SABINA CERRUTO RIBEIRO

ESTOQUE DE BIOMASSA E CARBONO EM CERRADO E EM PLANTIO COMERCIAL DE EUCALIPTO NO ESTADO DE MINAS GERAIS

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

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APROVADA: 27 de junho de 2011.

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No Brasil existem cerca de 6.510.693 hectares de florestas plantadas, as quais geralmente formam um mosaico com florestas nativas. Dessa forma é de grande importância que se promovam estudos de quantificação de biomassa e carbono considerando essas duas formações vegetais, de forma a balizar os projetos de créditos de carbono. Nesse sentido, o presente trabalho teve como objetivo a quantificação da biomassa e estoque de carbono de um plantio comercial de eucalipto e de um fragmento de cerrado *sensu stricto* (cerrado s.s.) localizado em meio a uma matriz de eucalipto. A quantificação da biomassa e do carbono nas duas formações vegetais se deu no município de Curvelo, no Estado de Minas Gerais, em áreas pertencentes a uma empresa florestal que atua na produção de ferro gusa. No fragmento de cerrado s.s. 120 árvores pertencentes a 18 espécies foram abatidas para a determinação da biomassa e teor de carbono do tronco, galhos e folhas. Cinco modelos alométricos foram testados, usando-se as variáveis independentes *DAP*, altura (*H*), DAP^2H e densidade básica da madeira para estimar a biomassa acima do solo de árvores individuais. Um modelo baseado na área basal como parâmetro também foi testado como alternativa para a predição da biomassa acima do solo no nível de povoamento. A biomassa e o teor de carbono do componente radicular foram estimados com base em dez sub-parcelas. Para o eucalipto foram abatidas 23 árvores para a determinação da biomassa acima do solo, das quais foram selecionadas 9 para se estimar a biomassa de raízes. Além da quantificação da biomassa do tronco, galhos, folhas e raízes, foi determinado o teor de carbono desses componentes em laboratório. Dois modelos foram testados para estimar a quantidade total de carbono e a biomassa total usando-se como variáveis independentes o *DAP*, *H* e DAP^2H. Uma estimativa do estoque de carbono no plantio de eucalipto também foi gerada. Para o fragmento de cerrado s.s. verificou-se que a biomassa média acima do solo (tronco, galhos e folhas) e a biomassa média abaixo do solo corresponderam a 62,97 t ha^{-1} e 37,50 t ha^{-1}, respectivamente. A estimativa da biomassa acima do solo

é maior do que o observado em outros estudos, enquanto que a estimativa de biomassa abaixo do solo está dentro da faixa de valores reportada por outros estudos. A melhor equação para estimar a biomassa acima do solo de árvores individuais foi aquela com as variáveis independentes *DAP* e densidade básica da madeira ($\bar{R}^2$ = 0,896; $S_{y.x}$ = 0,371). No nível de povoamento, a equação testada apresentou um bom ajuste ($\bar{R}^2$ = 0,926; $S_{y.x}$ = 0,224). O teor de carbono médio para o tronco+galhos, folhas, raízes, arbustos e serapilheira foi de 48%. O estoque de carbono total estimado para o fragmento de cerrado s.s. é de 54,36 tC ha^{-1}. Para o plantio de eucalipto, obteve-se um teor de carbono médio para o tronco, galhos, folhas e raízes de 44,6%, 43,0%, 46,1% e 37,8%, respectivamente. O teor de carbono do caule, galhos, folhas e raízes foi menor do que o valor genérico comumente usado (50%). Isso destaca a importância de se determinar o teor de carbono em laboratório em vez de se usar um valor padrão. O estoque de carbono total no plantio de eucalipto foi estimado em 73,38 t C ha^{-1}, estando dentro da faixa encontrada em outros estudos. As equações para se estimar a quantidade total de carbono e biomassa total que obtiveram melhor ajuste apresentavam DAP^2H como variável independente.

