RAFAEL GONÇALVES TONUCCI

SEQUESTRO E DISCRIMINAÇÃO ISOTÓPICA DE CARBONO EM SISTEMAS AGROSSILVIPASTORIS

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

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“Posso ouvir o vento passar assistir a onda bater mas o estrago que faz a vida é curta pra ver....”
(O Vento, Marcelo Camelo)

“Twice as much ain’t twice as good and can’t sustain like one half could.....”
(Gravity, John Mayer)

À minha filha Lara, pessoa mais importante na minha vida,
motivo de tudo que faço.

Dedico

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Biografia

RAFAEL GONÇALVES TONUCCI, filho de Erico Tonucci Filho e Ana Maria Oliveira Gonçalves Tonucci, nasceu em Belo Horizonte, Minas Gerais, em 17 de junho de 1978.

Em julho de 2004, graduou-se em Zootecnia pela Universidade Federal de Viçosa. Em agosto de 2004 entrou para o curso de mestrado em zootecnia pela UFV defendendo sua dissertação em outubro de 2006.

Em outubro de 2006 começou o curso de doutorado em zootecnia pela UFV. Pelo programa PDEE da CAPES ficou um ano na University of Florida, Gainesville, USA. Defendeu tese em maio de 2010.

Sumário

Resumo

TONUCCI, Rafael Gonçalves, D.Sc., Universidade Federal de Viçosa, maio de 2010. **Sequestro e discriminação isotópica de carbono em sistemas agrossilvipastoris.** Orientador: Rasmo Garcia. Co-Orientadores: Júlio Cesar Lima Neves e Dilermando Miranda da Foncesa.

O estudo foi realizado com o objetivo de avaliar o efeito de diferentes sistemas de uso da terra no estoque e na dinâmica do carbono orgânico do solo (COS). Para isso foram coletadas amostras de solo em seis diferentes sistemas de uso da terra na Fazenda Riacho, pertencente à Votorantim Siderurgia – Unidade Agroflorestal-, no município de Vazante, MG. Os sistemas de uso da terra escolhidos foram: uma pastagem exclusiva (estabelecida a aproximadamente 35 anos); uma floresta de eucalipto velha (estabelicida em 1985); uma floresta de eucalipto nova (estabelecida em 2005); um sistema agrossilvipastoril velho (estabelecido em 1994); um sistema agrossilvipastoril novo (estabelecido em 2004); e uma floresta nativa de referência do cerrado local. As amostras de solo foram coletadas em 4 camadas distintas (0 – 10; 10 – 20; 20 – 50; 50 – 100 cm) em quatro diferentes áreas do mesmo sistema de uso da terra. Cada uma desses áreas foi considerada uma repetição. O delineamento experimental utilizado foi o inteiramente casualizado. Após a coleta o solo foi passado através de peneira de 2 mm e as amostras foram levadas para a University of Florida, FL, USA para que as análises fossem realizadas. As amostras foram fracionadas fisicamente em 3 frações: areia grossa (250 – 2000 µm); areia fina (250 – 53 µm) e silte e argila (<53 µm). Foram realizadas análises de carbono total e de seu isótopo estável (^{13}C) em cada uma das fraçoes bem como no solo como um todo. As resultados de COT mostram que o estoque de carbono no solo, em um metro de profundidade, dos sistemas analisados seguiu a ondem: Sistema Agroflorestal Velho (148 Mg ha^{-1}) ≥ Eucalipto Novo (143 Mg ha^{-1}) ≥ Floresta nativa (137 Mg ha^{-1}) = Sistema Agroflorestal Novo (130 Mg ha^{-1}) ≥ Eucalipto Velho (121 Mg ha^{-1}) ≥ Pastegem (116 Mg ha^{-1}). A pastagem apresentou o maior estoque de COS na fração silte + argila e na fração areia fina que representam a forma mais estável do carbono no solo. A hierarquia dos agregados e os teores de carbono nas diferentes frações sugerem um impacto na sistema de uso da terra no estoque de carbon so solo mostrando que o solo das pastagens e dos sistemas agrossilvipastoris têm potêncial para o sequestro de carbono. Os resultados de $\delta^{13}C$ foram maiores para a pastagem e para os sistemas agrossilvipastoris tanto no solo como um todo como para as frações. A maior parte do COS, em todas as camdas, das pastagem e para sistemas agrossilvipastoris era de origem de plantas C4. As frações do solo destes sistemas apresentaram uma contribuição de COS de origem C4 de 40%; 35%; e 92% nos sistemas agroflorestais velho; novo; e pastagem, respectivamente, na camda de 0 – 10 cm da fração areia grossa. Na fração silte e argila a contribuição do carbono de origem C4 no COS na profundidade de 50 – 100 cm foi de 80%; 65%; e 80% para os sistemas agroflorestais velho; novo e pastagens, respectivamente. Os resultados de $\delta^{13}C$ apresentaram uma tendência de aumentar com aumento na profundidade do solo sugerindo que a a vegetação que se encontrava originalmente na região no passado mais distante (holoceno médio) era composta basicamente por plantas do ciclo C4 e não do ciclo C3 como se obseva hoje em dia. Maiores investigações precisam ser realizadas para uma afirmação mais conclusiva a respeito dessa afirmativa. Conclui-se que o sistema de uso da terra altera o estoque e a dinâmica do carbono no cerrado e que pastagens e sistemas agrossilvipastoris podem ser utilizados para mitigar o carbono atmosférico no solo.

Abstract

TONUCCI, Rafael Gonçalves, D.Sc., Universidade Federal de Viçosa, May, 2010. **Carbon sequestation and isotopic discrimination in agrosilvopasture.** Adviser: Rasmo Garcia. Co-Advisers: Júlio Cesar Lima Neves and Dilermando Miranda da Foncesa.

The aim of this research was to evaluate the effect of different land-use systems in the soil organic carbon (SOC) dynamic. Samples were collected in six different systems at the Riacho farm, Vazante, MG, Brazil. Land-use systems chosen were: open pasture; native forest (Cerrado); old agroforestry; new agroforestry; old eucalyptus; and new eucalyptus. From each system, replicated soil samples were collected from four depths (0–10, 10–20, 20–50, and 50–100 cm); the samples were fractionated into 250–2000, 53–250, and <53 μm size classes representing macroaggregates, microaggregates, and silt+clay, respectively, and their C contents and $\delta^{13}C$ determined. Up to 1 m depth, the total SOC contents (Mg ha^{-1}) in the systems were in the order: Old Silvopasture (148) ≥ New Eucalyptus (143) ≥ Forest (137) = New Silvopasture (130) ≥ Old Eucalyptus(121) ≥ Pasture (116). Pasture had the highest SOC content in the silt+clay and microaggregate fractions that represent more stable forms of C. The aggregate hierarchy and C content in different soil-size fractions suggest the likely impact of the (unknown) previous land-use on total C stock in these young systems, as well as the higher C sequestration potential of pasture and silvopastoral systems in the Cerrado. Results from $\delta^{13}C$ showed that pasture and agroforestry systems had higher values of $\delta^{13}C$ in whole soil and in the aggregate fractions. Soil organic carbon was mainly derivate from C4 plants in all land-use systems at all depths. At open pasture old agroforestry and new agroforestry systems C4 carbon in the microaggregate fraction at the layer of 0 – 10 cm corresponded to 92; 40; and 35%, respectively. At the silt+clay fraction at the layer of 50 – 100 cm C4 contribution to total SOC was 80; 80; and 65% in the open pasture; old agroforestry and new agroforestry, respectively. The $\delta^{13}C$ values showed a trend to increase with depth increasing suggesting that in the past (mid holocen) the vegetation placed there was basically composed by plants this C4 pathway

and not with C3 plants as it is seen now a day. Furthers studies are need to confirm and better understand this trend. The overall conclusion of this research was that agroforestry systems placed in the Cerrado Biome has the potential to mitigate C and might be recommended as a C sinker tool to farmers.

Introdução Geral

A emissão de gases na atmosfera terrestre é um problema que cada vez mais preocupa a sociedade. O aumento da frota de veículos, o desenvolvimento econômico concentrado em algumas regiões do mundo e a utilização de queimadas para abrir novas fronteiras agrícolas, principalmente em países em desenvolvimento, têm aumentado significativamente a emissão dos gases de efeito estufa (GEE) na atmosfera terrestre, com destaquepara o metano (CH_4), o dióxido de carbono (CO_2) e o óxido nitroso (N_2O). Esses gases têm capacidade de absorver parte da radiação solar que é refletida pela superfície terrestre. Como consequência a energia da radiação emitida sobre a Terra fica retida e não é liberada ao espaço, permanecendo maior do que seria na ausência desses gases.

Os GEE absorvem parte da radiação infravermelha emitida pela superfície da Terra e irradiam, por sua vez, parte dessa energia absorvida de volta à superfície. Essa conservação da energia promovida por esses gases tem um lado positivo que é tornar a temperatura do planeta compatível com a vida, mas nos últimos 200 anos tem-se observado um aumento crescente na emissão dos GEE, tornando esse aquecimento muito pronunciado acarretando uma série de mudanças no clima do planeta.

Dos gases causadores do efeito estufa o CO_2 e o CH_4 foram os que tiveram seus níveis mais aumentados nos últimos dois séculos. Esse aumento é creditado principalmente à queima de combustíveis fosseis e à praticas agrícolas não conservacionistas, que tem levado a alterações no reservatório de carbono (C) terrestre.

Os principais reservatórios do ciclo do C no planeta são o CO_2 atmosférico, a biota (na sua maioria na forma de vegetação), a manta orgânica do solo e os oceanos (IPCC, 2001). Deste total os oceanos contribuem com a maior quantidade cerca de 39.000 Pg C, que na sua maior parte encontra-se em camadas muito profundas, sendo considerado não circulante (Janzen, 2004). A atmosfera, agora com uma concentração de aproximadamente 370 ppmv (Keeling & Whorf, 2002) contribui com 785 Pg C na forma de CO_2. O estoque de C na biota é bastante incerto, mas estimado entre 400 e 600 Pg C, sendo que 75% deste valor estão em florestas (IPCC, 2001).

Em ambientes terrestres, o maior reservatório de C ativamente ciclável é o solo. Na camada da superfície até 1 metro, o solo contém 1500-2000 Pg C (IPCC, 2001) em diferentes formas orgânicas, desde “litter” de uma planta recém-caída até carvão vegetal bastante antigo. Aproximadamente 1/3 do C orgânico do solo ocorre em áreas florestais, mais 1/3 em áreas de pastagens e campos nativos e o restante encontra-se em terras alagadas e em solos de culturas agrícolas (Janzen, 2004).

O carbono orgânico do solo (COS) é derivado, principalmente, da biomassa da vegetação e constitui um elo fundamental para o ciclo do C. Esse componente pode conter entre 50 e 80% do carbono de uma floresta madura e mais de 95% do carbono de área de pastagem (Ogle et al., 2005). O estoque de C no solo reflete o balanço entre as entradas de C via resíduos vegetais e outros compostos orgânicos e as saídas (perdas) provenientes da decomposição, erosão e lixiviação (Cowie et al., 2006). Assim pode-se observar que a taxa de reciclagem e mineralização da matéria orgânica (MO) leva a um maior estoque de C em florestas temperadas de clima frio e pântanos devido a uma menor atividade da microbiota do solo do que em regiões de clima tropical onde a reciclagem da MO é muito rápido (Bolin et al., 2000).

O uso da terra e o sistema de manejo agrícola aplicado em uma área podem alterar o armazenamento do COS devido à variação de tecnologias como a irrigação, fertilização, aração dentre outras. Consequentemente o uso e o manejo da terra podem ser utilizados como capturadores de GEE, principalmente o CO_2, fazendo do solo um sumidouro de CO_2 (Lal et al., 1998; Ogle et al., 2005).

O termo sequestro de carbono pelo solo implica na transferência de CO_2 atmosférico para o reservatório de C no solo por meio de: (1) humificação dos resíduos culturais e os biosólidos adicionados ao solo; (2) formação de carbonatos secundários (Lal, 2007). O reservatório de carbono do solo pode ser tanto fonte como dreno do C atmosférico dependendo do uso e do manejo que se dá à terra. O aumento de 1 Pg no reservatório de carbono no solo é equivalente à redução da concentração de CO_2

atmosférico em 0,47ppm (Lal, 2007). O COS é rapidamente perdido pela conversão de ecossistemas naturais em ecossistemas agrícolas. A magnitude dessas perdas pode variar entre 50 a 70% depois de 5 a 20 anos do desflorestamento em solos tropicais e de 25 a 50% depois de 20 a 50 anos em solos de clima temperado (Lal, 2004). Em resumo, a magnitude dessas perdas é sempre maior quando o aporte de C no sistema for menor do que as exportações.

A depleção do COS tem efeito positivo, mas adverso, no aumento da concentração de CO_2 atmosférico. Uma perda severa de COS leva ao declínio na qualidade do solo provocado pelo balanço negativo dos nutrientes do solo, balanço negativo da água do solo, devido ao maior escoamento superficial e consequente aumento da erosão e redução da biodiversidade de microfauna do solo. Esse declínio na qualidade reduz a produção primária líquida (PPL), decrescendo a quantidade e a qualidade da biomassa que será retornada ao solo, acentuando ainda mais essa depleção do COS (Lal, 2007).

O carbono do solo é estimulado por práticas que maximizam as entradas de MO e minimizam suas perdas. Assim, técnicas como as que permitem que os resíduos culturais permaneçam no campo; a aplicação de fertilizantes que irá favorecer a PPL e por consequência o acumulo de C; a escolha de espécie com uma taxa de composição mais lenta ou ainda a mistura de espécies que irão potencializar o acúmulo de C e o manejo de culturas com distúrbios mínimos, que tem dentre outros objetivos, minimizar a perda de solo por erosão são técnicas bastante indicadas na tentativa de maximizar os valores de COS e aumentar das taxas de mitigação de CO_2 atmosférico.

