributos orgânicos do solo avaliados (Anexos, Tabela 2). Esses resultados condicionaram a abordagem somente dos efeitos das coberturas florestais e profundidades sobre os atributos orgânicos, considerando a média das adubações (Anexos, Tabela 3), o que permitiu incluir, desta maneira, a área sem cobertura (Sem Cob) e a Mata no conjunto dos tratamentos como fonte de variação nas análises estatísticas.

Os estoques de COT, assim como os de NT, não diferiram entre as coberturas Euc, Ang, Nat e Sem Cob, em todas as profundidades estudadas, o que não aconteceu quando comparado à Mata ($p<0,1$), a qual apresentou os maiores estoques. Houve uma tendência ($p<0,20$) do Euc apresentar maiores estoques de COT em relação a Sem Cob na camada de 20-40 cm. Contudo, quando avaliou-se todo o perfil de solo estudado, ou seja, a camada de 0-60 cm, foram observados menores valores de COT na área Sem Cob em relação a Euc e Ang, não diferindo, entretanto, da Nat. Para NT, os solos das áreas de Euc, Ang, Nat e Sem Cob não diferiram quanto aos estoques nesta profundidade.

A relação C/N apresentou diferenças significativas em relação as coberturas florestais estudadas ($p<0,1$), as quais se devem a Nat e Sem Cob na camada de 40-60 cm onde foram observados os maiores valores. Na camada de 0-60 cm, apesar de ter sido observado tendência da Mata em apresentar as menores relações C/N ($p<0,15$), esta diferença não foi confirmada a 10% de probabilidade, quando comparada às coberturas florestais plantadas. Houve diferenças apenas entre Sem Cob (apresentando as maiores relações C/N) e a Mata.

Diferenças significativas ($p<0,1$) foram observadas nos estoques de CL nas coberturas florestais estudadas, com o a Mata apresentando os maiores estoques. Houve tendência ($p<0,15$) das três coberturas florestais implantadas apresentarem maiores teores de CL em relação a área sem cobertura. Porém, a 10% de probabilidade, Euc, Ang e Nat não foram estatisticamente diferentes entre si, assim como em relação a Sem Cob, com exceção do Euc, com os maiores estoques de CL que a área Sem Cob na profundidade de 0-10 cm, o que representou um aumento de 850 kg ha^{-1}. Para as demais profundidades, de maneira geral, foram observadas diferenças apenas entre a Mata e as demais coberturas ($p<0,1$). As espécies florestais implantadas após a mineração de bauxita (Euc, Ang e Nat), propiciaram o aumento dos estoques de CL em relação a área Sem Cob, quando se analisa o solo na profundidade de 0-60 cm ($p<0,1$), não havendo diferença entre elas.

A análise dos resultados do IMC do solo mostrou não haver diferenças significativas ($p<0,1$) entre os solos das coberturas estudadas, em cada profundidade, sendo todas menores que a referência Mata. No entanto, quando avaliaram-se todas as camadas estudadas (0-60 cm) constataram-se maiores IMC nas alternativas de recuperação em relação a área Sem Cob, após 56 meses de reabilitação.

Tabela 2 – Estoques (t ha^{-1}) de C orgânico e N total (COT e NT), relação C/N, C lábil (CL) e índice de manejo de C (IMC) do solo sob coberturas florestais de eucalipto (Euc), angico vermelho (Ang), plantio misto de espécies nativas (Nat) e duas de áreas de referência: sem cobertura (Sem Cob) e Mata, após 56 meses de plantio nas camadas de 0-10, 10-20, 20-40, 40-60 cm e 0-60 cm de solo

Profundidades (cm)	Coberturas Florestais				
	Sem cob	Euc	Ang	Nat	Mata
	COT (t ha^{-1})				
0-10	13,92 Bc	21,54 Bb	21,26 Bb	19,98 Bb	54,59 Aa
10-20	12,06 Bbc	19,63 Bb	18,15 Bb	17,40 Bb	34,06 Ab
20-40	23,54 Ba	31,21 Ba	26,40 Ba	26,77 Ba	60,87 Aa
40-60	21,11 BCab	22,92 Bb	19,63 BCb	16,65 Bb	41,89 Ab
0-60	70,64 C	95,30 B	85,43 B	80,80 BC	191,42 A
	NT (t ha^{-1})				
0-10	1,01 Bab	1,58 Bb	1,52 Bab	1,43 Bb	4,34 Aa
10-20	0,82 Bb	1,32 Bb	1,26 Bb	1,21 Bbc	2,82 Ab
20-40	1,55 Ba	2,04 Ba	1,72 Ba	1,81 Ba	4,59 Aa
40-60	1,17 Bab	1,39 Bb	1,26 Bb	0,95 Bc	3,023 Ab
0-60	4,57 B	6,34 B	5,75 B	5,40 B	14,78 A
	C/N				
0-10	13,74 Ab	13,88 Ab	14,26 Ab	14,06 Ab	12,58 Aa
10-20	15,07 Aab	15,02 Aab	14,58 Ab	14,51 Ab	12,05 Aa
20-40	15,65 Aab	15,36 Aab	16,06 Aab	14,98 Ab	13,26 Aa
40-60	18,05 Aba	16,92 Ba	16,61 Ba	19,58 Aa	13,96 Ba
0-60	15,63 A	15,13 AB	15,15 AB	15,10 AB	12,96 B
	CL (t ha^{-1})				
0-10	1,03 Ca	1,88 Ba	1,82 BCa	1,76 BCa	4,38 Aa
10-20	0,61Ba	1,33 Bb	1,38 Bbc	1,35 Bb	2,50 Ac
20-40	1,03 Ba	2,03 Ba	1,78 Bab	1,63 Bab	3,58 Aa
40-60	0,86 Ba	1,12 Bb	1,07 Bc	1,21 Bb	2,24 Ac
0-60	3,53 C	6,35 B	6,04 B	5,96 B	12,70 A
	IMC (%)				
0-10	25,5 Aa	44,09 Aa	41,66 Aa	40,56 Aa	100
10-20	29,36 Aa	53,09 Aa	55,55 Aa	54,61 Aa	100
20-40	33,54 Aa	58,78 Aa	51,27 Aa	48,27 Aa	100
40-60	31,34 Aa	49,63 Aa	48,63 Aa	55,14 Aa	100
0-60	27,57 B	50,58 A	47,75 A	47,76 A	100