ABSTRACT

RIBEIRO, Sabina Cerruto, D.Sc., Universidade Federal de Viçosa, June, 2011. **Biomass and carbon stock of a Cerrado and a commercial planting of Eucalyptus in Minas Gerais**. Advisor: Laércio Antônio Gonçalves Jacovine. Co-Advisors: Carlos Pedro Boechat Soares and Agostinho Lopes de Souza.

In Brazil plantations occupy about 6,510,693 hectares and usually form a mosaic with native forests. Therefore biomass and carbon stock studies should consider both vegetation forms. This study aimed the quantification of biomass and carbon stock of a commercial Eucalyptus planting and a cerrado *sensu stricto* (cerrado s.s.) remnant embedded in an Eucalyptus matrix. The biomass and carbon stock quantification in both vegetation forms took place in Curvelo, in the state of Minas Gerais, in a privately owned forestry company that operates in pig-iron production. In the cerrado s.s. remnant, 120 trees from 18 species were destructively sampled for biomass and carbon content determination of the stem, branches and leaves. Five models with DBH, height (H), DBH^2H and wood basic density as independent variables were tested for the estimation of individual tree aboveground biomass. One model based on basal area as a stand parameter was also tested as an alternative approach for predicting aboveground biomass in the stand level. Belowground biomass and roots' carbon content was estimated by subsampling on 10 sample plots. For the Eucalyptus, 23 sample trees were harvested for aboveground biomass assessment. Nine of the 23 sampled trees were selected to assess the roots biomass. Beside of the biomass quantification of the stem, branches, leaves and roots, the carbon content of these compartments were determined in laboratory. Two models were tested to estimate the total amount of carbon and total biomass using DBH, H and DBH^2H as independent variables. An estimate of carbon stock in the stand level was also generated. In the cerrado s.s. remnant we verified that the mean aboveground tree biomass (bole, branches and leaves) and mean belowground biomass accounted for 62.97 t ha^{-1} and 37.50 t ha^{-1}, respectively. Our estimates of aboveground biomass are higher than reported by other studies developed in the same physiognomy, but the estimates of belowground biomass are within the range of values reported in other studies. The best-fit equation for the estimation of individual tree aboveground biomass include DBH and wood density as explanatory variables ($\bar{R}^2$ = 0.896; SEE = 0.371). In the stand level, the model tested presented a good fit ($\bar{R}^2$ = 0.926; SEE =

0.224). The mean carbon content of bole + branches, leaves, roots, shrubs and litter is 48%. The total estimated carbon stock for the cerrado s.s. remnant is 54.36 tC ha^{-1}. For the Eucalyptus plantation, we found an average carbon content for the stem, branches, leaves and roots of 44.6%, 43.0%, 46.1% and 37.8%, respectively. The carbon content of stem, branches, leaves and roots was smaller than the generic value commonly used (50%). This highlights the importance of determining the carbon content in laboratory instead of using a default value. Total stand carbon stock in the Eucalyptus plantation was estimated to be 73.38 tC ha^{-1}, being within the carbon stock range for Eucalyptus plantations. The best-fit allometric equations to estimate the total amount of carbon and total biomass had DBH^2H as independent variable.

INTRODUÇÃO GERAL

O aquecimento do sistema climático da Terra é inequívoco e tem como causa o aumento da concentração de gases de efeito estufa (GEE) na atmosfera terrestre. Até o ano de 2005 foi registrado um aumento de 0,76ºC na temperatura do planeta (IPCC, 2007a). As conseqüências deste aquecimento já podem ser notadas em muitos sistemas físicos e biológicos (IPCC, 2007b).

Em função deste aquecimento e das suas conseqüências, desde 1992 foram criados diversos tratados para lidar com a questão. O primeiro deles foi a Convenção-Quadro das Nações Unidas sobre Mudança do Clima (CQNUMC), que foi assinada em 1992 e entrou em vigor em 1994. A CQNUMC tem como objetivo a estabilização da concentração dos GEE na atmosfera em um nível que impeça a influência de ações humanas perigosas no clima terrestre (MCT, 2001a).