West and Marland (2003) postularam outro fator, de ordem econômica, pode influenciar o uso da terra como sequestrador de $CO_{2:}$ a demanda por alimento. Esses autores sugerem que à medida que se aumenta a demanda por terras agrícolas uma maior quantidade de CO_2 seja mitigado da atmosfera para o solo devido a uma maior produção da cultura, por outro lado quando esta demanda é reduzida menos CO_2 é mitigado, uma vez que áreas menores serão plantadas.

O manejo agrícola é iniciado com a conversão de um ecossistema natural (pastagem ou floresta) em uma plantação. Esta conversão requer a utilização de técnicas como a aração que levam a perdas do COS, devido a um intenso distúrbio que promove a ruptura das estruturas dos agregados do solo, aumentando a decomposição.

A produtividade de uma cultura individual influencia o acúmulo de carbono no solo devido a diferença na qualidade de resíduo cultural deixado no campo e que será incorporado na matéria orgânica do solo (MOS). Eghball et al. (1994) demonstraram maior produção de resíduos em um plantio contínuo de milho quando comparado com um plantio rotacionado entre milho e soja. Essa maior produção de resíduo levou a um maior acúmulo de C no solo.

Os efeitos do manejo e do uso da terra determinam de forma bastante significativa o balanço de C em solos agrícolas. Deve-se, entretanto, ressaltar que o potencial dos solos em servir como absorvedores de CO_2 da atmosfera via técnicas de uso e manejo da terra muda com o clima (tropical ou temperado), com o regime hidrológico (seco ou úmido), com o tipo de solo bem como sua textura e a profundidade.

A mudança do uso da terra de uma floresta ou pastagem para uma plantação agrícola irá, provavelmente, levar a uma perda no COS (Cowie et al., 2006). Guo e Gifford (2002), realizando uma meta análise, encontraram que o estoque de C no solo foi reduzido em 50% ou mais quando pastagens foram convertidas em agricultura. Por outro lado a substituição de uma área onde existia uma agricultura por uma pastagem ou floresta é normalmente acompanhada de um incremento no C do solo. Nos trópicos onde a reciclagem do C é mais rápido, Binkley e Resh (1999) não observaram impacto da conversão de uma cultura de cana de açúcar para uma floresta de eucalipto, após 32 meses, no C total do solo. Entretanto observou-se uma forte queda na participação do C advindo da cana.

O impacto no COS na conversão de uma pastagem para uma floresta não é ainda muito claro, mas normalmente ocorrem perdas muito significativas (Gifford e

Barrett, 1999; Turner e Lambert, 2000). O carbono do solo decresce inicialmente, como resultado do declínio do aporte de “litter” oriundo das pastagens e depois volta a aumentar quando as entradas provenientes da floresta começam a serem adicionados ao sistema (Jonhson, 1992; Grigal e Berguson, 1998). Com o crescimento o C é restabelecido pela queda do “litter” e do reciclagem de raízes, normalmente atingindo os níveis de C original em 30 anos (Paul et al., 2002).

De uma maneira geral as florestas possuem mais da metade de todo o C terrestre e são responsáveis por cerca de 80% da troca de carbono entre o ecossistema terrestre e a atmosfera. O ecossistema florestal tem uma absorção anual de C estimada em 3 Pg (Montagnini e Nair,2004). Entretanto nas últimas décadas, esse balanço tem sofrido algumas alterações devido ao grande número de desmatamentos que ocorreram, principalmente, nos trópicos.

Sendo assim promover a agrofloresta é uma alternativa bastante interessante e uma excelente oportunidade para solucionar os problemas relacionados com o uso da terra e a emissão de CO_2 que induz ao aquecimento global.

Sistemas agroflorestais têm papel central no ciclo global do C e contém aproximadamente 12% do C terrestre mundial (Dixon, 1995). A degradação do solo como resultado de uma má utilização da terra tem sido apontada como uma das maiores causas de perda de C e consequente acúmulo de CO_2 na atmosfera. A agrofloresta pode envolver práticas que favoreçam a emissão de GEE, tais como controle da pastagem com fogo, aplicação de adubos nitrogenados e a produção animal que contribui para a produção de metano (Dixon, 1995). Entretanto, vários estudos têm mostrado que a inclusão de árvores em ambientes agrícolas comumente melhora a produtividade do sistema além de proporcionar uma oportunidade de mitigação do CO_2 atmosférico, funcionando como dreno de C (Dixon et al.1994; Dixon, 1995).

Basicamente existem três categorias de atividades nas quais o manejo florestal pode reduzir o carbono atmosférico. A primeira seria o sequestro de carbono que ocorre através de reflorestamento e restauração de áreas degradadas com atividades silvícolas. A segunda seria a conservação do carbono através da conservação da biomassa e do carbono do existente nas florestas, melhorando as técnicas de colheita com a redução dos impactos do carregamento e um melhor uso do fogo tanto em sistemas agrícolas quanto florestais. A terceira é a substituição do carbono que é o aumento da conversão da biomassa florestal em produtos de madeira de vida longa na forma de móveis, aumento da utilização de biocombustíveis (Bass et al., 2000). A agrofloresta pode se enquadrar na categoria de sequestradores de C devido à sua aplicabilidade em recuperar áreas agrícolas degradadas, assim como em reflorestamentos.

Essencialmente o sequestro de carbono é a diferença entre o C adquirido pela fotossíntese e o carbono perdido ou liberado pela respiração de todos os componentes do sistema. A maioria do C entra no ecossistema via fotossíntese ocorrida nas folhas e o seu acúmulo é mais óbvio quando ocorre na biomassa que se acumula acima do solo. Entretanto, mais da metade do carbono acumulado é transportado para o solo via crescimento e reciclagem de raízes, decomposição do "litter" e por consequência o solo contêm o maior estoque de C no ecossistema.

Práticas que aumentam a produção primária líquida e/ou retornam uma grande proporção da biomassa para o solo têm o potencial de aumentar o estoque e C no solo (Montagnini e Nair, 2004).Com o manejo adequado das árvores em áreas agrícolas ou pastoris uma fração significativa do C atmosférico pode ser capturada e armazenando na biomassa das plantas ou no solo. Entretanto, aumentar o estoque de C por um período de tempo é apenas uma etapa e o que determina que o C está de fato sequestrado é o seu armazenamento por um período grande de tempo (Albrecht e Kandji, 2003).

Em sistemas agroflorestais o sequestro de carbono é um processo dinâmico que pode ser dividido em fases. No estabelecimento a grande maioria dos sistemas atua como uma fonte de GEE. Em seguida há uma fase de rápido acúmulo e um período de manutenção onde grande quantidade de carbono é armazenada nos galhos, troncos e raízes das plantas e também no solo. No final do período de rotação ocorre a colheita das árvores, a terra é novamente utilizada para a cultura agrícola e parte do C fixado é novamente liberado para a atmosfera (Dixon, 1995). Assim, só existirá um sequestro efetivo se o balanço líquido de C do estoque final e inicial for positivo após algumas décadas (Albrecht e Kandji, 2003). Pode-se sumarizar que três fatores são necessários para determinar a quantidade de carbono sequestrada: (1) o incremento da quantidade de C na biomassa remanescente devido à mudança no uso da terra e do aumento da produtividade; (2) a quantidade de C recalcitrante remanescente acima do solo ao final da colheita das árvores; (3) a quantidade de C sequestrado em produtos pela madeira colhida, incluído o seu destino final (Johnson et al., 2001).

A grande maioria das estimativas do potencial de sequestro de carbono pelos sistemas agroflorestais são originadas dos trópicos úmidos. Estimativas baseadas no projeto “Alternativas para as derrubadas e queimadas” do ICRAF, concluíram que para os trópicos úmidos os sistemas agroflorestais têm um melhor potencial de sequestro de carbono acima do solo (através do acúmulo de biomassa das árvores) e não abaixo do solo. Segundo a conclusão do projeto isso se daria com a implantação de sistemas baseados em árvores em regiões de pastagens degradadas e pastagens nativas. Entretanto as savanas tropicais armazenam aproximadamente 1/3 do C na forma de vegetação, assim como as florestas tropicais úmidas, mas esse bioma também apresenta um alto estoque de C no solo, assim como as florestas boreais (Montagnini e Nair, 2004).

Estudos comparando o sequestro de C em um sistema árvore-cutura e a cultura solteira mostraram que o sistema árvore-cultura foi muito mais eficiente em acumular C do que a monocultura, mas acumulou menos C do que a floresta sozinha. Quando se compara diferentes tipos de sistemas agroflorestais como o plantio de árvores em faixas, dentro da cultura, utilização de culturas perenes combinadas com árvores, essa última pode ser considerada uma boa sequestradora de C, no entanto quando é intensamente manejada, esse potencial de mitigar o CO_2 é bastante reduzido, mostrando que quanto mais intenso é o manejo do solo maiores são as chances de perda de C do sistema (Montagnini e Nair, 2004).

Sendo assim os sistemas silvipastoris, uma outra modalidade do sistema agroflorestal onde coexistem na mesma área árvores, pastagem e animal tornam-se uma boa alternativa como acumulador de C, uma vez que o manejo na pastagem estabelecida na floresta é bem conservador e as gramíneas também apresentam, assim como as árvores, grande potencial de armazenar C. As pastagens podem acumular tanta MO quanto as florestas (Corre et al., 2000), mas sua contribuição é normalmente menos enfatizada porque a maior parte do que é armazenado no sistema radicular. Taylor e Lloyd (1992) postularam que as gramíneas de clima temperado e as florestas são essencialmente iguais em seu papel como sumidouros de C, mas diferem fundamentalmente em como o C é armazenado no ecossistema. A maior parte do carbono absorvido em pastagens temperadas é estocada na forma de MOS, enquanto em florestas maduras mais da metade do C esta na forma de biomassa lenhosa e o restante como MOS.

Potencialmente sistemas silvipastoris podem acrescentar mais carbono nos sistemas que florestas e pastagens exclusivas. A maior eficiência em compartilhar os recursos do meio entre as árvores e as gramíneas; a fixação de N pelas leguminosas e o microclima criado pelas árvores pode aumentar significativamente a produção liquida total da fitomassa disponível para armazenamento (Sharrow e Ismail, 2004). Sistemas silvipastoris podem ser eficientes em sequestrar C e N com o passar do tempo porque apresentam duas vias de sequestro ativas, tanto das árvores quanto das gramíneas inseridas no sub-bosque (Sharrow et al., 1996). Isto pode ser manifestado em um maior estoque de C e N quando as gramíneas estão mais vigorosas no sub-bosque e a floresta ainda é jovem e com o passar do tempo esse C passa a ser também armazenado na biomassa das árvores em materiais que irão compor a MOS.

Sharrow e Ismail (2004) avaliando o estoque de C e N em sistemas silvipastoris, florestas plantadas e pastagens solteiras no oeste do estado do Oregon, EUA observaram que a produção de forragem entre o sistema silvipastoril e a pastagem solteira não diferiram estatisticamente e foram de 624 e 649 kg.ha^{-1}, no mês de avaliação, respectivamente, entretanto a produção de litter saiu de 4 kg.ha^{-1} na pastagem para 95 kg.ha^{-1} no sistema silvipastoril. A quantidade de C armazenado no solo da pastagem e do sistema foi bem maior do que a encontrada na floresta plantada com valores de 40,9; 38,0 e 34,1 kg.ha^{-1}, respectivamente. O acúmulo de total médio de C foi maior para o sistema silvipastoril (109,3 kg.ha^{-1}) quando comparado à pastagem solteira (103,5 kg.ha^{-1}) e à floresta plantada (101,2 kg.ha^{-1}).

Em outro experimento avaliando o estoque de C e N em um sistema silvipastoril formado por três espécies de árvores (*Acácia nilótica, Dalbergia sissou* e *Prosopis juliflora*) e duas espécies de gramíneas (*Desmostachya bpinnata e Sporobolus manginatus*), Kaur et al. (2002) observaram que o acúmulo de C foi de 1,18 a 18,55 Mg C ha^{-1} e o input de C na produção primária liquida variou entre 0,98 e 6,50 Mg C ha^{-1} ano. O fluxo de carbono na produção primária líquida aumentou significativamente devido à interação dos gêneros Prosopis e Dalbergia com as gramíneas. Comparado com o sistema de pastagem solteira a MOS a produtividade biológica e o estoque de carbono foram melhores nos sistemas silvipastoris. Esses mesmos autores observaram que o total de C inserido no sistema 38 a 42% estava associada com o C abaixo do solo e que 62 a 58% esta associado com a parte aérea.

Esse estudo também mostrou que a alocação dos produtos da produção primaria no solo foi maior nas pastagens solteiras (1,33 a 3,88 Mg C ha^{-1}.ano^{-1}) do que no sistemas silvipastoris (1,00 a 2,93 Mg C ha^{-1} ano). Os autores concluíram que a associação de árvores com gramíneas promoveu um aumento no input de resíduos de plantas no solo e que este apresenta um papel importante no incremento da ciclagem de nutrientes e da produtividade biológica dos sistemas baseados em árvores.