Médias seguidas de letras maiúsculas na linha comparam as coberturas florestais entre si e as minúsculas na coluna comparam cada cobertura florestal nas diferentes profundidas e quando seguidas pela mesma letra na linha ou na coluna não diferem entre si pelo teste Tukey a 10%.

Os resultados das avaliações de C nas frações físicas da matéria orgânica mostraram não haver diferenças entre as coberturas florestais implantadas e a área Sem Cob para CMAM, bem como CMOP, (p<0,1), nas duas primeiras profundidades de solo estudadas (0-10 e 10-20 cm) (Tabela 3). Nessas camadas de solo, a Mata apresentou os maiores estoques de CMAM e CMOP. Já na camada de

20-40 cm, Euc e Nat se diferenciaram da Sem Cob apresentando os maiores estoques de CMAM. Para CMOP, os estoques foram iguais em todas as coberturas estudadas nas duas ultimas camadas de solo. Quanto às frações de C na camada de 0-60 cm, não foram observadas diferenças significativas em relação as coberturas florestais implantadas e a área Sem Cob, apresentando estoques de CMAM e CMOP menores que os observados na Mata

De maneira geral, os estoques de NMAM apresentaram-se diferentes em relação as coberturas estudadas ($p<0,1$), sendo maiores na Mata. Em relação aos resultados de NMOP, das coberturas estudadas, a Mata apresentou os maiores estoques ($p<0,1$) nas duas primeiras camadas de solo (0-10 e 10-20 cm). As coberturas florestais implantadas e a área Sem Cob não se diferenciaram quantos aos estoques de NMAM e NMOP na camada de 0-60 cm, sendo observado os maiores estoques para a Mata.

As coberturas estudadas apresentaram diferenças entre si em relação ao CBM ($p<0,1$) (Tabela 3, anexo), sendo que a área Sem Cob apresentou os menores estoques de CBM e a Mata os maiores valores (Tabela 3). As três coberturas florestais Euc, Ang e Nat não apresentaram diferenças entre si e ocuparam posição intermediária entre Sem Cob e Mata nos estoques de CBM. Já para o NBM, a Mata apresentou os maiores estoques ($p<0,1$), porém, Euc, Ang e Nat não diferiram da área Sem Cob.

Tabela 3 - Estoques de C e N em frações da matéria orgânica (t ha^{-1}) em área minerada com bauxita em recuperação do solo sob coberturas florestais de eucalipto (Euc), angico vermelho (Ang), plantio misto de espécies nativas (Nat) e duas de áreas de referência: sem cobertura (Sem Cob) e Mata, após 56 meses de plantio nas camadas de 0-10, 10-20, 20-40 e 40-60 cm de solo

Profundidades (cm)	Coberturas Florestais				
	Sem cob	Euc	Ang	Nat	Mata
			CMAM (t ha^{-1})		
0-10	12,59 Ba	17,46 Bb	18,46 Bb	17,43 Bb	41,88 Ab
10-20	11,47 Ba	17,42 Bb	16,63 Bb	15,88 Bb	29,45 Ac
20-40	19,67 Ca	27,81 Ba	22,75 BCa	24,41 Ba	57,03 Aa
40-60	17,92 BCa	21,02 Bb	17,45 BCb	14,42 Cb	36,93 Abc
0-60	61,65 B	83,71 B	75,29 B	72,14 B	165,29 A
			CMOP (t ha^{-1})		
0-10	1,33 Ba	4,07 Ba	2,79 Bab	2,55 Ba	12,71 Aa
10-20	0,59 Ba	2,21 Bb	1,52 Bb	1,52 Ba	4,61 Ab
20-40	3,87 Aa	3,39 Aab	3,63 Aa	2,36 Aa	3,84 Ab
40-60	3,19 Aa	1,89 Ab	2,18 Aab	2,24 Aa	4,96 Ab
0-60	8,98 B	11,57 B	10,13 B	8,67 B	26,12 A
			NMAM (t ha^{-1})		
0-10	0,87 Ba	1,39 Bab	1,37 Bab	1,26 Bab	3,33 Aab
10-20	0,65 Ba	1,24 Bb	1,11 Bb	1,06 Bb	2,27 Ab
20-40	1,34 Ba	1,70 Ba	1,54 Ba	1,62 Bb	4,05 Aa
40-60	1,07 Ba	1,23 Bb	1,11 Bb	0,91 Bb	2,66 Abc
0-60	3,94 B	5,57 B	5,14	4,85 B	12,32 A
			NMOP (t ha^{-1})		
0-10	0,14 Ba	0,19 Bab	0,15 Ba	0,17 Ba	1,01 Aa
10-20	0,17 Aa	0,08 Ac	0,15 Aa	0,15 Aa	0,55 Ab
20-40	0,21 Aa	0,34 Aa	0,17 Aa	0,19 Aa	0,54 Ab
40-60	0,13 Aa	0,16 Aab	0,15 Aa	0,04 Ba	0,36 Ab
0-60	0,65 B	0,77 B	0,62 B	0,54 B	2,45 A
			CBM (t ha^{-1})		
0-10	0,0602 C	0,1781 B	0,1595 B	0,1506 B	0,6839 A
			NBM (t ha^{-1})		
0-10	0,0177 B	0,0241 B	0,0275 B	0,0214 B	0,0660 A