Em 1997 foi criado o Protocolo de Quioto que é um acordo internacional que estabelece metas obrigatórias de redução de emissões de GEE para 37 países e a comunidade européia. Estes países deverão reduzir as suas emissões, em média, a 5,0% abaixo dos níveis observados em 1990, no período de 2008 a 2012 (MCT, 2001b). As metas de redução de emissões de GEE foram estabelecidas apenas para os países desenvolvidos (países Anexo I). Até o final de 2012, quando será finalizado o primeiro período de compromisso, os países em desenvolvimento (países não-Anexo I) não terão metas obrigatórias de redução de emissões a serem cumpridas.

O Protocolo de Quioto estabeleceu três mecanismos adicionais de implementação (comércio de emissões, implementação conjunta e mecanismo de desenvolvimento limpo) como meio de auxiliar os países Anexo I a cumprirem as suas metas de redução de emissões de GEE (Frondizi, 2009). Dentre esses mecanismos, apenas o Mecanismo de Desenvolvimento Limpo (MDL) permite a participação de países não-Anexo I, como o Brasil.

O MDL representa uma oportunidade para os países Anexo I adquirirem Reduções Certificadas de Emissões (RCEs) geradas em atividades de projeto estabelecidas em países não-Anexo I. Essas RCEs, as quais representam o crédito de carbono gerado por projetos no âmbito do MDL, podem ser usadas pelos países Anexo I para abater as suas metas de redução de emissões estabelecidas no Protocolo (Frondizi, 2009).

Diversos são os escopos setoriais elegíveis para o desenvolvimento de atividades de projeto no âmbito do MDL. Dentre estes escopos setoriais, o florestamento/reflorestamento é a categoria que abrange especificamente as atividades florestais. Estas também podem ser desenvolvidas fora do Protocolo de Quioto no âmbito do mercado voluntário e do mecanismo de Redução de Emissões por Desmatamento e Degradação e incremento dos estoques de carbono (REDD+).

No mercado voluntário não existem metas obrigatórias de redução de emissões, mas sim o abatimento de metas estabelecidas voluntariamente por empresas ou governos locais (Kollmuss et al., 2008). Já o REDD+ é um instrumento de incentivo econômico para a redução das taxas de desmatamento (Eliasch, 2008). Este mecanismo ainda não se encontra formalmente regulamentado junto a CQNUMC, mas espera-se que nos próximos anos estas definições sejam estabelecidas.

As florestas, além de possuírem um expressivo papel nos processos ambientais globais, são uma importante fonte de produtos e serviços para a humanidade (Baskent e Keleş, 2009). O sequestro e a estocagem de carbono na biomassa destacam-se como um relevante serviço ambiental prestado pelas florestas. A elaboração de projetos florestais e REDD+ passa pela quantificação da biomassa florestal como meio de se estimar o estoque de carbono em uma área. Uma vez tendo sido obtidos em campo os dados de biomassa e o teor de carbono em laboratório, é possível estimar o estoque de carbono de um local.

Segundo Bombelli et al. (2009), existem quatro formas principais de quantificar a biomassa florestal: i) uso de método destrutivo *in situ*; ii) estimativas por métodos não-destrutivos *in situ*; iii) inferência a partir de sensoriamento remoto e iv) uso de modelos.

i) Uso de método destrutivo *in situ*: este método envolve o corte de árvores, arbustos e gramíneas. O material recolhido é seco e pesado a fim de se determinar a massa seca ou a biomassa. Este método pode ser aplicado para árvores individuais, no qual a biomassa de cada indivíduo é mensurada, ou por meio de parcelas. Neste último, a biomassa total de uma área específica ou parcela amostral é mensurada. Em geral, o método destrutivo *in situ* é comumente usado em pesquisas para o desenvolvimento e ajuste de equações alométricas que permitam a estimação da biomassa em grandes áreas.