As pastagens são um dos melhores agroecossistemas em aumentar o estoque de MO do solo (Desjardins et al., 1994). Entretanto estudos conduzidos em pastagens na Amazônia mostraram evolução diferente dessas reservas orgânicas observando um decréscimo na quantidade de C, enquanto Serrão et al. (1979) e Hetch (1982) observaram um constante acréscimo nos valores iniciais e após 5 anos de substituição da florestas por pastos de gramíneas do gênero *Brachiaria*. Choné et al. (1991) e Koutika et al. (1997) também observaram incremento nos teores de C no solo após alguns anos de pastagens. Uma serie de fatores podem ser responsáveis por essas diferenças tais como a localização geográfica, tipo de solo, práticas culturais e manejo do solo.

Em estudo bem completo tentando mostrar o impacto do desflorestamento e sua conversão em pastagens nos teores de C e na dinâmica da MOS em diferentes tipos de solo, Desjardins et al. (2004) observaram que em solos mais argilosos o teor de carbono na camada superficial é maior e aumenta após a conversão para pastagem de 43,6 g kg^{-1} sobre solo de floresta para 54,6 g kg^{-1} em pastagem de 15 anos. Em solos arenosos os teores de C no solo foram bem menores, mas apresentaram o mesmo comportamento passando de 14,4 g kg^{-1} para 18,5 g kg^{-1} quando em floresta e em pastagem de 15 anos, respectivamente. Esse aumento nos teores de C nos dois tipos de solo é devido a um aumento deste elemento na camada superficial (0 a 5 cm) do solo. Neste mesmo estudo os autores utilizaram o δ^{13} C para avaliar a contribuição relativa do C derivado da floresta e do C derivado das pastagens nas diferentes frações da MOS. Nos solos com maiores teores de argila a proporção de C derivado das pastagens foi maior na fração fina quando comparada com a fração mais grossa, após 15 anos de pastagens cerca de 26 a 35% do C na fração fina é originário das gramíneas dos pastos. Em solos arenosos a incorporação do C das pastagens é mas rápida e varia de 42 a 48% de acordo com fração, com menores valores observados para as frações mais finas.

Os solos de cerrado compreendem uma enorme variedade de vegetação e ocupam área de aproximadamente 204 milhões de hectares. Essas regiões têm sido foco de uma intensa expansão agrícola desde os anos 60, e hoje enormes áreas de vegetação nativa encontram-se substituídas por agricultura, pastagens cultivadas e áreas de reflorestamento (Embrapa Cerrado, 1999). Silva et al. (2004) objetivando analisar as perdas e os ganhos de C em seis diferentes tipos de pastagens comparadas com uma pastagem nativa observaram que os teores de C variaram de acordo com o manejo que é dado ao pasto. Nos pastos onde o manejo era menos intenso e em seu histórico não constava a utilização de adubação nitrogenada, observou-se uma redução nos teores de C (97 Mg C ha^{-1}) quando comparados à pastagem nativa (100 Mg C ha^{-1}). Por outro lado nas pastagens que foram manejadas de forma mais intensa com aplicação de N ou consorciada com leguminosas, observou-se um incremento nos teores de C fixado no solo de 100 Mg C ha^{-1} para 114 Mg C ha^{-1} para pastagem nativa e bem manejada, respectivamente. Uma possível explicação para esse fato é a maior produção de biomassa pelas gramíneas e por consequência maior incorporação desta biomassa na MOS. Os autores concluíram que pastagens degradadas ou com algum nível de degradação podem deixar de ser drenos do CO_2 atmosférico para ser fonte, contribuindo ainda mais para o aumento dos GEE na atmosfera terrestre.

A relação de isótopos estáveis em compostos orgânicos e inorgânicos da natureza frequentemente mostram informações relacionadas ao tipo de processo de formação desses compostos; a taxa na qual esses processos ocorreram e; as condições ambientais no período em que esses componentes foram formados. Essas informações assim como a variação natural desses compostos são extremamente úteis em identificar e quantificar as fontes e as taxas dos fluxos entre os ciclos biogeoquímicos desses elementos, em especial o C e o N.

No que diz respeito ao sistema solo-planta a relação do isótopo natural estável ($^{13}C/^{12}C$) do carbono orgânico do solo contêm informações a respeito da presença ou ausência de espécies com o ciclo fotossintético C3 (baixa $^{13}C/^{12}C$) e C4 (alta $^{13}C/^{12}C$) nas comunidades de plantas existentes e a sua contribuição para a produção primária liquida no tempo. Assim as mensurações de carbono orgânico no solo tem sido utilizadas para documentar os efeitos do uso da terra na estrutura do ecossistema, para quantificar as taxas e a dinâmica de vegetações em ecossistemas naturais.

O carbono é encontrado naturalmente na natureza em duas formas: o ^{12} C e o ^{13}C. Aproximadamente 99% de todo o carbono da natureza se apresenta na forma de ^{12}C e apenas 1% e encontrado na forma ^{13}C. A razão entre estes dois isótopos estáveis em materiais naturais varia muito pouco ao redor de seus valores médios como um resultado do fracionamento desses isótopos durante processos físicos, químicos e biológicos. Essas diferenças naturais entre os isótopos do carbono permitem que o C derivado de diferentes vias fotossintéticas possam ser rastreados na matéria orgânica do solo. As plantas do ciclo fotossintético C3 apresentam valores de $\delta^{13}C$ variando de -32‰ a - 22‰, com um valor médio de 27‰ (Boutton, 1996). Por outro lado plantas do cilco fotossintético C4 apresentam valores $\delta^{13}C$ variando de -17‰ a -9‰ com valores médios de -13‰ (Leary, 1988). Assim os valores de $\delta^{13}C$ relatados para plantas C3 e

C4 não se sobrepõem , diferenciando um do outro por um valor médio de 14‰ (Boutton, 1996) o que faz das análises de carbono isótopo um mecanismo muito poderoso e útil no estudo da dinâmica do carbono em ambientes naturais.

Diante do exposto foram conduzidos trabalhos como o objetivo de avaliar o estoque e a dinâmica do carbono do solo de diferentes sistemas de uso da terra no cerrado de Minas Gerais, Brasil.

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Chapter 1

Soil Carbon Storage in Silvopasture and Related Land-use Systems in Brazilian Cerrado

Abstract

Silvopastoral management of fast-growing tree plantations is becoming popular in the Brazilian Cerrado (savanna). In order to understand the influence of such systems on soil carbon (C) storage, we studied C content in three aggregate-size classes in six land-use systems (LUS) on Oxisols in Minas Gerais, Brazil. The systems were a native forest, a treeless pasture, 24- and 4-year-old eucalyptus plantations, and 15- and 4-year-old silvopastures of fodder grass plus animals under eucalyptus. From each system, replicated soil samples were collected from four depths (0–10, 10–20, 20–50, and 50–100 cm), fractionated into 2000 to 250, 250 to 53, and <53 μm size classes representing macroaggregates, microaggregates, and silt+clay, respectively, and their C contents determined. Macroaggregate was the predominant size-fraction under all LUS especially in the surface soil layers of tree-based systems. In general, C concentrations (g kg^{-1} soil) in the different aggregate-size fractions did not vary within the same depth. The soil organic carbon (SOC) stock (Mg C ha^{-1}) to 1 m depth was highest under old agroforestry systems compared with other LUS. The soils under all LUS had higher C stock compared to other reported values for managed tropical ecosystems: down to 1 m, total SOC stock values ranged from 148 Mg ha^{-1} under old agroforestry system to 116 Mg ha^{-1} under pasture. Considering the possibility for formation and retention of microaggregates within macroggregates in low management-intensive systems such as silvopasture, the macroaggregate dynamics in the soil seem to be a good indicator of its C-storage potential.

Introduction

The average surface temperature is reported to have risen globally by 0.55° C since 1970 due to anthropogenic enrichment of greenhouse gases (GHG) such as carbon dioxide (CO_2) in the atmosphere (IPCC, 2007). Possible implications of this unprecedented global warming include increases of extreme weather events, sea level rise, and precipitation changes (Allen and Ingram, 2002; Trenberth et al., 2007). Recognizing the role of soils as a potential sink for atmospheric C (Ogle et al., 2004; Feller and Bernoux, 2008), there is a growing interest in methods to store C in soils for mitigating GHG emissions. Since agroforestry systems (AFS) fall under the afforestation and reforestation programs that have been approved by the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCC) as a GHG offset activity, soil C storage potential of AFS is of special significance (Nair et al., 2009; 2010).

Globally, land-use changes in forestry and agriculture are responsible for 25% of GHG emissions (Weyant et al., 2006), but in Brazil, these sectors are reported to be responsible for more than two thirds of the emissions (Comunicação Nacional, 2004). Most of these agricultural areas are grasslands, of which at least 60% are in some stage of degradation (IBGE, 2006). Silvopasture, an agroforestry practice that combines trees with forage (pasture or hay) and livestock production, has recently gained prominence as an ecologically sustainable and environmentally desirable approach to managing degraded pasture lands (Mosquera-Losada et al., 2005; Haile et al., 2008; Nair et al., 2008). This system of tree plantation development on pasture lands is now becoming popular in Brazil.

Information on soil C stored in the Cerrado (Brazilian savanna) is somewhat scanty compared with data from other ecosystem types of the country. Bustamante et al. (2006) estimated the total C stock in the vegetation plus soil (to 1 m depth) in the Cerrado as 265 Mg ha^{-1}, with nearly 70% as SOC. Silva et al. (2004) found a sequestration rate of -0.87 to 3 Mg C ha^{-1} yr^{-1} under different options of pasture management. Other reported rates of C changes in the Cerrado soils include the accumulation of 1.2 Mg C ha^{-1} yr^{-1} (0 to 100 cm soil depth) after 12 years of hybrid eucalyptus (*Eucalyptus* sp.*)* cultivation on land cleared from its native Cerrado vegetation (Corazza et al., 1999) as well as the losses of 0.4 Mg C ha^{-1} yr^{-1} (0 to 60 cm soil depth) under a 20-yr-old stand of pine (*Pinus* sp.) on an Oxisol and 1.3 Mg C ha^{-1} yr^{-1} under a 7-yr-old eucalyptus stand on an Entisol, both in the Cerrado (Zinn et al., 2002). However, lack of uniformity in methods for soil sampling and C determination in these different studies make it difficult to compile and compare the reported data. Based on a study of silvopasture stands of 11-yr-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with perennial ryegrass (*Lolium perenne* L.) and clover (*Trifolium* sp.) in Oregon, USA, Sharrow and Ismail (2004) reported that the combination of pasture and trees stored more C in aboveground biomass compared to tree stand or pasture alone, and pointed out the need for conducting research on silvopastures rather than deriving or extrapolating results from research on tree plantations or pasture.

Soil aggregates and size fractions are known to have an important effect on the retention of C in soil (Six et al., 2004). Aggregates, which are secondary particles formed through the combination of mineral particles with organic and inorganic substances (Bronick and Lal, 2005), are classified, depending on their size, into macroaggregates (2000 to 250 µm) and microaggregates (250 to 53 µm). Aggregates physically protect soil organic matter by (1) forming a physical barrier between microorganisms, microbial enzymes and their substrates, (2) controlling food web interactions, and (3) influencing microbial turnover (Six et al., 2000). It has been established that the inclusion of organic materials within soil aggregates reduces their decomposition rate (Oades, 1984; Elliott and Coleman, 1988). Tisdall and Oades (1982) found greater concentrations of organic C in macroaggregates than in microaggregates and suggested that the presence of decomposing roots and hyphae within macroaggregates not only increased C concentrations but also contributed to their stabilization. Given the relevance of size fractions in soil C storage, recent studies on the potential for C sequestration in soils under agroforestry systems have emphasized the importance of determining the extent of C storage in different aggregate classes at different soil depths (Haile et al., 2008, 2010; Gama-Rodrigues et al., 2010; Saha et al., 2010; Nair et al., 2010).

The primary objective of the research reported here was to determine the extent of soil carbon storage in various aggregate-size fractions at different depths under eucalyptus-based silvopastoral systems in comparison with sole stands of eucalyptus, open pasture as well as a native forest, in the Cerrado biome in Minas Gerais, Brazil.

Materials and Methods

Study Area

The study was conducted on an 80,000 ha commercial forestry and wood charcoal enterprise in the municipality of Paracatu, Minas Gerais, Brazil (Latitude 17° 36' 09"S and Longitude 46° 42' 02"W). The area receives an average precipitation of 1,350 mm (mainly in the summer months from November to March), has an annual average temperature of 22° C and average air humidity around 72.5%. It is located in the Cerrado biome that includes vegetation of different physiognomy, forming a gradient from completely open Cerrado, an open field dominated by grass, to the closed and dense Cerrado “Cerradão" (high Cerrado), a closed canopy forest (Ratter et al., 1997). Intermediate Cerrado, which is an open arboreal savanna (also called Cerrado *sensu stricto*), is the dominant type in the study area. All the study sites were on Oxisols.

Out of the several parcels (designated as “blocks” in the company’s records), each extending over thousands of hectares and planted to different LUS, six LUS described below were selected for the study.

1. **Forest** (Native local forest): An intermediate Cerrado with trees that have characteristic twisted trunks covered by a thick bark, and broad and rigid leaves; the major tree species include *Dalbergia* spp., *Machaerium scleroxylon* Tul. and *Vateria* spp. The site, approximately 300 ha in area, is one of the 10 permanent native forest reserve sites on the enterprise.

2. **Pasture** (“Treeless” or “open” pasture): A 210-ha pasture, established in 1975 following slash and burn and removal of economically important wood, by planting *Brachiaria decumbens* Stapf. and *B. brizantha* (Hochst. Ex A. Rich.) Stapf cv. Marandu, with cattle-stocking rates in the range of 0.5 animal ha^{-1} in the dry season

to 2.5 animal ha^{-1} in the wet season; the site was fertilized with urea at the rate of 75 kg ha^{-1} every three years until 2005.