CMAM= C da matéria orgânica associada aos minerais; CMOP= C matéria orgânica particulada; NMAM = N da matéria orgânica associada aos minerais; NMOP = N matéria orgânica particulada; CBM = C da biomassa microbiana do solo; NBM = nitrogênio da biomassa microbiana do solo. Médias seguidas de letras maiúsculas na linha comparam as coberturas florestais entre si e as minúsculas na coluna comparam cada cobertura florestal nas diferentes profundidas e quando seguidas pela mesma letra na linha ou na coluna não diferem entre si pelo teste Tukey a 10%.

Ao se estudar o efeito da presença ou ausência do litter nos atributos orgânicos do solo, não foram constatados, pela ANOVA, diferenças significativas das interações e dos efeitos principais para todos os atributos orgânicos estudados, a exceção de CL, o qual foi maior (1,55 t ha^{-1}, $p<0.1$), na presença do *litter*, comparativamente a ausência (1,33 t ha^{-1}).

4. Discussão

Apesar do emprego de adubação, mineral ou orgânica, propiciarem aumentos dos estoques de C e N em diferentes sistemas de manejo do solo, sendo assim, importante estratégia de manejo e conservação da qualidade do solo (LEITE et al., 2003; LOSS et al., 2009, 2011; VALADÃO et al., 2011), os tipos de adubação aplicados no presente estudo não influenciaram o atributos orgânicos do solo estudados. Os tratamentos de adubação foram aplicados no momento do plantio e seus efeitos foram associados ao crescimento das espécies florestais plantadas, ou seja, no favorecimento de melhores condições iniciais para o desenvolvimento das árvores, porém, após 56 meses, não houve constatação de diferenciação nos atributos orgânicos do solo sob plantio em função dos diferentes tipos de adubação.

Contudo, o efeito cumulativo das coberturas florestais implantadas na área de mineração de bauxita foi positivo, pois os estoques de COT, comparativamente a área Sem Cob foram maiores, porém, menores que a área de referência Mata, não minerada. Já os estoques de NT do solo sob as coberturas florestais ainda não se diferenciaram da área Sem Cob. Esses resultados levam a crer que o tempo de implantação das coberturas florestais não foi suficiente para que houvesse recuperação destas áreas mineradas, uma vez que, o retorno dos atributos orgânicos do solo ao estágio original, representado pela área de referência, não minerada, raramente acontece em curto espaço de tempo. Alguns estudos indicam longos períodos para a recuperação da matéria orgânica do solo como são os casos de 18 anos em área minerada com bauxita em Poços de Caldas, Minas gerais (CARNEIRO et al., 2008) e 33 anos em solos de mineração de bauxita na Austrália (SCHWENKE; MULLIGAN; BELL, 1999, 2000a, 2000b). A eficiência de técnicas de manejo aplicadas podem reduzir esses períodos, como constatados por Anderson; Ingram; Stahl (2008) em área minerada de carvão quando, 10 anos após reabilitação, foram suficientes para a recuperação dos estoques de COT das várias áreas estudadas (mais da metade) foram comparáveis às áreas não mineradas, sendo que um terço destas áreas apresentaram estoques de COT maiores que as áreas de referência.

A redução dos estoques de COT é causada não somente pela retirada da camada superficial do solo e estocagem durante o período da lavra (CARNEIRO et al., 2008), mas também, pela mistura de horizontes superficiais e subsuperficiais mais pobres em matéria orgânica (SCHWENKE;, MULLIGAN;, BELL, 1999) ou até com rejeitos estéreis eventualmente devolvidos a área com objetivo de uniformização do relevo. Além disso, o revolvimento do solo e, consequentemente, a quebra dos agregados estáveis, expõe a MOS, antes protegida, à decomposição microbiológica acelerada (CHAPLOT; COOPER, 2015; SCHIMIDT et al., 2011), favorecendo a perda de C através da emissão de CO_2. Estudos realizados em solos de mineração de bauxita em Minas Gerais mostraram redução de até 99% nos teores de carbono orgânico, nitrogênio total e na biomassa microbiana (CARNEIRO et al., 2008). Esta redução dos estoques totais (0-60 cm) de COT e NT foram observadas no presente estudo tendo sido observado o aumento destes estoques por meio da implantação das coberturas florestais.

O carbono lábil (CL) é aquele potencialmente mais acessível aos microrganismos do solo e sua determinação tem sido recomendada como indicador de mudanças precoces na MOS, decorrentes de alterações no uso do solo, uma vez que ele se reduz e também se restaura rapidamente em comparação ao COT (BLAIR; LEFROY; LISLE, 1995). Apesar de ser constada a tendência das três coberturas florestais implantadas após mineração de bauxita de elevar os estoques de CL em relação a área Sem Cob, até o momento, apenas o Euc apresentou diferenças significativas na primeira camada de solo estudada. Na análise da camada total de solo (0-60 cm), a influência das coberturas florestais sobre o CL do solo foi identificada, elevando os seus estoques em relação a área Sem Cob.