ii) Estimativas por métodos não-destrutivos *in situ*: neste método são mensuradas variáveis dendrométricas que não impliquem no corte das árvores, tais como o diâmetro do tronco e a altura da árvore. Com base em relações alométricas ou fatores de conversão, essas variáveis são usadas para se obter estimativas de biomassa por unidade de área. O uso de equações alométricas para estimar a biomassa florestal é um método considerado acurado, desde que a equação usada tenha sido desenvolvida com base em um número de árvores adequado que garanta a representatividade do ecossistema avaliado.

iii) Inferência a partir de sensoriamento remoto: o uso de dados provenientes de sensoriamento remoto permite ampliar as estimativas de biomassa para grandes áreas, nas quais a execução de um inventário florestal poderia estar limitada por questões espaciais. Além disso, este método também pode ser usado para complementar estimativas obtidas a partir de inventários florestais, principalmente quando há falhas temporais ou espaciais nos dados. Diversas técnicas podem ser usadas para a estimativa de biomassa, conforme o nível de precisão requerida e os dados disponíveis.

iv) Uso de modelos: os modelos são usados para extrapolar as estimativas de biomassa ao longo do tempo e/ou espaço a partir de um banco de dados limitado (*in situ* ou provenientes do uso de sensoriamento remoto). Geralmente são usados modelos empíricos baseados em medições periódicas de árvores, feitas em parcelas permanentes, que incluem estimativas de biomassa embutidas ou podem requerer o uso de relações alométricas para converter o volume em biomassa. Quando os modelos empíricos não estiverem disponíveis podem ser usados modelos de processo baseados em variáveis ambientais.

Uma vez obtidas as estimativas de biomassa, é possível estimar o estoque de carbono por meio da multiplicação do valor da biomassa pelo teor de carbono. Os estudos que visem a quantificação da biomassa e a determinação do estoque de carbono em diferentes formações florestais devem ser estimulados. Os resultados encontrados podem ser usados por desenvolvedores de projetos florestais e REDD+ para embasar as estimativas de estoque de carbono de seus projetos.

No Brasil existe um grande número de empresas florestais. Nestas empresas é comum a existência de áreas de plantio e de florestas nativas, que visam atender às exigências previstas na legislação ambiental do país (ex. áreas de preservação permanente e reserva legal). Em algumas empresas, as áreas protegidas são estabelecidas de forma voluntária, como é o caso da reserva particular do patrimônio natural. Segundo a ABRAF (2011), em 2010 as suas empresas associadas possuiam para cada 1,0 ha de plantio florestal, 0,81 ha de floresta nativa.

Dada a relevância das florestas para o sequestro e estoque de carbono na biomassa e considerando que, no Brasil, existem cerca de 6.510.693 hectares de florestas plantadas (ABRAF, 2011), as quais geralmente formam um mosaico com florestas nativas, é de grande importância que se promovam estudos de quantificação de biomassa considerando essas duas situações. Nesse sentido, o presente trabalho teve como objetivo a quantificação da biomassa e estoque de carbono de um plantio comercial de eucalipto e de um fragmento de cerrado *sensu stricto* em Minas Gerais.

A tese foi estruturada em dois capítulos. Cada capítulo encontra-se na forma de artigo, conforme apresentado a seguir:

Capítulo 1: “Above- and belowground biomass in a Brazilian Cerrado” (artigo publicado na For. Ecol. Manage. 262 (2011), 491-499). Neste estudo foram geradas estimativas de biomassa e estoque de carbono acima e abaixo do solo para um fragmento de cerrado *sensu stricto* a partir do método destrutivo e foram ajustados modelos alométricos para estimar a biomassa.

Capítulo 2: “Above- and belowground biomass and carbon estimates for clonal Eucalyptus trees in southeastern Brazil”. O teor de carbono no tronco, galhos, folhas e raízes de um plantio clonal de *Eucalyptus urograndis* foi determinado e equações alométricas para estimar a quantidade total de carbono e a biomassa total foram ajustadas. Uma estimativa do estoque de carbono do plantio de eucalipto também foi gerada.