3. **Old eucalyptus (OEC):** This 160-ha eucalyptus plantation was established in 1985 following slash-and-burn by which all the native forest was burned and all residues removed from the area. The eucalyptus saplings were planted at a density of 1090 plants ha^{-1}. The site was fertilized with 450 kg ha^{-1} NPK (8–30–4 mixture) and an additional 50 kg ha^{-1} ammonium sulfate, both mixed with soil in the entire area (as opposed to spot application) before planting. No fertilizer has been applied since planting the eucalyptus.

4. **Old agroforestry (OAF):** A 70-ha silvopasture established in 1994, as follows: the natural forest was cleared by removing large trees by chain saw and burning the remaining vegetation. Limestone was applied to raise base saturation to 50% and superphosphate was added at the rate of 150 kg ha^{-1}. Eucalyptus seedlings were planted in rows 10 m apart in an East – West direction with 4 m between plants giving a density of 250 plants ha^{-1}. In the beginning of the rainy season (October – November), rice (*Oryza sativa* L.) was planted between the eucalyptus rows after applying 300 kg ha^{-1} of fertilizer (NPK 5–25–15). After rice harvest (mechanical) in year 1, soybean (*Glycine max* (L.) Merr.) was grown between tree rows with fertilizer application (NPK, 2–30–15) of 450 kg ha^{-1}. Zinc (zinc sulphate), boron (boric acid), cobalt (cobalt sulfate), and molybdenum (sodium molybdate) were applied as one time only applications at rates of 10, 1, 2 and 1 kg ha^{-1}, respectively. In the third year, seeds of the grass species (*Brachiaria brizantha* cv. Marandu) were sown at the beginning of the rainy season between the eucalyptus rows, with fertilizer application of 150 and 200 kg ha^{-1} of superphosphate and phosphate rock, respectively, and urea at the rate of 75 kg ha^{-1} of N. Animals were allowed to graze the area 90 days after sowing grass seeds; the average animal stocking rates were 0.6 and 2.5 animal ha^{-1} in the dry and wet seasons, respectively.

5. **New eucalyptus (NEC):** This 220-ha eucalyptus plantation was established in 2005 after felling the large trees with a chain saw, removing economically important wood, and plowing the surface soil (0 to 20 cm). The seedlings were planted at a density of

1650 plants ha^{-1} after an initial (one-time only) application of a fertilizer mixture (NPK, 10–28–6), 100 g per plant.

6. **New agroforestry (NAF):** Similar to OAF, except that NAF was established in 2004 on 180 ha area; the average stocking rates were 1.0 and 2.8 animal ha^{-1} in the dry and wet seasons, respectively.

Soil Sampling

Soil samples were collected in July 2008 from all six LUS from four randomly selected sampling sites in four parcels of each. The selected parcels of each LUS were > 500 m apart from each other. At each sampling site for both silvopasture (OAF and NAF) and eucalyptus (OEC and NEC) systems, the samples were collected from two positions (locations) each: near the tree (50 cm from the tree trunk) and far from the tree (5 m from the trunk in the silvopasture treatments and 1.5 m from the trunk in the eucalyptus stands), giving a total of 32 sampling locations in these four LUS sites (2 positions x 4 LUS sites x 4 replications). There were four replicates for the forest and pasture systems giving a total of eight sampling locations for these two systems (2 LUS x 4 replications). At each sampling location, samples were collected from four depths (0–10, 10–20, 20–50, and 50–100 cm), which were chosen in accordance with the protocol used for a multi-country study at the University of Florida (UF) on soil C sequestration in AFS (Nair et al., 2010). Thus there was a total of (32 + 8) x 4 = 160 samples. Each sample was a composite of four sub-samples collected from the specific location and depth.

Soil bulk density (BD) for each depth interval was measured by the core method. Core samples were collected from all depth intervals using an 86 cm^3 stainless steel cylinder. Pits of 1m x 2m x 1m size were dug and the cylinder was inserted horizontally on the soil profile at the center of each depth class. The initial weight of soil inside the cylinder from each depth was measured to calculate the bulk density. All samples were air-dried and sieved (2 mm sieve) at the Federal University of Viçosa, Viçosa, MG, Brazil soils laboratory, and were bagged and sent to the University of Florida, Gainesville, FL, USA, for further analyses.

Soil Fractionation

The soil samples were manually fractionated into three aggregate size classes (2000 to 250 µm, 250 to 53 µm, <53 µm) at the Soil and Water Science Department laboratory, UF, according to a procedure from Elliott (1986) adapted by the above-mentioned protocol used for a multi-country study at UF on soil C sequestration in AFS. Soil samples were physically fractionated by wet-sieving through a series of two sieve sizes (250 and 53 µm) to obtain three fraction size classes: macro- (2000 to 250 µm), micro- (250 to 53 µm) and silt+clay-sized (<53 µm) fractions. The procedure, modified by Haile et al. (2008), consisted of submerging a subsample of 100 g of the composite soil sample in a 500 mL beaker of deionized water for about 5 min before placing it on the top of 250 µm sieve to release the air that is trapped inside soil pores. An attempt was made to use comparable energy input by moving the sieve up and down approximately 50 times in 2 minutes; the fraction remaining on the top of a 250 µm sieve was collected in a hard plastic pan, oven dried at 65^{o}C and weighed. Water plus soil <250 µm was poured through a 53 µm sieve, and the same sieving procedure was repeated. The overall procedure yielded water-stable, macro-, micro-, and silt+clay-sized fractions (2000 to 250, 250 to 53, and <53 µm, respectively). The average recovery mass percentage of soil fractions after the sieving procedure for this study ranged from 96% to 99% of the initial soil mass.

Soil Analysis

For chemical analysis, whole (non-fractionated) and oven-dried fractionated soils were ground to fine powder using a QM-3A High Speed Vibrating Ball Mill (MTI Corp., Richmond, CA) for 10 minutes. Total SOC was determined for whole soil and for fractionated soil samples by dry combustion using an automated C analyzer (Thermo Finnegan Flash EA 1112 NC; Thermo Fisher Scientific Inc., Waltham, MA). Soil pH in a 1:10 soil: water suspension and particle size analyses (Day, 1965) were determined for these soils. Details of soil characteristics are presented in Table 1.

Table 1. Bulk density, pH, and textural composition of soils at different depths to 1 m in six land-use systems in the Cerrado biome, Minas Gerais, Brazil

Land-use System	Soil Depth (cm)	Bulk Density (Mg m^{-3})	pH	Fractions (g kg^{-1})		
				Sand	Silt	Clay
Forest	0 – 10	0.99	5.27	171	150	679
	10 – 20	1.02	5.02	156	138	706
	20 – 50	0.94	5.00	159	339	502
	50 – 100	0.94	5.10	177	343	480
Pasture	0 – 10	1.28	5.91	157	213	630
	10 – 20	1.24	5.36	148	264	588
	20 – 50	1.29	5.05	147	260	593
	50 –1 00	1.11	5.11	154	284	562
OEC†	0 – 10	0.82	4.78	217	151	632
	10 – 20	1.02	4.73	229	150	622
	20 – 50	0.91	4.86	220	134	647
	50 –1 00	0.93	5.10	229	135	637
OAF§	0 – 10	1.03	5.25	141	111	749
	10 – 20	0.93	5.30	141	96	763
	20 – 50	0.97	4.94	147	101	753
	50 –1 00	0.89	5.11	150	128	722
NEC¶	0 – 10	1.06	5.92	138	144	718
	10 – 20	0.92	5.10	129	124	747
	20 – 50	0.94	4.95	106	119	776
	50 – 100	0.90	4.89	108	135	757
NAF‡	0 – 10	0.95	6.01	239	427	334
	10 – 20	1.06	5.08	241	434	325
	20 - 50	1.04	4.76	229	435	336
	50 - 100	0.95	5.07	228	433	339

†OEC = old eucalyptus; §OAF = old agroforestry (silvopasture); ¶NEC = new eucalyptus; ‡NAF = new agroforestry (silvopasture).

The carbon storage was calculated as:

C_s= $C_{conc.}$ x BD x Depth X Fraction weight
where,
C_s = C storage expressed in Mg ha^{-1} (per unit cm unless specified otherwise) in each fraction for a given depth
$C_{conc.}$ = C concentration in size fraction, g kg^{-1} of soil of that fraction size
BD = Bulk density, Mg m^{-3}
Depth = Depth of soil profile, cm and
Fraction weight = % weight of the fraction in the whole soil.

Statistical Analysis

The data were analyzed by ANOVA as a completely randomized design with four replicates. Tukey's studentized range test was used to compare the mean differences among LUS in SOC in whole soil, macro-sized, micro-sized, and silt+clay-sized fractions. Statistical analyses were performed using SAS (SAS Institute, 2004), separately for all depths, and differences were considered significant at $p < 0.05$.

Results

Soil Characteristics

Overall, the soil BD in the different LUS ranged from 0.82 to 1.29 Mg m^{-3} and the soil pH from 4.7 to 6.0 (Table 1). The soil under pasture had higher BD and pH compared with that under OEC and OAF systems, with other systems coming in between. In general, BD and pH values decreased with soil depth within each LUS. The particle size distribution (sand, silt, and clay contents) did not vary considerably among LUS except in the NAF system. Overall, the soils contained 10 to 24% sand. The NAF soil contained roughly 43% silt and 33% clay, whereas for all the other soils, the values ranged from 10 to 23% silt and 55 to 75% clay (Table 1).

SOC Stock in the Whole Soil

In general, soil C stock values (Mg ha^{-1}) near and far (away) from the trees were not significantly different; therefore those values were averaged for the respective plots. Overall, in all land-use systems, SOC stock declined with increase in soil depth at all sampling sites, with the exception of the NEC and NAF sites, where higher SOC values were observed in the 10-to-20-cm depth than in the top layer (Table 2). The amount of SOC in the whole soil varied among LUS (Fig. 1). In terms of the total SOC values to 1m depth (all depths combined), the LUS were in the order: OAF ≥ NEC ≥ Forest = NAF ≥ OEC ≥ Pasture the highest and lowest values being 148 and 116 Mg C ha^{-1} for OAF and pasture, respectively.

The SOC stock values within the depth classes also showed similarities with the overall ranking results of the LUS (Table 2). In the top layer (0 to10 cm), forest and OEC had higher stocks of SOC than NAF. In the mid-top layer (10 to 20 cm), forest and NEC had higher SOC values compared to OEC and pasture. No differences were observed among LUS in the mid-lower layer (20 to 50 cm) and in the lower layer (50 to 100 cm). Although no statistical differences were observed OAF had the highest (1.57 Mg ha^{-1}) and pasture the lowest (1.13 Mg ha^{-1}) SOC stock in the mid-lower layer. The same tendency was observed in the lower layer where OAF had a SOC stock of 1.10 Mg ha^{-1} and pasture a SOC stock of 0.82 Mg ha^{-1} (Table 2).

SOC Stock in Macro-Sized Fraction (2000 to 250 µm)

At the top (0 – 10 cm) soil layer forest had the highest SOC values while NEC, OAF and OEC had intermediary SOC values ranging from 1.47 to 1.55 Mg ha^{-1}. Pasture and NAF had the lowest SOC values (Table2). At the mid-top (10 – 20 cm) soil layer NEC had the highest (1.71 Mg ha^{-1}) and OEC had the lowest (0.68 Mg ha^{-1}) SOC values. Following the same tendency of the whole soil no statistical differences were observed for the SOC stock the two lower soil layers for the macro-sized fraction. The highest SOC value at the mid-lower layer was in the OAF and the lowest SOC value in the lower layer was in the OEC (Table 2).

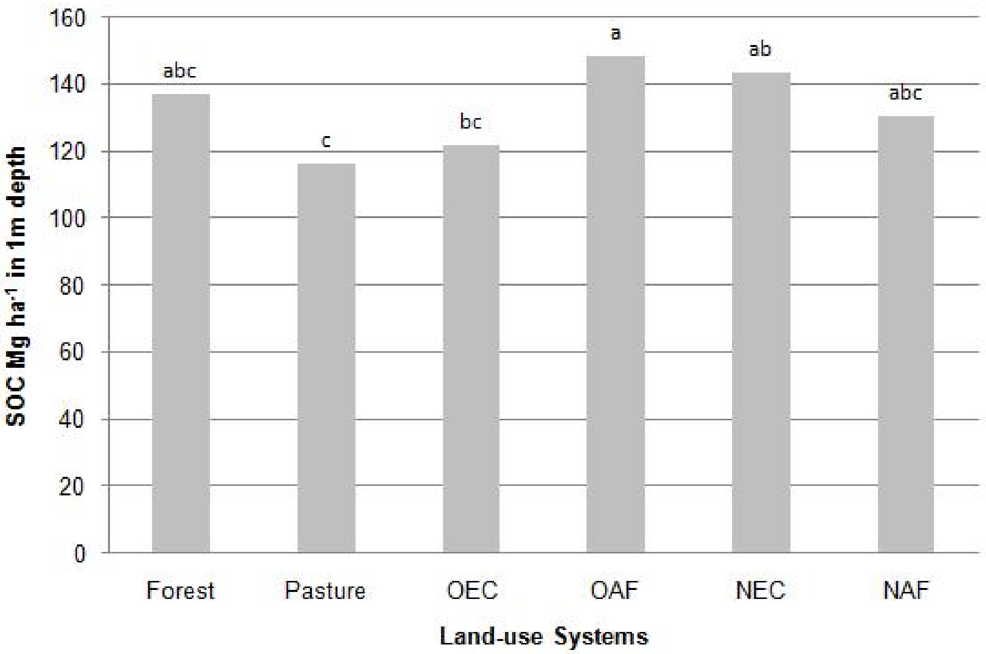

Figure 1. Total soil organic carbon (SOC) content in the whole (non-fractionated, 2 mm-sieved) soil to 1 m depth in six land-use systems in the Cerrado biome of Minas Gerais, Brazil. Lowercase letters indicate differences (at the 0.05 probability level) in SOC among land-use systems.