A rizodeposição contribui substancialmente para o aporte de CL ao solo (RASSE; RUMPEL; DIGNAC, 2005), bem como, o aporte resíduos orgânicos de parte aérea pelas coberturas florestais. Durante 30 meses de avaliação Euc, Ang e Nat aportaram ao solo cerca de 20.810,0 kg ha^{-1}, 9.875 kg ha^{-1} e 15.805,16 kg ha^{-1} de resíduos orgânicos de parte aérea, respectivamente, sendo que a presença deste *litter* refletiu em aumento do CL (1,55 t ha^{-1}) em relação a sua ausência (1,33 t ha^{-1}). As coberturas florestais permitam aumento dos estoques de CL, na camada de 0-60 cm de solo, em relação a área Sem Cob na ordem de 73% . Demolinari (2013) em estudo semelhante, observou que os estoques de CL foram semelhantes à referência não minerada após cinco anos de reabilitação. Porém, a referência utilizada pela autora apresentou estoques de CL (2,91 t ha^{-1}) bem inferiores ao do presente estudo (4,38 t ha^{-1}).

O IMC é um indicativo do impacto do uso do solo sobre os estoques de MOS e pode ser usado para monitorar as mudanças na dinâmica de C ao longo do tempo, considerando uma condição referência (BLAIR; LEFROY; LISLE, 1995), no caso, a Mata. Apesar da não existência de diferenças significativas em cada profundidade, os resultados obtidos indicaram que as áreas revegetadas apresentam um IMC menor que 100 %, o que reflete que as alternativas de cobertura testadas não proporcionaram a recuperação dos estoques aos níveis da referência considerada. No entanto, quando avaliou-se a camada de 0-60 cm de solo, diferenças significativas entre as coberturas florestais implantadas e a área Sem Cob foram observadas. O índice de manejo de carbono (IMC) da área minerada e revegetada com Euc, Ang e Nat (42 %), indicou que ainda não foi possível a recuperação total dos estoques de C, uma vez que estão bem menores que a Mata.Porém, a implantação destas coberturas permitiram, após 56 meses, a elevação deste índice em relação a área Sem Cob (25 %), indicando como efetivo pode ser o uso dessas espécies para a recuperação dos estoques de C de áreas mineradas.

No presente trabalho ficou evidente que a maior proporção de C e N estão relacionada a fração MAM. As maiores proporções de C associado a MAM se devem a elevada superfície específica da frações argila e silte, comparativamente a areia (ZINN et al.,2007). Santos et al. (2011) observaram, em área não impactada (campo nativo), maiores teores de C associado aos minerais, relacionando esse efeito aos mecanismos de proteção química da matéria orgânica com os teores de argila. Solos com baixos teores de argila têm menor proteção da matéria orgânica e baixa capacidade da fração mineral em manter um elevado estoque de C na MAM, impondo certa condição de vulnerabilidade ao sistema de manejo empregado (SANTOS et al., 2013).

Alterações no COT decorrentes de mudanças no uso do solo ocorrem, principalmente, na fração MOP, considerada de resposta mais rápida (FIGUEIREDO; RESCK; CARNEIRO, 2010; LEHMANN; CRAVO; ZECH, 2001) sendo, portanto, indicador sensível das alterações ocorridas na MOS. Neste trabalho, não foram detectadas alterações nos teores de C e N da MOP entre os tratamentos de cobertura florestais utilizados. Apenas foram observadas diferenças entre a Mata, referência de área não minerada, e as demais coberturas. Os menores estoques de C e N na fração MOP das áreas mineradas são esperados pelo impacto que a atividade de mineração causa aos atributos orgânicos do solo, como a quebra da proteção física da matéria orgânica pelos agregados do solo e a exposição deste C à degradação microbiológica (LEHMANN; CRAVO; ZECH, 2001).

A mineração de bauxita proporcionou a redução de mais de 90 % nos estoques de CBM quando avaliaram-se as áreas Sem Cob de solo e Mata, enquanto as coberturas florestais Euc, Ang e Nat aumentaram este estoque em cerca de 62 %, ainda quatro vezes menor em relação a Mata. A rápida recuperação do CBM está associada a revegetação da área, que restabelece aporte de C pela rizosfera e proporciona C orgânico para a microbiota do solo (CARNEIRO et al., 2008). A maior relação CBM/COT na Mata pode estar relacionada à maior diversidade do substrato orgânico produzido e aportado ao solo destas áreas, além do fato de não ter havido revolvimento de solo. A não existência de diferenças nos estoques de NBM nas áreas Sem Cob, Euc, Ang e Nat, diferenciando-se apenas da Mata, com os melhores estoques, contraria resultados documentados em condições semelhantes (Carneiro et al., 2008) tendo observado a recuperação do NBM após um ano de reabilitação.

5. *Conclusões*

As atividades de mineração provocam queda acentuada nos atributos orgânicos do solo, tais como, COT e NT e suas frações.

O carbono lábil e da biomassa microbiana, na camada superficial do solo (0-10 cm), são os atributos orgânicos que primeiro sinalizam mudanças positivas em áreas mineradas de bauxita em decorrência da implantação de coberturas florestais após 56 meses de reabilitação.

As coberturas florestais proporcionam aumento nos estoques de COT, CL e do IMC na camada de 0-60 cm de solo em relação a área Sem Cob.