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CAPÍTULO 1

ABOVE- AND BELOWGROUND BIOMASS IN A BRAZILIAN CERRADO

Resumo

O Cerrado é um bioma que ocupa cerca de 25% do território brasileiro e é caracterizado por um gradiente de formações campestres, savânicas e florestais com alta riqueza de espécies. Esse bioma vem sendo severamente afetado pela degradação e desmatamento nas últimas 4-5 décadas. Apesar da importância ecológica do Cerrado, existem poucos estudos que focaram na quantificação da biomassa neste bioma. Considerando o exposto, este estudo objetivou a geração de estimativas de biomassa acima e abaixo do solo, de estoque de carbono e o desenvolvimento de equações alométricas em um cerrado *sensu stricto* (cerrado s.s.) no sudeste do Brasil. Para isso, 120 árvores pertencentes a 18 espécies foram selecionadas para a quantificação da biomassa de folhas, galhos e tronco pelo método destrutivo. Cinco modelos foram testados para o desenvolvimento de equações alométricas para estimar a biomassa arbórea acima do solo (folhas + galhos + tronco). As variáveis independentes usadas nos modelos foram o DAP (D), a altura (H), D^2H e a densidade básica da madeira (WD). Um modelo usando a área basal (BA) como parâmetro do povoamento também foi testado como alternativa para a predição da biomassa acima do solo em nível de povoamento. A biomassa abaixo do solo foi estimada pela amostragem de 10 sub-parcelas. A biomassa arbórea média acima do solo (tronco, galhos e folhas) foi estimada em 62,97 t ha^{-1} ($S_{\bar{Y}\%}$= 14,6%) e a biomassa abaixo do solo correspondeu a 37,50 t ha^{-1} ($S_{\bar{Y}\%}$= 23%). A equação de melhor ajuste para a estimação da biomassa acima do solo em nível de árvore individual apresentou o DAP e a densidade básica da madeira como variáveis explicativas ($\bar{R}^2$ = 0,896; $S_{y.x}$ = 0,371). Essa equação é aplicável para a variação diamétrica deste estudo (5,0 – 27,6 cm) e em ambientes com condições similares ao cerrado s.s. amostrado. Em nível de povoamento, o modelo testado apresentou um melhor ajuste do que os modelos em nível de árvore individual ($\bar{R}^2$ = 0,926; $S_{y.x}$ = 0,224). As estimativas de biomassa acima do solo são maiores do que as encontradas em outros estudos desenvolvidos na mesma fisionomia. Entretanto, as estimativas de biomassa abaixo do solo estão dentro dos limites apresentados por outros estudos em áreas de cerrado s.s. No entanto, ambas as estimativas possuem erros-padrão relativamente altos. A razão raiz-parte aérea das árvores-amostra foi similar aos valores apresentados na literatura para ecossistemas savânicos, porém são menores do que os estimados em outros estudos em áreas de cerrado s.s.

Palavras-chave: estimação da biomassa, Cerrado, Brasil, equação alométrica.

Abstract

Cerrado is a biome that occupies about 25% of the Brazilian territory and is characterized by a gradient of grassland to savanna and woodland formations and by high species richness. It has been severely affected by degradation and deforestation and has been heavily fragmented over the past 4-5 decades. Despite the recognized overall ecological importance of the Cerrado, there are only few studies focusing on the quantification of biomass in this biome. We conducted such a case study in the Southeast of Brazil in a cerrado *sensu stricto* (cerrado s.s.) with the goal to produce estimates of above- and belowground biomass, carbon stock and to develop allometric equations. A number of 120 trees from 18 species were destructively sampled and partitioned into the components leaves, branches and bole. Five models with DBH (D), height (H), D^2H and wood density (WD) as independent variables were tested for the development of allometric models for individual tree aboveground biomass (leaves + branches + bole). One model based on basal area (BA) as a stand parameter was also tested as an alternative approach for predicting aboveground biomass in the stand level. Belowground biomass was estimated by subsampling on 10 sample plots. Mean aboveground tree biomass (bole, branches and leaves) was estimated to be 62.97 t ha^{-1} (SE = 14.6%) and belowground biomass accounted for 37.50 t ha^{-1} (SE = 23%). The best-fit equation for the estimation of individual tree aboveground biomass include DBH and wood density as explanatory variables ($\bar{R}^2$ = 0.896; SEE = 0.371) and is applicable for the diameter range of this study (5.0 – 27.6 cm) and in environments with similar conditions of the cerrado s.s. sampled. In the stand level, the model tested presented a higher goodness of fit than the single tree models ($\bar{R}^2$ = 0.926; SEE = 0.224). Our estimates of aboveground biomass are higher than reported by other studies developed in the same physiognomy, but the estimates of belowground biomass are within the range of values reported in other studies from sites in cerrado s.s. Both biomass estimates, however, exhibit relatively large standard errors. The root-to-shoot ratio of the sample trees is in the magnitude of reported values for savanna ecosystems, but smaller than estimated from other studies in the cerrado s.s.