OEC = old eucalyptus; OAF = old agroforestry (silvopasture); NEC = new eucalyptus; NAF = new agroforestry (silvopasture).

SOC Stock in Micro-Sized Fraction (250 to 53 μm)

The OEC had the highest SOC content (1.05 Mg ha^{-1}), whereas forest and NEC had the lowest values at the top layer (0 to10 cm). At the mid-top (10 to 20 cm) and mid-lower (20 to 50 cm) layers, OEC had the greatest values and forest, pasture and NEC (this last one only in the lower layer) had the lowest values (Table 2). Both agroforestry systems (OAF and NAF) showed intermediary SOC values for the micro-sized fraction. In the lower 50 cm, OAF had the greatest SOC value and pasture the lowest; the other land-use systems had lower SOC values compared to OEC with no significant differences among them.

Table 2. Soil organic carbon (SOC) stock in the whole (non-fractionated) soil and aggregate-size fractions at different depth classes to 1 m in six land-use systems in the Cerrado biome, Minas Gerais, Brazil

Land-use System	SOC stock (Mg ha^{-1}) in soil layers at various depths (cm) 0–10	10–20	20–50	50–100
Whole soil				
Forest	2.87 a	2.53 a	1.35 a	0.85 a
Pasture	2.34 ab	1.74 bc	1.13 a	0.82 a
OEC†	2.93 a	1.45 c	1.19 a	0.84 a
OAF§	2.60 ab	2.04 abc	1.57 a	1.10 a
NEC¶	2.37 ab	2.63 a	1.51 a	0.96 a
NAF‡	2.03 b	2.16 ab	1.48 a	0.87 a
Macroaggregate fraction (2000 to 250 μm)				
Forest	1.88 a	1.64 ab	0.81 a	0.42 a
Pasture	1.22 bc	0.84 cd	0.54 a	0.37 a
OEC†	1.47 abc	0.68 d	0.55 a	0.33 a
OAF§	1.52 ab	1.26 bc	0.95 a	0.53 a
NEC¶	1.55 ab	1.71 a	0.94 a	0.51 a
NAF‡	1.06 c	1.33 ab	0.89 a	0.46 a
Microaggregate fraction (250 to 53 μm)				
Forest	0.42 c	0.40 b	0.31 b	0.32 ab
Pasture	0.51 bc	0.43 b	0.32 b	0.27 b
OEC†	1.05 a	0.57 a	0.47 a	0.35 ab
OAF§	0.62 b	0.48 ab	0.42 ab	0.41 a
NEC¶	0.40 c	0.47 ab	0.31 b	0.31 ab
NAF‡	0.64 b	0.49 ab	0.36 ab	0.28 ab
Silt + clay fraction (<53 μm)				
Forest	0.54 ab	0.49 a	0.22 a	0.11 a
Pasture	0.61 a	0.47 ab	0.27 a	0.18 a
OEC†	0.41 bc	0.20 c	0.17 a	0.16 a
OAF§	0.46 bc	0.30 c	0.20 a	0.15 a
NEC¶	0.42 bc	0.45 ab	0.25 a	0.15 a
NAF‡	0.33 c	0.33 bc	o.23 a	0.13 a

Means followed by different letters in same column within each section (sub-heading) are significantly different, *p*= 0.05.

†OEC = old eucalyptus; §OAF = old agroforestry (silvopasture); ¶NEC = new eucalyptus; ‡NAF = new agroforestry (silvopasture).

SOC Stock in the Silt+Clay-Sized Fraction (<53 µm)

Pasture had the highest SOC value at the top layer and forest in the mid-top soil layer; at the top layer, pasture SOC value was 0.61 Mg ha^{-1}, at the mid-top layer forest SOC value was 0.49 Mg ha $^{-1}$. The lowest values were in the OEC, NAF, and NEC systems (Table 2). In the mid-top layer (10 to 20 cm) the same tendency was observed where forest had the highest SOC value; pasture and NEC had an intermediary value and OEC and OAF had the lowest values. At the lower layers (below 50 cm) too, no statistical differences were observed among LUS.

Discussion

Soil Carbon Stock

The total soil C stock to 1m depth was high in all land-use systems, ranging from 116 to 148 Mg ha^{-1} (Fig. 1). These values are in agreement with some other SOC values reported under tropical AFS (Nair et al., 2009; Nair et al., 2010). Although higher values than those under the present study have been reported from elsewhere in the tropics: Bernoux et al. (1999) in pastures of different ages and native forest in the Amazon basin, Brazil; Veldkamp et al. (2003) in a tropical wet forest in Costa Rica; Desjardins et al. (2004) in a pasture and native forest in the Amazon basin, Brazil; and Bustamante et al. (2006), in a grassland and native forest in the Cerrado of Brazil. Some studies also have reported higher SOC values in the pasture systems to 1m depth (Fisher et al., 1994; Moraes et al., 1996; Neil et al., 1998; Maia et al., 2009). As noted in the Introduction section, lack of uniformity in the methods of soil sampling and C determination in these different studies makes it difficult to compare the reported data. Nevertheless, the high values noted in the present study possibly reflect two factors. First, these sites were all under natural vegetation until they were converted rather recently (33 yr for pasture at the time of soil sampling for the study and lesser for other systems) to their current land-use, and natural ecosystems are known to contain generally higher C stock than managed systems. Secondly, the LUS are not management-intensive; they do not involve repeated use of heavy machinery, soil disturbance, and crop removal, which are known to cause soil degradation and decline in soil C. Furthermore, the clay content in these soils is fairly high (Table 1), and it is well known that clayey soils contain more C than lighter-textured soils (Feller and Beare, 1997; Corazza et al., 1999; Lardy et al., 2002; Six et al., 2002; Desjardins et al., 2004).

Carbon Stock in Soil Size-Fractions

Distribution of aggregate-size classes showed the predominance of macroaggregate fraction in all LUS (Table 3). In general, C concentrations in the different aggregate-size fractions did not vary considerably within the same depth (Table 3); consequently, total C stock (Mg ha^{-1}) was highest in the macroaggregate fraction, which is the general trend in most tropical soils under various agroforestry systems (Nair et al., 2010). However, exceptions to this general trend have also been reported. Zotarelli et al. (2005), Zotarelli et al. (2007), and Oades and Waters (1991) found no differences in C and N content across aggregate-size fractions in the top 20 cm layers of Oxisols under crop and pasture systems in southern Brazil. Arevalo et al. (2010) noted in a study involving five LUS in north central Alberta, Canada (not tropics), that the general trend for C stocks in soil particle-size fractions decreased in the order: fine > medium > coarse. However, the fraction sizes reported in that study are fractions after sonication and since microaggregates retained in macroaggregates will be separated out by sonication, the fraction sizes in that study may not correspond to silt+clay-, microaggregate- and macroaggregate size-fractions, respectively, of our study. Considering that soil disturbance may alter the stability of macroaggregates (Angers and Chenu, 1998), the absence of tillage and use of machinery (no-till) in the systems in this study, coupled with the constant addition of organic materials via litter fall may have helped maintain the binding effect and increased the number of macroaggregates in the present study.

In general, at any given depth, the highest SOC values (Mg ha^{-1}) in microaggregate-sized fraction were under the pasture and OEC systems (Table 2). These two systems, besides forest, were under the same management regime involving the least soil disturbance for the longest period of time, except for possible increase in soil BD under pasture due to soil compaction caused by cattle trampling. The low level of soil disturbance may have enhanced the formation of microaggregates (Angers and Chenu, 1998).

Stabilization of Soil Organic Carbon

Chemical stabilization of SOM is understood to be the result of the chemical or physicochemical binding between SOM and soil minerals (Six et al., 2002). The macroaggregate-sized fraction contains the more active pool of C and is more susceptible to land use and soil management. This pool is formed by recent C depositions in soil (Carter, 1996); therefore, it is sensitive to changes in organic matter dynamics with time (Saha et al., 2009). On the other hand, the SOC content in silt+clay-sized fraction is considered to be more stable than in larger soil fractions (Six et al., 2002); this stability comes from the interaction between clay minerals and organic matter such as humic substances (Brady and Weil, 2008). Organic matter is stored within the micropores created by clay particles and can remain unreachable to decomposers (Jastrow and Miller, 1998).

The formation and stability of microaggregates depend mostly on the strength by which clays and other inorganic components of the soil are sorbed to soil organic matter (SOM), microbial debris, and a variety of other organic colloids and compounds primarily of microbial origin (Jastrow and Miller, 1998). Zotarelli et al. (2007) noted that although Oxisols did not exhibit the aggregate hierarchy as found in temperate soils (Oades and Waters, 1991; Six et al., 2002), stabilization of POM (particulate organic matter)-C within macroaggregates was likely in less disturbed soils as in no-till systems that included legume crops. In clayey soils, C derived from pasture appears to be highest in the fine fraction (Desjardins et al., 2004). In some situations, grassland-derived soils are reported to have a higher potential for C stabilization than forest-derived soils, probably because pasture-derived C is rapidly associated in the fine fraction (Collins et al., 2000).

The occluded C that is physically protected within soil aggregates represents a relatively more stable C pool (Christensen, 1992; John et al., 2005). Although this fraction was not specifically evaluated in this study, it is known that in LUS with no-tillage, a slow macroaggregate turnover allows time for the formation of fine occluded POM that gradually becomes encrusted with clay particles and microbial products to form microaggregates (containing young crop-derived C) within macroaggregates (Six et al., 1998; 1999; 2000). Gama-Rodrigues et al. (2010) reported based on fractionation and sonication of slaking-resistant aggregates in an Oxisol under cacao (*Theobroma cacao* L.)-based agroforestry systems in Bahia, Brazil, that about 70% of SOC in the whole soil was located inside the macroaggregates at all soil depths studied (to 1 m). Furthermore, they found that the proportion of soil C occluded in aggregates was considerably higher than that of other systems reported in the literature, e.g. Sarkhot et al. (2007). Gama-Rodrigues et al. (2010) argued that the constant replacement of organic matter, as in the land-use systems in the present study, maintained the binding effect and increased the number of water stable macroaggregates (John et al., 2005). Moreover, high concentrations of fine roots that are likely to be present in the surface soil to 15 cm depth in these relatively undisturbed (no-till) soils and lignified coarse roots at the subsurface soils to 100 cm contribute substantially to belowground C stocks in these systems. Thus, this study supports the notion that clay content alone is not necessarily an appropriate measure for protection of C in Oxisols, which do not show the same aggregate hierarchy as temperate-zone soils (Oades and Waters, 1991; Six et al., 2002), and high levels of organic matter could lead to a change in the dominant binding agents of aggregates from oxides to organic molecules in Oxisols as suggested also by Gama-Rodrigues et al. (2010).

Being the first study of this nature in these systems and location, its results are inadequate to lead to more convincing trends and extrapolation to other systems. The higher BD of the soil under pasture seems to be the main reason for higher values of C stock per unit volume of the soil to 1 m depth under that treatment. That was possibly caused by compaction by animals, although animal-stocking rate was relatively low (0.5 and 2.5 animal ha^{-1} in the dry and wet seasons respectively). The BD differences mean that the mass of soil being compared for the surface 1 m differs among management systems, while the actual C concentration (on a mass basis) does not (Table 3). Thus it is unclear if pasture is actually storing more C than the other systems throughout the whole soil profile, or if the soil profile has just been compressed under pasture and the overall soil C concentration remains unchanged. Interestingly, the BD values of soils under the agroforestry treatments (Table 1), which also had animal components, though at lower stocking rates, were much lower than those of the pasture treatment, even in the case of OAF, which had incorporated animals for the past 15 years (compared to 34 for pasture: established in 1975). The textural differences among the soils are not conspicuous (Table 1) enough to account for differences in C stock values. It seems that the presence of trees, especially for relatively longer periods of time in OEC and OAF, has had a positive influence on total C stock. The site has only recently (since 1975) been opened up for conversion to the current land uses; unfortunately no information could be obtained about the previous site history. Carbon dating (^{14}C) technique could shed some light on the source of C stock and C dynamics in these little-studied biomes.

Table 3. Soil organic carbon (SOC) content in soil aggregate size-fractions at different depths to 1 m in six land-use systems in the Cerrado biome, Minas Gerais, Brazil

Land-use System	Soil Depth (cm)	Size Fractions (µm) (% of total soil by weight)			SOC content (g kg^{-1} soil) in aggregate size-fractions(µm)		
		2000 to 250	250 to 53	< 53	2000 to 250	250 to 53	< 53
Forest	0 – 10	62.8	15.8	18.2	54.8	53.7	62.3
	10 – 20	61.1	15.4	18.6	53.5	46.9	53.4
	20 – 50	57.9	22.4	16.0	44.2	41.5	44.2
	50 –1 00	47.8	36.5	12.6	39.2	38.3	40.4
Pasture	0 – 10	49.4	21.4	25.4	48.4	44.6	45.8
	10 – 20	46.3	23.5	26.1	43.9	41.7	43.9
	20 – 50	45.1	27.6	22.3	38.7	38.2	39.2
	50 –1 00	42.6	31.8	20.9	37.6	37.2	38.2
OEC†	0 – 10	53.9	26.8	15.0	57.2	51.9	54.6
	10 – 20	51.1	30.8	14.6	44.9	43.9	49.1
	20 – 50	47.1	33.3	14.8	41.9	41.5	44.6
	50 –1 00	37.7	40.7	17.6	38.8	39.0	40.4
OAF§	0 – 10	55.7	23.3	16.5	54.4	48.6	53.5
	10 – 20	58.6	23.0	14.2	51.3	45.7	51.0
	20 – 50	57.9	25.4	12.4	45.2	43.7	47.1
	50 –1 00	46.2	36.0	13.3	42.1	41.0	42.7
NEC¶	0 – 10	63.1	16.4	17.0	55.3	55.7	59.4
	10 – 20	62.5	17.1	16.5	53.3	51.6	55.6
	20 – 50	59.8	20.2	16.2	45.5	44.3	46.6
	50 –1 00	50.8	30.6	14.8	40.6	38.7	41.2
NAF‡	0 – 10	56.2	22.4	16.3	50.0	46.7	53.8
	10 – 20	58.6	22.6	14.5	49.1	45.4	51.7
	20 – 50	55.2	25.6	14.6	43.6	41.8	45.3
	50 –1 00	45.7	35.3	14.1	39.3	38.0	40.6

†OEC = old eucalyptus; §OAF = old agroforestry (silvopasture); ¶NEC = new eucalyptus; ‡NAF = new agroforestry (silvopasture).