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ANEXO

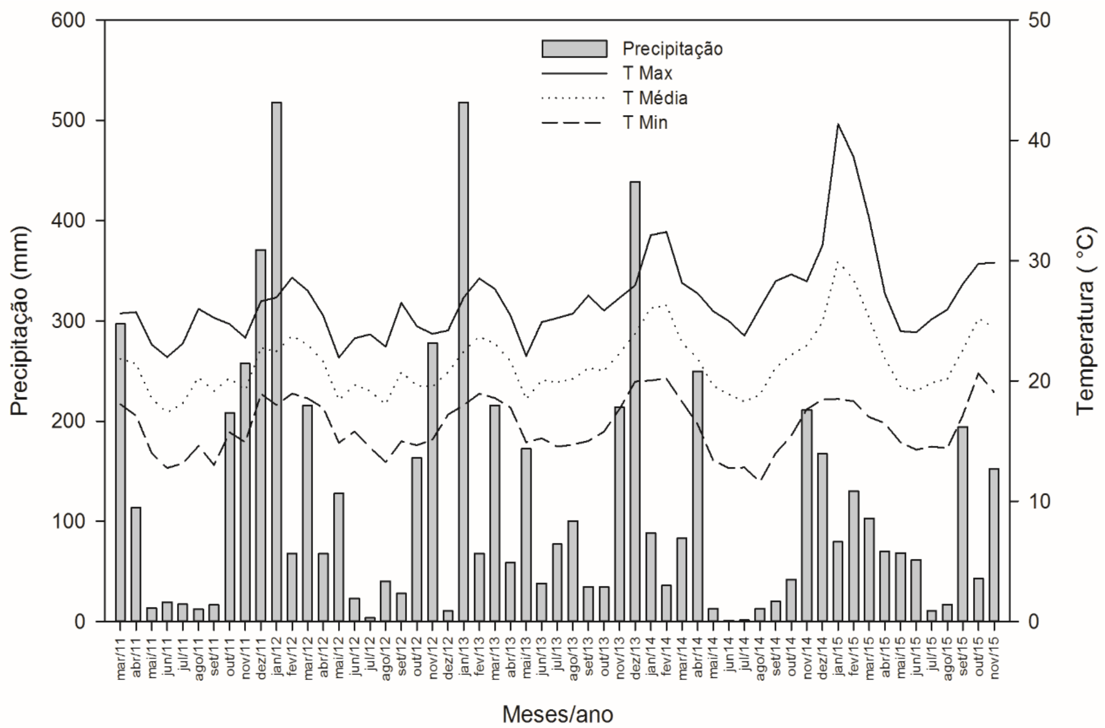

Figura 1 - Médias mensais da precipitação e temperaturas máxima (Tra Max), mínima (Tra Min) e média (Tra Média) na área do experimento, no período de março de 2011 a novembro de 2015, em área minerada de bauxita em São Sebastião da Vargem Alegre-MG.

Tabela 1 – Propriedades físicas e químicas do solo na camada de 0-20 cm em área minerada com bauxita em processo de recuperação com eucalipto (Euc), angico (Ang), plantio misto de espécies nativas (Nat), mata nativa em estágio secundário de regeneração (Mata) e área sem cobertura (Sem Cob) após 56 meses da instalação dos tratamentos

Atributos	Sem cob	Mata	AE			AO			AQ			AO+AQ		
			Euc	Ang	Nat	Euc	Ang	Nat	Euc	Ang	Nat	Euc	Ang	Nat
pH em água (1:2,5)	5,89	6,00	5,28	5,40	5,57	5,78	5,40	5,62	5,57	5,50	5,67	5,48	5,61	5,89
COT, dag kg^{-1}	1,35	3,64	2,14	1,98	2,08	2,01	2,01	1,99	2,02	1,95	1,75	2,31	2,23	1,92
NT, dag kg^{-1}	0,11	0,28	0,14	0,13	0,14	0,15	0,15	0,15	0,13	0,14	0,12	0,17	0,16	0,14
P, mg dm^{-3}	22,37	4,90	6,40	5,55	5,05	43,07	21,18	11,68	6,12	3,12	15,65	55,95	25,62	16,95
K, mg dm^{-3}	16,33	52,33	51,50	57,33	39,83	63,00	66,17	56,67	52,17	54,00	71,33	61,33	82,00	72,00
Ca^{+2}, cmol$_c$ dm^{-3}	2,44	0,50	1,24	1,53	2,11	2,87	3,07	2,48	2,40	2,42	2,77	3,58	3,63	3,22
Mg^{+2}, cmol$_c$ dm^{-3}	0,93	0,30	0,46	0,50	0,77	1,04	1,08	0,74	0,80	0,73	0,89	1,29	1,09	1,07
Al^{+3} , cmol$_c$ dm^{-3}	0,02	1,57	0,20	0,07	0,02	0,02	0,03	0,00	0,07	0,00	0,00	0,02	0,00	0,00
H^{+}+Al^{+3} , cmol$_c$ dm^{-3}	3,43	14,33	7,70	6,53	6,22	5,45	5,10	5,87	5,53	5,77	4,55	5,52	5,83	4,53
SB, cmol$_c$ dm^{-3}	3,40	0,94	1,83	2,18	2,98	4,07	4,32	3,36	3,33	3,30	3,84	5,02	4,92	4,47
T , cmol$_c$ dm^{-3}	3,42	2,50	2,03	2,25	3,00	4,09	4,35	3,36	3,40	3,30	3,84	5,04	4,92	4,47
t , cmol$_c$ dm^{-3}	6,84	15,27	9,53	8,71	9,20	9,52	9,42	9,23	8,87	9,06	8,39	10,54	10,76	9,00
V, %	49,15	5,97	18,12	24,77	32,68	41,77	44,33	35,97	39,17	35,98	45,03	46,33	45,57	49,40
m, %	1,42	62,75	14,02	3,75	0,87	0,67	1,32	0,00	3,00	0,00	0,00	0,75	0,00	0,00
P-Rem, mg L^{-1}	7,30	12,85	9,57	9,63	6,33	12,43	12,95	6,60	8,23	9,28	7,43	12,48	13,10	8,83
S, mg dm^{-3}	10,98	23,92	7,72	8,68	6,18	10,87	10,82	6,15	7,37	10,78	7,98	8,28	11,17	6,65
Cu, mg dm^{-3}	0,27	0,31	0,37	0,22	0,29	0,28	0,26	0,39	0,20	0,22	0,35	0,35	0,26	0,34
Mn, mg dm^{-3}	7,82	6,38	8,13	5,93	6,23	16,37	11,58	11,93	7,73	5,85	8,53	14,12	14,63	10,72
Fe, mg dm^{-3}	38,32	100,37	104,43	53,75	52,23	57,62	48,92	84,08	61,35	64,37	67,88	59,43	61,78	59,93
Zn, mg dm^{-3}	5,15	0,72	3,41	3,01	2,63	12,53	6,94	6,36	3,57	1,94	4,27	11,58	8,64	6,14
Ds, g cm^{-3}	1,13	0,97	1,41	1,28	1,16	1,32	1,23	1,23	1,25	1,23	1,33	1,22	1,25	1,25
Dp, g cm^{-3}	2,73	2,54	2,71	2,68	2,68	2,70	2,63	2,68	2,70	2,63	2,69	2,70	2,67	2,72
Pt, %	0,59	0,62	0,48	0,52	0,56	0,51	0,53	0,54	0,54	0,53	0,51	0,55	0,53	0,54

AE = adubação da empresa; AO = adubação orgânica; AQ = adubação química; AO+AQ = adubação orgânica e química combinadas; COT = carbono orgânico total por Walkey Black (YEOMANS; BREMMER (1988)); NT = nitrogênio total por Kjedhal (TEDESCO et al., 1995); P e K = extraído por Mehlich 1 e determinado por absorção molecular e fotometria de chama (DEFELIPO; RIBEIRO, 1997); Ca^{2+}, Mg^{2+} e Al^{3+}extraídos com KCl 1 mol L^{-1} e determinados por absorção atômica e fotometria de chama (VETTORI, 1969); H+Al extraído por acetato de cálcio 0,5 mol L^{-1} a pH 7 (EMBRAPA, 2011); SB = soma de bases trocáveis; T =capacidade de troca catiônica a pH 7,0; t = capacidade de troca catiônica efetiva; V = índice de saturação por bases; m = índice de saturação por alumínio (VETTORI, 1969); P-rem = extraído por CaCl$_2$ e determinado por absorção molecular (ALVAREZ V. et al., 2000); S, Cu, Mn, Fe e Zn extraídos por Mehlich 1 e determinado por absorção atômica (DEFELIPO; RIBEIRO, 1997); Ds = densidade do solo, determinada pelo método do anel volumétrico; Dp = densidade de partícula, determinada pelo método do balão volumétrico; Pt = porosidade total (EMBRAPA, 2011)..

Tabela 2 – Resumo da análise de variância (ANOVA) com quadrados médios e probabilidades das variáveis C lábil (CL), C orgânico total (COT), C da matéria orgânica associada aos minerais (CMAM), C da matéria orgânica particulada (CMOP), N total (NT), N da matéria orgânica associada aos minerais (NMAM), N da matéria orgânica particulada (NMOP) e relação C/N do solo área minerada de bauxita em recuperação com eucalipto (Euc), angico (Ang) e nativas (Nat) submetidas a adubação padrão (AE), química (AQ), orgânica (AO) e a combinação de orgânica e química (AO+AQ) nas profundidades 0-10, 10-20, 20-40 e 40-60 cm após 56 meses de plantio

FV	GL	Quadrados Médios							
		CL	COT	CMAM	CMOP	NT	NMAM	NMOP	C/N
Bloco	2	$0,3611^{0,693}$	$31,7924^{0,664}$	$61,7770^{0,443}$	$2,7655^{0,746}$	$1,1522^{0,221}$	$1,6491^{0,096}$	$0,1666^{0,299}$	$47,6075^{0,032}$
CF (Cobertura Florestal)	2	$0,1335^{0,866}$	$98,3145^{0,345}$	$107,6158^{0,284}$	$6,3006^{0,541}$	$0,6877^{0,358}$	$0,3308^{0,479}$	$0,0412^{0,688}$	$3,2556^{0,578}$
Erro A (Bloco x CF)	4	0,8991	69,9742	61,4434	8,7568	0,5118	0,3713	0,1004	5,1583
Adubação (A)	3	$0,1598^{0,701}$	$23,5413^{0,652}$	$100,3333^{0,097}$	$8,8395^{0,026}$	$0,2595^{0,495}$	$0,3536^{0,431}$	$0,0945^{0,066}$	$2,1726^{0,848}$
CF *A	6	$0,0390^{0,993}$	$28,6230^{0,673}$	$42,5015^{0,434}$	$3,7122^{0,195}$	$0,1628^{0,786}$	$0,2033^{0,760}$	$0,0105^{0,919}$	$6,5753^{0,575}$
Erro B (A x Bloco)+(A x Bloco x CF)	18	0,3335	42,5412	40,9587	2,2729	0,3131	0,3665	0,0330	8,1071
Prof (Profundidade)	3	$4,2848^{0,012}$	$531,2774^{0,021}$	$534,3426^{0,001}$	$18,2599^{0,134}$	$3,1803^{0,002}$	$1,9910^{0,001}$	$0,1037^{0,341}$	$90,5186^{0,003}$
Erro C (Prof *Bloco)	6	0,4798	74,2546	19,7151	6,6030	0,1834	0,0859	0,0762	6,0683
CF * Prof	6	$0,1506^{0,557}$	$17,6516^{0,544}$	$38,2496^{0,025}$	$3,1976^{0,108}$	$0,1316^{0,350}$	$0,0636^{0,886}$	$0,0475^{0,452}$	$11,2224^{0,014}$
A *Prof	9	$0,3056^{0,115}$	$19,5602^{0,505}$	$13,6927^{0,500}$	$2,60350^{0,173}$	$0,1991^{0,102}$	$0,0804^{0,851}$	$0,0983^{0,052}$	$4,9494^{0,259}$
CF * A * Prof	18	$0,1082^{0,894}$	$17,1415^{0,676}$	$7,2247^{0,952}$	$1,9461^{0,364}$	$0,0489^{0,978}$	$0,0707^{0,965}$	$0,0277^{0,912}$	$3,7379^{0,499}$
Erro D	66	0,1834	21,0286	14,6244	1,7552	0,1156	0,1530	0,0490	3,8369
Total	143								