Note: The C values in the last three columns represent the mass of C (g) per kg of that particular aggregate fraction. Those values can be expressed in terms of the whole soil by multiplying the values with the respective fraction weight %. For example, C in the 2000 to 250 µm fraction at the 0–10 cm depth of the forest system accounted for 34.4 g C per kg of the whole soil (54.8 g kg^{-1} soil x 62.8 %).

Conclusions

The Cerrado biome has a relatively high stock of C in soil. Most of this C is in a biodegradable form and could be lost to the atmosphere with soil disturbance such as conversion of lands for production of agricultural commodities and biofuel. The soil C concentration on a mass basis was somewhat similar under the various LUS. While determinations of C in a soil gives an indication of its current status of C stock, that alone may not give much insight into the long-term C sequestration potential of the soil and the LUS it supports. Movement of C through soil can be a long-term process, and the effect of a specific system or its management practice may not be clear in a short time span. In spite of the inadequacy of one-time soil sampling and analysis from these recently established LUS in explaining the C storage dynamics in the site, data from various soil-size fractions could be valuable in getting more insight into the mechanism of C sequestration following land-use changes. Although the macroaggregates (corresponding to the 2000 to 250 μm fractions) are short-lived they are known to have a great impact on the formation and protection of the more stable microaggregates (250 to 53 μm). Thus, the relative presence of macroaggregates in the pasture and silvopasture systems in the present study could be a good indicator of the higher C sequestration potential of these practices. The results from this study could be integrated with other already available data, to develop an index (or a range of indices) depending on soil type, land-use history, etc., which could be applied to total SOC value to obtain the C sequestration potential of that soil.

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Chapter 2

Effects of Land-use Systems on $\delta^{13}C$ in Brazilian Cerrado Soil

Abstract

Silvopastoral management of fast-growing tree plantations is becoming popular in the Brazilian Cerrado (savanna). While soil particle-size and land management practices are known to influence carbon (C) storage in soils, such information is lacking for the Brazilian savanna, especially the recent silvopastoral systems. We studied total $\delta^{13}C$, and the contribution of C4 and C3-derived SOC in three fraction-size classes in six land-use systems on Oxisols in an 80,000-ha commercial establishment in Minas Gerais, Brazil. The systems were 24- and 4-year-old *Eucalyptus* hybrid plantations; a native forest; 15- and 4-year-old silvopasture stands of *Brachiaria brizantha* under Eucalyptus, and an open (treeless) pasture. From each system, replicated soil samples were collected from four depths (0–10, 10–20, 20–50, and 50–100 cm); the samples were fractionated into 250–2000, 53–250, and <53 µm size classes representing macroaggregates, microaggregates, and silt+clay, respectively, and their $\delta^{13}C$ determined. $\delta^{13}C$ values increase with depth in all site and in all sized-fraction ranging from -14.16‰ to -26.82‰ in the top layer and -14.82‰ to -23.98 in the lower layer. The old systems showed a higher contribution of C4-derived SOC in all depths. Results suggest that southeast Brazilian cerrado was in the past a plant community based on C4 plants that somehow was substitute by C3 plants.

Introduction

Agroforestry systems that combine trees and/or shrubs with crops and/or livestock production are planned and managed agroecosystems (Garrett et al. 2000). Increasing the overall productivity and efficiency of the land-use system are major goals of agroforestry (Nair, 2005). Agroforestry systems have the potential to enhance carbon (C) sequestration in soil compared with treeless (agricultural) systems (Montagnini & Nair, 2004). Such claims are based on the premise that tree components in agroforestry systems can be significant sinks of atmospheric C due to their long-term storage of high amounts of C in biomass, especially in the deep root systems. Furthermore higher diversity of grassland species and specific plant functional traits were report to increase uptake of C into the soil system through resource partitioning (Steinbeiss et al., 2008). Similarly Saha et al. (2009) found that homegardens with higher, compared to those with lower, number of plant species, as well as higher species richness and tree density had higher soil C, especially in the top 50 cm of soil.

Silvopasture - the integration of trees into forage or /and livestock – has been practiced in the Brazilian Cerrado biome since 1980s (Garcia & Couto, 1997). Indeed, silvopasture is the most common form of agroforestry in the Cerrado, and has been increased areas in the past 5 years. These agroecosystems are usually established in two different ways: by incorporating tree in existing, managed pasture or by using planted forest understory as fodder to livestock.

Functional consequences of integration of trees into grass-dominated vegetation include changes of above and below ground productivity (Archer et al., 2001; Scholes & Hall, 1996), modifications to rooting depth and distribution (Gill & Burke, 1999), and changes in the quantity and quality of litter inputs (Connin et al., 1997; Jackson et al., 2000). Soil organic matter (SOM) is extremely vulnerable to land-use changes (IPCC, 2001), as well as to intensification of agricultural practices (Matson et al., 1997). Thus, in order to quantify the strength and longevity of the C sink in tree-based pasture systems, it is important to understand the mechanisms and processes associated with C transformation and storage. Soil organic matter has a very complex and heterogeneous composition, and is associated with mineral soil constituents to form soil aggregates. The nature and extent of turnover of soil organic carbon (SOC) is intimately linked to organic matter size fractions as well as to soil structure and extent of aggregation (Martens, 2000). Different components of SOC have different residence time, ranging from labile to stable forms (Carter, 1996). Thus, evaluate changes in soil C and SOM dynamics correctly, is necessary to separate out functionally different SOM fractions. Soil size fractionation helps to differentiate these different SOC fractions. It is based on the premise that SOC associated with sand-size aggregates (or macroorganic matter > 250μm) is often more labile than SOC in the clay and silt fractions (Tiessen & Stewart, 1983).

Stable isotopic-ratio analysis in SOC studies emerged as a tool to trace the source of SOC to C3 and C4 components in vegetation. Numerous studies (Bernoux et al., 1998; Accoe et al., 2002; Haile et al., 2009) have been successful in applying δ^{13} C to understand plant-soil SOM dynamics, making stable isotopic analysis a useful technique. When one type of vegetation is replaced with another, δ^{13} C values can be used to identify SOM derived from residues in the native vegetation and the new vegetation based on discrimination between C3 and C4 plants. The reported δ^{13} C values range from -9 to -19‰ for C4 plants and -20 to -35‰ for C3 plants (Biedenbender et al., 2004; Boutton, 1996). When a C4 plant is introduced to a system that had previously been under a C3 plant (or vice versa), the relative contribution of new vs. old soil organic C can be quantified using the mass balance of stable isotope contents based on the change in ^{13}C signature of SOM (Dawson et al., 2002). In a combined tree and grass land-use system, C3 inputs are dominated by either woody shrubs or tree and C4 inputs are dominated by grass (Boutton, 1996). In eucalyptus based silvopastoral systems where C3 and C4 plants are grown simultaneously, such studies that use natural abundance of δ^{13} C to understand the C dynamics are rare or absent.

The δ^{13} C isotopic technique requires comparison between a site where the photosynthetic pathway of the dominant vegetation (C3 or C4) has been changed and the reference site where photosynthetic pathway of vegetation remains unchanged. The plant community in most of the silvopastoral systems in the Brazilian cerrado is composed of eucalyptus (*Eucalyptus ssp.*) a C3 plant with a $\delta^{13}C \approx -27.8$‰ and a grass normally *Brachiaria brizantha* a C4 plant with $\delta^{13}C \approx -12.6‰$. The $\delta^{13}C$ value ranges of C3 and C4 plants do not overlap. Therefore, differences in isotope ratio can be used to quantify the relative contribution of plants of each photosynthetic pathway to SOM (Balesdent et al., 1988). The present study was undertaken with the objective of assessing the impact of difference land-use systems on the SOC content and SOM fraction size and quantifying the relative SOC of C3 and C4 in each land-use systems.

Materials and Methods

Study Area

The study was conducted on a farm at the city of Paracatu, Minas Gerais, Brazil (Latitude 17°36'09"S and Longitude 46°42'02"W). The farm is located inside the Cerrado biome and has as climate characteristics an average rain precipitation of 1,350 mm (concentrated in the summer –Nov to Mar), annual average temperature of 22°C and air humidity around 72.5%.

Soil samples were taken from six different land-use sites:

1. The native local forest that belongs to the Cerrado biome (Brazilian Savannah). The Cerrado includes different physiognomy, forming a gradient from completely open Cerrado (open field dominated by grass) to the closed and dense Cerrado and “Cerradão" (high cerrado), which is a closed canopy forest (Ratter et al., 1997). Intermediate Cerrado, which is an "open arboreal savanna”, is the dominant type (also called Cerrado “sensu strict”). The forest area used in this research might be classified as intermediate Cerrado with trees that have characteristic twisted trunks covered by a thick bark, and leaves which are usually broad and rigid.

2. Eucalyptus’ forest planted in 1985, here called as old eucalyptus forest. In order to plant this forest a slash and burn technique was used burning all the native forest and all the residues were removed from the area. The site was fertilized with phosphors, nitrogen and sulfur chemicals fertilizers. Tree density used in this site was 1090 plants per hectare.

3. Eucalyptus' planted in 2005, here called as new eucalyptus. The forest was established by felling the large tree with a chain saw, removing economically important wood. No burn was used to create this site. Soil was ploughed in the top soil surface (0–20cm). On each seedling tree 100g of NPK formula 10 – 28 – 6 was used to increase soil fertility. Tree density used in this site was 1650 plants per hectare.

4. Pasture field. This site was established in 1965 using a slash and burn technique after the harvester of economically important wood trees. After that some sporadic fertilization was done every 5 year. Urea was used as source of N in all fertilization. The last fertilization was done in October of 2005. The grasses species used in this site were *Brachiaria decumbens* Stapf. and *B. brizanta* cv. Marandu. The stock rate in this area ranges from 0.5 animal ha^{-1} in the dry season to 2.5 animal ha^{-1} in the wet season when the productivity increases.

Sites 5 and 6 here called as old agroforestry and new agroforestry, followed the same steps to be established in 1994 and 2004, respectively.

In the first year (year zero) natural forest was removed by felling the large trees with a chain saw and burning the remaining vegetation. After that limestone was incorporated in the whole area to elevate the base saturation up to 50% and also 150 kg ha^{-1} of reactive phosphate to increase P values. Eucalyptus was planted in lines 10m wide from each other and 4m from each plant, in the same line. Tree density used in this two site was 250 plants per hectare. The orientation of the trees plantation was East-West, in order to provide more sun light penetration underneath the trees.

At the beginning of the rain season (Oct-Nov) rice (*Oryza sativa*) associated with 300 Kg ha^{-1} fertilizer of the NPK (5, 25, 15) was seeded in between the eucalyptus lines. In the appropriated time rice was harvested mechanically. In the second year (year 1) the area in between the trees was used to cultivated soybean (*Glycine max*). No soil revolving was used at this time and the following fertilization protocol was used: 450kgha^{-1} of the NPK formula 2 – 30 – 15 plus 0.3% Zn and also 10, 1, 2 and 1 kg ha^{-1}, at only one application, of zinc sulfate, boric acid, cobalt sulfate and sodium molybdate, respectively. In the appropriated time soybean was harvested mechanically. In the third year (year 2) as soon as the rain season started grass specie (*Brachiaria brizantha* cv.

Marandu) was sown in between the eucalyptus' trees. At this phase fertilization with 150 and 200 kg ha^{-1} of simple super phosphate and reactivity phosphate, respectively was done. Nitrogen fertilization was also done using 75k g ha^{-1} of N, urea was used as N source. No other fertilization was done until sampling. Animals were allowed to graze the area 90 days after the sown. Animal average stock rate in the old agroforestry area ranged between 0.6 to 2.5 animal ha^{-1} in the dry and rain season, respectively, and for the new agroforestry area this rate ranged between 1.0 to 2.8 animal ha^{-1} in the dry and rain season, respectively.

Soil Sampling

Soil samples were collected from four randomly selected plots of each of the land-use systems. In old agroforestry (OAF), new agroforestry (NAF), old eucalyptus forest (OEF) and new eucalyptus forest (NEF) samples were collected at two position: near the tree (50cm from the tree trunk) and far from the tree (5m form the trunk at the agroforestry systems and 1.5m from the trunk at the eucalyptus' forest). To collect the sub-samples near the tree roles were made around it and to collected samples far from the tree sub-samples were collected in a row at center of the alley. In each sampling plot, soil was collected from four depths (0 – 10; 10 – 20; 20 – 50 and 50 – 100 cm) from four randomly selected sampling point. The four sub-samples at each location and depth class were composited to get one composite sample for each depth class per plot. There were a total of 128 samples (4 land-use types x 4 replications x 2 positions x 4 depths) from the tree based land-use systems and 32 samples (2 land-use x 4 replications x 4 depths) from the pasture and forest sites, totaling 160 samples. Since pasture have no trees and in the forest trees are all over without a standard distribution there were no horizontal distances sampling in these two systems.