Tabela 3 – Resumo da análise de variância (ANOVA) com quadrados médios e probabilidades das variáveis C lábil (CL), C orgânico total (COT), C da matéria orgânica associada aos minerais (CMAM), C da matéria orgânica particulada (CMOP), N total (NT), N da matéria orgânica associada aos minerais (NMAM), N da matéria orgânica particulada (NMOP) e relação C/N do solo área minerada de bauxita em recuperação com eucalipto (Euc), angico (Ang), nativas (Nat), área sem cobertura (Sem Cob) e mata nativa (Mata) não minerada em estágio secundário de regeneração (Mata) nas profundidades 0-10, 10-20, 20-40 e 40-60 cm após 56 meses de plantio

FV	GL	Quadrados Médios							
		CL	COT	CMAM	CMOP	NT	NMAM	NMOP	C/N
Bloco	2	$0,2111^{0,683}$	$23,9627^{0,622}$	$7,7755^{0,8141}$	$9,5821^{0,477}$	$0,4972^{0,293}$	$0,8140^{0,158}$	$0,0660^{0,591}$	$39,9340^{0,007}$
CF (Cobertura Florestal)	4	$9,2258^{0,001}$	$2067,8907^{0,000}$	$1487,1258^{0,000}$	$48,4218^{0,059}$	$14,8395^{0,000}$	$9,5633^{0,000}$	$0,5883^{0,039}$	$19,5447^{0,040}$
Erro A (Bloco x CF)	8	0,5280	47,4956	36,8455	11,7683	0,3464	0,3467	0,1174	3,9720
Prof (Profundidade)	3	$5,0096^{0,004}$	$867,7639^{0,001}$	$738,6439^{0,000}$	$32,5900^{0,004}$	$4,3119^{0,001}$	$3,2483^{0,000}$	$0,1483^{0,154}$	$57,6317^{0,004}$
Erro B (Prof x Bloco)	6	0,3710	37,6502	23,7934	2,4315	0,1884	0,0729	0,0588	4,0467
CF * Prof	12	$0,4549^{0,007}$	$73,9222^{0,000}$	$70,7258^{0,000}$	$13,7325^{0,000}$	$0,3861^{0,002}$	$0,2741^{0,095}$	$0,0756^{0,074}$	$6,3351^{0,175}$
Erro C	132	0,1859	18,3642	19,4400	2,9631	0,1362	0,1697	0,0445	4,5370
Total	167								

Tabela 4 – Resumo da análise de variância (ANOVA) com quadrados médios e probabilidades das variáveis C lábil (CL), C orgânico total (COT), C da matéria orgânica associada aos minerais (CMAM), C da matéria orgânica particulada (CMOP), N total (NT), N da matéria orgânica associada aos minerais (NMAM), N da matéria orgânica particulada (NMOP) e relação C/N do solo área minerada de bauxita em recuperação com eucalipto (Euc), angico (Ang) e nativas (Nat), com presença e ausência de *litter* nas profundidades 0-10, 10-20, 20-40 e 40-60 cm após 56 meses de plantio

FV	GL	Quadrados Médios							
		CL	COT	CMAM	CMOP	NT	NMAM	NMOP	C/N
Bloco	2	$0,0162^{0,974}$	$27,3959^{0,793}$	$18,8564^{0,833}$	$0,9281^{0,932}$	$0,3169^{0,746}$	$0,4355^{0,608}$	$0,0550^{0,440}$	$20,6270^{0,444}$
CF (Cobertura Florestal)	2	$0,5746^{0,471}$	$411,5085^{0,124}$	$413,5735^{0,104}$	$4,9129^{0,705}$	$2,3067^{0,216}$	$1,6383^{0,235}$	$0,0269^{0,642}$	$8,0428^{0,700}$
Erro A (CF*Bloco)	4	0,6077	111,6153	98,4678	12,8651	1,0024	0,7696	0,0541	20,6264
Litter	1	$2,0256^{0,046**}$	$183,4954^{0,106}$	$137,8662^{0,230}$	$3,2453^{0,429}$	$0,2703^{0,507}$	$0,1161^{0,748}$	$0,0031^{0,841}$	$14,9631^{0,403}$
CF*Litter	2	$0,1938^{0,577}$	$42,5290^{0,477}$	$20,7103^{0,772}$	$9,7315^{0,197}$	$0,1378^{0,784}$	$0,0648^{0,939}$	$0,0090^{0,880}$	$0,3504^{0,981}$
Erro B (Litter*Bloco+CF*Litter*Bloco)	6	0,3208	50,5966	76,7708	4,5178	0,5430	1,0249	0,0695	18,4838
Prof (Profundidade)	3	$3,2134^{0,022}$	$700,2630^{0,001}$	$509,1404^{0,001}$	$16,3560^{0,062}$	$2,9751^{0,001}$	$2,5462^{0,002}$	$0,0586^{0,008}$	$61,6389^{0,000}$
Prof*Bloco	6	0,4621	28,8327	22,7366	3,8356	0,1153	0,1309	0,0056	1,6827
CF*Prof	6	$0,3465^{0,179}$	$51,8129^{0,070}$	$54,8032^{0,044}$	$0,9761^{0,948}$	$0,2923^{0,105}$	$0,1378^{0,443}$	$0,0196^{0,846}$	$6,6085^{0,167}$
Litter*Prof	3	$0,0855^{0,771}$	$4,4366^{0,914}$	$1,0481^{0,988}$	$2,8934^{0,489}$	$0,0229^{0,935}$	$0,0156^{0,953}$	$0,0180^{0,746}$	$3,3877^{0,497}$
CF*Litter*Prof	6	$0,0944^{0,868}$	$28,0903^{0,370}$	$16,3937^{0,671}$	$3,3195^{0,475}$	$0,1960^{0,306}$	$0,0579^{0,870}$	$0,0793^{0,106}$	$1,8484^{0,853}$
Erro C	102	0,2278	25,6232	24,3223	3,5588	0,1616	0,1408	0,0439	4,2406
Total	143								

Tabela 4 – Resumo da análise de variância (ANOVA) com quadrados médios e probabilidades das variáveis C (CBM) e N (NBM) da biomassa do solo de área minerada de bauxita em recuperação com eucalipto (Euc), angico (Ang) e nativas (Nat), submetidas a adubação padrão (AE) e a combinação de química e orgânica (AO+AQ), com presença e ausência de *litter* na profundidade 0-10 cm após 56 meses de plantio

FV	GL	Quadrados Médios	
		CBM	NBM
Bloco	2	$0,0011^{0,871}$	$0,00014^{0,424}$
Cobertura Florestal (CF)	2	$0,0023^{0,760}$	$0,00011^{0,481}$
Erro A (CF*Bloco)	4	0,008	0,00013
Adubação (A)	1	$0,0008^{0,560}$	$0,00014^{0,425}$
CF*A	2	$0,0029^{0,337}$	$0,00015^{0,480}$
Erro B (A*Bloco+CF*A*Bloco)	6	0,0022	0,00019
Litter	1	$0,0018^{0,109}$	$0,000022^{0,644}$
CF*Litter	2	$0,0004^{0,497}$	$0,000001^{0,995}$
Adub*Litter	1	$0,0005^{0,4000}$	$0,00040^{0,066}$
CF*A*Litter	2	$0,0021^{0,063}$	$0,00002^{0,829}$
Erro C	12	0,0006	0,000099
Total	35		

Tabela 5 – Resumo da análise de variância (ANOVA) com quadrados médios e probabilidades das variáveis C (CBM) e N (NBM) da biomassa do solo de área minerada de bauxita em recuperação com eucalipto (Euc), angico (Ang), nativas (Nat), área sem cobertura (Sem Cob) e mata nativa (Mata) não minerada em estágio secundário de regeneração (Mata) na profundidade 0-10 cm após 56 meses de plantio

FV	GL	Quadrados Médios	
		CBM	NBM
Bloco	2	$0,0019^{0,4122}$	$0,0002^{0,2797}$
Cobertura florestal (CF)	4	$0,2034^{0,000}$	$0,00133^{0,000}$
Erro (Bloco* CF)	35	0,002103	0,000092
Total	41		

CONSIDERAÇÕES FINAIS

Na área pós mineração de bauxita estudada, em recuperação com espécies florestais, os tratamentos de adubação aplicados, sendo eles, adubação orgânica e química combinadas e a adubação orgânica, após 56 meses, refletiram em maior crescimento em volume nas árvores de *E. urophylla x E. grandis*, porém, não influenciaram o volume das árvores de angico e plantio misto de nativas. A biomassa e o estoque de C de *E. urophylla x E. grandis* também foram influenciados por estes tratamentos de adubação, chegando a 499 Mg ha^{-1} e 119,6 Mg ha^{-1}, respectivamente, na adubação combinada, valores estes cerca de quatro vezes maiores aos observados em angico e plantio de nativas.

A adubação não influenciou a produção, o acúmulo sobre o solo e a taxa de decomposição da serapilheira das coberturas florestais estudadas. O angico vermelho foi a cobertura florestal que apresentou a menor produção de serapilheira (*litterfall*), independentemente da época do ano e também a que menos acumula *litter* no solo. A época do ano influenciou a produção de serapilheira em *E. urophylla x E. grandis* e no plantio consorciado de nativas, sendo os maiores valores observados na época chuvosa e seca, respectivamente. Angico foi a cobertura com maior taxa de decomposição, observada, principalmente, na época chuvosa.

Das coberturas florestais implantadas em área pós mineração de bauxita, o folhedo do plantio misto de nativas foi o que apresentou maior teor nutricional em relação aos seguintes nutrientes estudados: P, K, Ca, Mg e S e, consequentemente, a que aportou mais nutrientes a superfície do solo.

A implantação de coberturas florestais em área pós mineração de bauxita aumenta o efluxo de CO_2 do solo, principalmente, no período de maior umidade do solo, sendo a maior parte deste CO_2 proveniente da respiração heterotrófica. Nos períodos mais secos, essa emissão se assemelha a área de Mata nativa, não minerada. O fluxo de metano apresentou-se negativo (influxo) em todas as coletas realizadas para todas as coberturas de solo estudadas.

As atividades de mineração reduzem drasticamente os estoques de COT e NT do solo, porém, a implantação de coberturas florestais, permite a elevação destes estoques em relação à área Sem Cobertura alguma. Os atributos orgânicos que primeiro sinalizam aumento dos estoques de C em decorrência do reflorestamento após 56 meses são o carbono lábil e da biomassa microbiana.