Soil bulk density for each depth interval was measured by the core method. Cores samples were collected from all depth intervals using an 86 cm^3 stainless steel cylinder. Pits of 1m x 2m x 1m size were dug and the cylinder was inserted horizontally on the soil profile at the center of each depth class. The initial weight of soil inside the cylinder from each depth class was measured to calculate the bulk density. All samples were air-dried and sieved (2 mm sieve) at the Federal University of Viçosa, Viçosa, MG, Brazil soils laboratory, bagged and sent to the University of Florida, Gainesville, FL, USA, for further analyses.

Soil Fractionation

The soil samples were manually fractionated into three aggregate size classes (250 – 2000 µm, 53 – 250 µm, <53 µm) at the Soil and Water Science Department laboratory, University of Florida, according to a procedure from Ellliot (1986) adapted by Haile et al. (2008; 2010). Haile et al. (2008); Takimoto et al. (2008); and Sara et at. (2009; 2010) reported a recovery of 97.5%, 97.5 to 99% and 95 to 99%, respectively, of the initial soil mass. Soil samples were physically fractionated by wet-sieving using disruptive forces of slaking and wet-sieving through a series of two sieve sizes (250 and 53 µm) to obtain three fraction size classes: macro (250 – 2000 µm), micro (53 – 250 µm) and silt- and- clay sized fraction (<53 µm).The procedure, modified by Haile et al. (2008), consisted of submerging a subsample of 100 g of the composite soil sample in a 500 mL beacker of deionizer water as disruptive forces of slaking for about 5 min before placing it on the top of 250 µm sieve to release the air that is trapped inside soil pores. An attempt was made to use comparable energy input by moving the sieve up and down approximately 50 times in 2 min. the fraction remaining on the top of a250 µm sieve was collected in a hard plastic pan and allowed to oven dry at 65^{o}C and weighed. Water plus soil <250 µm was poured through a 53 µm sieve, and the same sieving procedure was repeated. The overall procedure yielded a water-stable, macro sized fraction 250 to 2000 µm; a micro sized fraction 53 to 250 µm; and silt+clay size fraction <53 µm. The overall average recovery mass percentage of soil fractions after the sieving procedure ranged from 96% to 99% of the initial soil mass.

Soil Analysis

For chemical analysis, whole and oven-dried fractionated soils were ground to fine powder using a QM-3A High Speed Vibrating Ball Mill (MTI Corp., Richmond, CA) for 10 min. Total SOC was determinate for whole soil and for fractionated soil samples by dry combustion using an automated C analyzer (Thermo Finnegan Flash EA 1112 NC; Thermo Fisher Scientific Inc., Waltham, MA).

For stable C isotope analysis, whole soil and oven-dried fraction soils were analysed for C concentrations and for $\delta^{13}C$ values using a Carlo Erba EA-1108 (CE Elantech, Lakewood, NJ) interfaced with a Delta Plus (thermo Finnigan, San Jose, CA) isotope ratio mass spectrometer operating in continuous flow mode. Carbon isotope ratios are presented in δ-notation:

$$\delta^{13}C= ([R_{sample} – R_{STD}]/R_{STD}) \text{ x } 10^3 \quad (1)$$

where R_{sample} is the $^{13}C/^{12}C$ ratio of the sample, and R_{STD} is the $^{13}C/^{12}C$ ratio of the Vienna Pee Dee Belemnite (VPDB) standard (Coplen 1996). Precision of duplicate was 0.1‰ and nome of the samples contained $CaCO_3$ or other form of inorganic C. The percentage of SOC derived from the *Brachiaria* ssp., a C4 plant, or from the eucalyptus or native forest, a C3 plant, was estimated based on the equations (Balesdent & Mariotti, 1996):

$$\text{\% C4-derived SOC} = (\delta- \delta_T)/(\delta_G- \delta_T) \text{ x } 100, \quad (2)$$

$$\text{\% C3-derived SOC} = 100 - \text{\% C4-derived SOC}, \quad (3)$$

where δ is the $\delta^{13}C$ of a given samples, δ_T a composite samples of the C3 plant (from Eucalyptus) and δ_G is a composite sample of pasture grass, C4.

Based on the equations 2 and 3 and in the C content in each soil sample were calculated the contributions of each C3 and C4 species in SOC C-derived, as follows:

$$\text{C3-devived SOC (Mg ha}^{-1}\text{) = (\% C3-derived SOC) x (SOC content, Mg ha}^{-1}\text{),} \quad (4)$$

$$\text{C4-derived SOC (Mg ha}^{-1}\text{) = (\% C4-derived SOC) x (SOC content, Mg ha}^{-1}\text{).} \quad (5)$$

Statistical Analysis

A complete randomized design with land-use as a factor was used. Planned-comparison ANOVA with Tukey's studentized range test was used to compare the mean differences between land management practices on $\delta^{13}C$, C3-devived SOC and C4-derived SOC in whole soil , macro-sized, micro sized, and silt+clay sized fractions at all six sites. Statistical analysis were performed separately with SAS (SAS Institute, 2004), and differences were considered significant at p <0.05.

Results

Whole Soil

Differences in the natural abundance of ^{13}C soil organic carbon (SOC)

Pasture showed the highest δ ^{13}C values at any given soil layers, with an average of -14.45‰. On the other hand, NEC had the lowest δ^{13}C values, at any given depth, with an average of -25.52‰. Both agroforestry systems showed intermediary values ranging from -17.21‰, at the lower layer of OAF, to -22.65‰, at the top layer of NAF (Table 1). Native forest δ13C values increased with the depth increasing from -26.82‰ to -18.24‰, from the top layer to the lower layer, respectively. Overall, even if no statistical analysis, δ13C values showed a trend to increase when soil layer become deeper.

Table 1– δ^{13}C values of soil organic carbon (SOC) in whole soil in different depths of six different land-use systems in the Brazilian Cerrado, MG

	δ^{13}C values of SOC (‰)					
	Site					
Depth (cm)	Pasture	OEC	NEC	OAF	NAF	Forest
0–10	-14.16 a	-24.07 c	-26.53 d	-21.87 b	-22.65 bc	-26.82 d
10–20	-14.32 a	-20.05 b	-26.13 d	-20.10 b	-22.45 c	-25.06 d
20–50	-14.53 a	-16.50 b	-25.45 e	-18.30 c	-21.96 d	-22.20 d
50–100	-14.82 a	-15.85 ab	-23.98 d	-17.21 abc	-19.64 c	-18.24 bc

Lowercase letters in the same row indicate significant differences in SOC at a given depth and site.
OEC, old eucalyptus; NEC, new eucalyptus; OAF, old agroforestry; NAF, new agroforestry.

C4-derived SOC in pasture showed higher values than any other site, in any given depth. New eucalyptus showed the lowest contribution of C4 plants in its SOC. The agroforestry systems, showed intermediary values. Old and new agroforestry systems had a mean value of 2.70 and 2.15 Mg ha^{-1}, respectively (Table 2). Native forest showed a bigger contribution of C4 plants in its SOC in the lower layer (2.56 Mg ha^{-1}), the other layers C4-derived SOC might be consider low. A reverse trend was observed in the C3-derived SOC where NEC showed higher values and pasture lower, 4.28 and 0.34 Mg ha^{-1} in the NEC mid-top layer (10–20 cm) and pasture top layer (0–10), respectively (Table 3), excepted to the top layer where native forest showed the highest value (4.82 Mg ha^{-1}).

Table 2 – C4-derived soil organic carbon (SOC) in the whole soil in different depths of six different land-use systems in the Brazilian Cerrado, MG

	C4-devived SOC (Mg ha^{-1})					
	Site					
Depth (cm)	Pasture	OEC	NEC	OAF	NAF	Forest
0–10	5.50 a	1.83 c	0.86 d	2.48 b	1.98 bc	0.97 d
10–20	4.99 a	2.39 b	1.14 c	2.59 b	2.21 b	1.43 c
20–50	4.61 a	3.17 b	1.04 d	2.96 b	2.13 c	1.78 c
50–100	3.65 a	2.98 ab	1.28 c	2.73 b	2.29 b	2.56 b

Lowercase letters in the same row indicate significant differences in SOC at a given depth and site.
OEC, old eucalyptus; NEC, new eucalyptus; OAF, old agroforestry; NAF, new agroforestry.

Table 3 – C3-derived soil organic carbon (SOC) in the whole soil in different depths of six different land-use systems in the Brazilian Cerrado, MG

	C3-derived SOC (Mg ha^{-1})					
	Site					
Depth (cm)	Pasture	OEC	NEC	OAF	NAF	Forest
0–10	0.35 d	3.61 b	3.78 b	2.81 c	2.71 c	4.82 a
10–20	0.38 d	1.72 c	4.28 a	1.89 c	2.90 b	3.75 a
20–50	0.41 d	0.82 d	3.08 a	1.34 c	2.46 b	2.20 b
50–100	0.40 c	0. 58 c	2.50 a	0.88 bc	1.51 b	1.31 bc

Lowercase letters in the same row indicate significant differences in SOC at a given depth and site.
OEC, old eucalyptus; NEC, new eucalyptus; OAF, old agroforestry; NAF, new agroforestry.

Soil Fraction sizes

Differences in δ^{13}C in SOC

Soil organic carbon $\delta^{13}C$ followed the same trend in all fractions with values being higher at the pasture and lower at NEC. In macro-sized fraction (250–2000 µm) pasture and NEC showed an average of -14.95‰ and -25.52‰, respectively. Within the agroforestry systems OAF always showed a higher $\delta^{13}C$ values than NAF, in any given depth (Table 4). Native forest $\delta^{13}C$ values might be considerate low ranging from -26.81‰, in the top layer to -21.40‰, in the lower layer.

The same trend was observed in the micro-sized fraction (250–53 µm) where pasture (-14.90‰) and NEC (-26.50‰) showed the highest and the lowest $\delta^{13}C$ values, respectively. In this fraction OAF and NAF showed similar $\delta^{13}C$ values in most soil layers, except for the mid-lower and the lower layer where OAF had higher values. In silt+clay fraction (<53 µm) pasture and NEC showed higher and lower $\delta^{13}C$ values, in any given depth. At the two first layers (top and mid-top) pasture showed the highest (-14.95‰) $\delta^{13}C$ value; OEC, OAF and NAF showed intermediary and, NEC and native forest (-26.33‰) the lowest one. This trend changed in the bottom layers (mid-lower and lower) where pasture and OEC had the highest values; OAF, NAF and native forest had intermediary and, NEC showed the lowest (-23.72‰).

All sites showed an increasing in $\delta^{13}C$ values in any given depth with depth increasing. Although comparisons among depth in the same site were not analyzed in this trial, results showed that OEC had a sharply increasing in $\delta^{13}C$ values and pasture had a more steady behavior, with depth increasing.

Plant sources of SOC

The amount of C3 and C4-derived SOC in the soil fractions were significantly different among sites and depths. Compared with the C3-derived SOC, the proportion of C4-derived SOC increased with soil depth in all sites (Fig 1). For example, in NEC site 85%, 87%, 75% and, 62% of SOC were C3-derived in the top, mid-top, mid-lower and lower sol layer, respectively. The corresponding values for pasture site were 6% 7%, 8% and, 11%.

Table 4 – Differences in δ^{13}C (‰) of soil organic carbon (SOC) in macro-sized (250–2000 μm), micro-sized (250–53 μm), and silt+clay (<53 μm) fractions in six different land-use systems at four different depths in the Brazilian Cerrado, MG

	Depth (cm)	0–10			10–20			20–50			50–100		
Site	Fraction (μm)	250–2000	250–53	<53	250–2000	250–53	<53	250–2000	250–53	<53	250–2000	250–53	<53
Pasture		-14.47^{a}	-14.90^{a}	-14.95^{a}	-14.51^{a}	-15.14^{a}	-15.04^{a}	-15.35^{a}	-15.36^{a}	-15.20^{a}	-15.47^{a}	-16.20^{a}	-16.84^{a}
OEC		-24.14^{b}	-24.30^{c}	-22.46^{b}	-19.82^{b}	-20.04^{b}	-20.53^{b}	-16.83^{ab}	-15.92^{a}	-16.39^{a}	-16.27^{a}	-15.46^{a}	-15.90^{a}
NEC		-26.66^{c}	-26.50^{d}	-26.03^{c}	-26.33^{d}	-26.08^{d}	-25.74^{c}	-25.50^{d}	-25.38^{d}	-25.18^{d}	-23.60^{c}	-23.13^{c}	-23.72^{c}
OAF		-22.25^{b}	21.45^{b}	-21.70^{b}	-20.30^{b}	-20.45^{bc}	-20.58^{b}	-18.24^{b}	-17.71^{b}	-18.32^{b}	-17.60^{a}	-16.44^{a}	-17.10^{a}
NAF		-22.47^{b}	-22.72^{bc}	-22.25^{b}	-22.72^{c}	-22.26^{c}	-22.25^{b}	-22.38^{c}	-21.92^{c}	-21.91^{c}	-20.08^{b}	-19.14^{b}	-20.11^{b}
Forest		-26.81^{c}	-26.76^{d}	-26.33^{c}	-25.73^{d}	-25.91^{d}	-25.25^{c}	-23.70^{cd}	-22.59^{c}	-23.02^{c}	-21.40^{bc}	-19.90^{b}	21.30^{b}

Lowercase letters in the same column indicate significant differences in SOC at a given depth and site.
OEC, old eucalyptus; NEC, new eucalyptus; OAF, old agroforestry; NAF, new agroforestry.

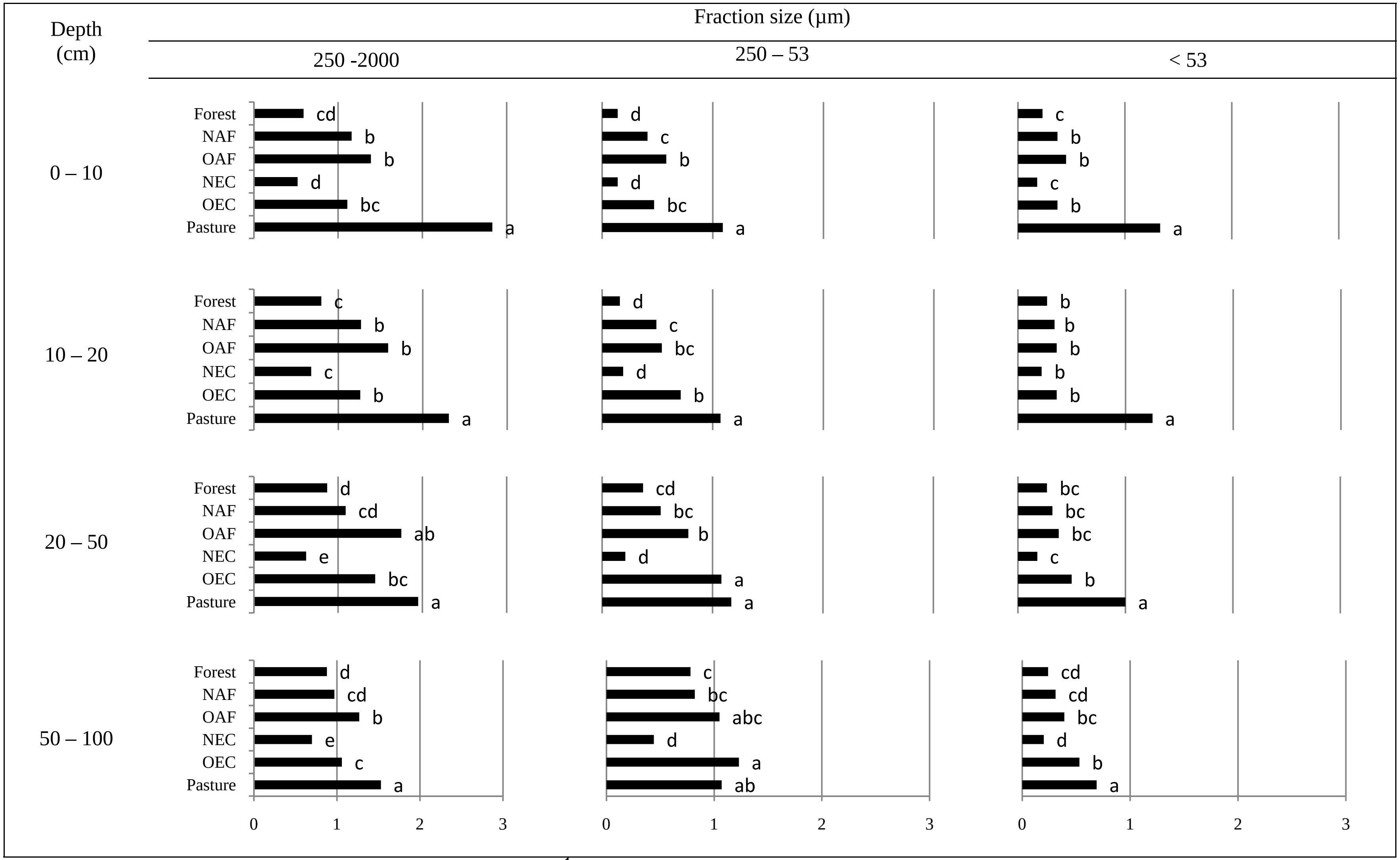

Figure 1- C4-derived soil organic carbon (Mg ha^{-1}) in macro-sized (250–2000 µm), micro-sized (250–53 µm), and silt+clay (<53 µm) fractions in six different land-use systems at four different depths in the Brazilian Cerrado, MG.

Lowercase letters indicate significant differences in SOC at a given depth, fraction, and site. OEC, old eucalyptus; NEC, new eucalyptus; OAF, old agroforestry; NAF, new agroforestry.

In macro-sized fraction (250–2000 μm) pasture showed more C4-derived SOC than any other site, at any given depth. Agroforestry systems showed intermediary values of C4-derived SOC with values ranging from 1.75 Mg ha^{-1} to 0.97 Mg ha^{-1}, in the OAF at mid-lower layer and NAF at the lower layer, respectively (Fig 1). Native forest showed intermediary to lower C4-derived SOC values, and these values tend to be steady with soil depth. New eucalyptus showed the lowest contribution of C4 plants group in its SOC, at any given depth. Except from pasture in this fraction the other sites C4-derived values tend to be steady with the depths, with very low variation.

Micro-sized fraction (250–53 μm) followed the same trend of micro-sized fraction. Pasture showed higher values in all depths with values ranging from 1.17 to 1.07 Mg ha^{-1}. A reverse trend was observed in micro-sized fraction regarding site behavior with depth. In this fraction pasture was the only site to show a steady values behavior, while all the other five sites tend to be increase C4-derived SOC with the increasing in soil depth. Pasture also showed the highest values in any given depth at the silt+clay fraction (<53 μm). In the top layer agroforestry systems showed intermediary values and, forest lower (0.23 Mg ha^{-1}). In the mid-lower layer (20–50 μm) OAF, NAF and native forest did not showed significant differences with each other and NEC had the lowest values (0.18 Mg ha^{-1}). In this fraction size the percentage of C4-derived SOC was 89%, 89% 88% and, 78% in pasture at top, mid-top, mid-low and, low depths, respectively. Corresponding values to the native forest were 20%, 27%, 40% and, 51%, respectively. The site that showed the C4-derived SOC with lowest values was the NEC where were observed values of 22% of C4 SOC origin in the top layer.

All sites tend to increase the percentage of C4-derived with the increasing in soil depth, in all sized fractions.

As expected, once its calculation is done by difference over a 100%, C3-derived SOC showed a reverse trend compared to the C4-derived. New eucalyptus showed the highest values in all fractions and depths. Both agroforestry systems showed intermediary to low C3-derived SOC, with higher values in the top and mid-top layers. Forest showed intermediary values of C3-derived SOC.

Discussion

Whole Soil

Higher $\delta^{13}C$ values in pasture were expected once plants with C4 photosynthesis discriminate less against $^{13}CO_2$ during photosynthesis and, therefore, have larger $\delta^{13}C$ values than C3 plants (Boutton, 1996). These differences are probably due to differences in stomatol diffusion and carboxylation of phosphenol pyruvate, the two photosynthesis steps that are significant for isotope fractionation (O'Leary, 1988).

The intermediary values of agroforestry systems can be explain by the increasing participation of C4-derived SOC due to the establishment of pasture as an understory within the trees. Trouve et al. (1994) studying SOC dynamics under Eucalyptus and Pines planted on savannas in Congo observed that in the upper 50 cm layer of the savanna the $\delta^{13}C$ were close to those of C4 plants. This had clearly resulted from mixing of old organic matter of tree origin with more recent organic matter derived from present savanna plants. On the other hand, Alcântara et al. (2004) observed that converting the savanna to a planted forest caused a decrease in signature of $\delta^{13}C$ and theses values were on average 3.40‰ lower.

Increasing in $\delta^{13}C$ values with depth have been reported by many author (Vitorello et al., 1989; Volkoff et al., 1982; Alcântara et al., 2004) and may be a result from a preferential decomposition and removal of ^{13}C-impoverished components or molecules. Thus, $\delta^{13}C$ values may increase as a result of humification transformation. This increasing in $\delta^{13}C$ seems to be characteristic of all biologically active soils. This increase can be as large as 3‰ to 4‰ within the upper 1m in tropical forest soils (Desjardins et al., 1991). In some cases, such an increase may be emphasized by the selective mitigation and redeposition of clay-humic material with ^{13}C content higher than that of the whole soil organic matter (SOM).

The increasing $\delta^{13}C$ enrichment with depth is probably due to decomposition of SOM (Pessenda et al., 1998). Jobbagy and Jackson (2000) working with a database of different soil in texture, land-use, environmental and climate conditions and their relations with vertical distribution of SOC highlighted that the relative distribution of SOC with depth was slightly correlated with climate and more associated to precipitation and vegetation types.

A wider range of $\delta^{13}C$ values observed in this work (Table 1) suggest a predominance of C4 vegetation that should represent the middle Holocene, and showed a process of changing to a vegetation community consisting predominantly of C4 plants to a C3. Similar $\delta^{13}C$ profiles have been reported by Schwatz et al. (1986), in Africa, and Desjardins el al. (1991; 1996) and Pessenda et al. (1997; 1998), in Brazil.

Soil organic carbon derived from C4 plants increased in all sites at any given depth what indicated significant inputs in C derived from pasture. The increase of the proportions of C4-derived SOC is more rapid in OEC, OAF and somewhat too slow in NEC. At native forest site the proportion of C4- derived SOC was moderate. In clayey soils near Manaus Choné et al. (1991) found higher inputs of C4-derived C in carbon stock of the 0–3 cm upper layer: 30% after 2 years and 68% after 8 years. In coarse-textured soil in Amazonia, Desjardins et al. (1994) found that 10 years after deforestation 49% of the total carbon stock of the 0–10 cm upper layer was derived from pasture.

Old established systems showed a higher contribution of C4 SOC than new systems, in all depths. This trend might be due to a faster turnover of C4-derived SOC when compare to C3-derived SOC. So with timing C4-derived C are more rapid incorporated to soil organic carbon as a whole. Another explanation for this founds may be management practices (such as choice of graminaceous, control weeds, use fertilizers and control of stocking rate) probably have a influence on the pasture (C4) derived inputs. Pasture management plays a important hole in C accumulation or loss, as reported by Trumbore et al. (1995) and Fearnside and Barbosa (1998), but very few studies have examined the effects of management practices on the soil C content. Moraes et al (1996) studying the soil properties under Amazon soil organic matter showed that forest derived carbon declines sharply in the first year of pasture installation.

Roscoe and Buurman (2003) studied, in southeast region of Brazil, a soil previously under wood savanna (C3 dominated) and cultivated with maize/beans in conventional and no-tillage systems. They related the ^{13}C enrichment after cultivation to the incorporation of new C4-derived SOC from maize. The highest δ^{13}C values were found in the topsoil of cultivated areas. In the upper 7.5 cm of the soil, 33% of total C came from maize after 30 years, while at 30–45 cm this fraction was reduced to 15%. In a clayey Oxisol, Roscoe et al. (2001) found a high replacement of organic carbon after convertion into pasture. After 23 years on continuous pasture, the carbon replacement in the Ap horizon was 36%, suggesting a fast turnover rate. Alcântara et al. (2004) working at a grassy cerrado converted to riparian forest and its impact on SOM dynamic found that under forest the input of C3 material has increased while C4 input decreased. The replacement follows a gradual trend with depth. Data also showed a strongly decreased in forest derived C below 5 cm were grass-derived SOM still dominant.

Sized Fractions

δ^{13}C values of organic carbon associated with particle size fraction differed by 12‰ in the top layer and by 8.2‰ in the lower layer (Table 4). The bigger difference in the top layer is probably due to higher pasture and eucalyptus fine roots contribution, at the lower layer the decreasing may be associated to an stabilization of the organic matter turnover, or a greater contribution of C4-derived SOC in the past vegetation that originally exist.

Desjardins et al. (2004) studying the effects of forest convertion to pasture on soil carbon content and dynamic in Brazilian Amazon found that the installation and increasing age of pasture results in clear increasing in δ^{13}C in the whole soil and particle-size fractions. This δ^{13}C increasing with depth is correlated with increasing and decay of organic carbon (Balesdent and Mariotti, 1996).

Isotopic methods confirm that all size fractions were affected by inputs of C4-derived carbon (Figure 1). Usually, faster substitution of C3-derived carbon by C4-derived carbon are observed in the coarse SOM fractions than in the fine ones (Feller and

Beare, 1997) the difference of SOM turnover between fractions is more pronounced in temperate soils than in tropical soils (Vitorello et al., 1989; Desjardins et al., 1994).

Desjardins et al., (2004) working in two different texture soils in Brazilian Amazon found that in pasture of 15 years and 38 and 42% of the clay fraction carbon was derived from pasture, confirming that pasture-derived C is quickly incorporated in the finest fraction, whatever the soil texture. Balesdent and Mariotti (1996) reported an increasing of $\delta^{13}C$ in soil sized fractions in maize cultivated fields over 13 years and the residence time of C in each fraction. The 200–2000µm and 50–200µm fraction exhibited an exponential kinetic pattern, indicating that each fraction was rather homogeneous with respect to age distribution and the transit time through coarse fraction was short. Turnover times were 4±1.5 years for the 200–2000µm fraction, and 13±2 years for the 50–200µm fraction.

Conclusions

We conclude that land-use systems differed in the $\delta^{13}C$ values in the cerrado biome and in the whole soil and soil sized-fractions. Agroforestry systems and pasture may be considerate a good carbon sinker once a great part of the SOC are found in the more stable fractions (silt+clay).

We also suggest that the cerrado biome, where we study, was in the past not a forest, as today, but a grassland with high proportion of C4 plants. This suggestion is based on the $\delta^{13}C$ signature trend of all sites, in all deeper soil depths and, fractions size. Further studies are needed to better understand this trend.

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