Keywords: biomass estimation, Cerrado, Brazil, allometric equation.

1. Introduction

Savannas are spread worldwide, especially in tropical regions, and cover about one-fifth of the global land surface (Sankaran et al., 2005). Tropical savannas cover half the area of Africa and Australia, 45% of South America and 10% of India and Southeast Asia (Scholes and Archer, 1997). The savanna formation in Brazil constitutes the *Cerrado* which is, after Amazonia, the second largest biome of Brazil (Klink and Machado, 2005).

Cerrado occupies about a quarter of the Brazilian territory (IBGE, 2004) and is characterized by a gradient of grassland, savanna and woodland formations. The Cerrado is not a homogeneous vegetation type: according to Coutinho (1978) and Ribeiro and Walter (1998), its physiognomies range from *campo* forms (grassland formation), and the typical cerrado *sensu stricto* (savanna formation with trees and shrubs up to 3-6 m high and with a grass understory) to the cerradão (woodland formation with trees up to a height of 8-15 m). More detailed descriptions of Cerrado physiognomies can be found in Goodland (1971), Eiten (1972) and Oliveira-Filho and Ratter (2002).

Despite the fact that Cerrado has a high species richness (including many endemic species) and is considered a biodiversity hotspot, only about 2.2% of its area has a legal protection status (Marris, 2005); that points to the little attention that this biome receives as compared to tropical rain forest (Giambelluca et al., 2009). The Cerrado has been severely fragmented and degraded due to deforestation over the past 4-5 decades, where the land was subsequently used for cash crops and cattle ranching (Klink and Moreira, 2002). A recent remote sensing study comes to the conclusion that about 47.9% of Cerrado's original cover had been cleared by 2008 (Brasil, 2009). After the Atlantic Forest, Cerrado is the Brazilian biome that most suffered anthropogenic impacts and it has been classified among the most threatened biomes of the world (Myers et al., 2000; Mittermeier et al., 2005).

Among the very relevant features of Cerrado is its role in the global carbon balance. The high rates of deforestation caused greenhouse gas emissions in the order of magnitude of 64.5 TgC per year over the period from 2002 to 2008 (Brasil, 2009). However, this figure can only be taken as a rough estimate as there are only a very limited number of studies that deal with the quantification of biomass and carbon in this biome in a comprehensive manner.

Most biomass studies in Cerrado areas looked only into the aboveground component, while other carbon pools such as litter and belowground biomass were rarely studied and only a very small number of studies to date published estimates on above- and belowground biomass for cerrado *sensu stricto* (e.g. Abdala et al., 1998; Castro and Kauffman, 1998; Lilienfein et al., 2001). Also, only a small number of studies estimated aboveground biomass in other Cerrado physiognomies (Kauffman et al., 1994; Araujo et al., 2001; Ottmar et al., 2001; Santos et al., 2002; Vale et al., 2002; Barbosa and Fearnside, 2005; Delitti et al., 2006; Rezende et al., 2006).

The biomass stock is an immediate measure for the quantity of carbon that will be emitted to the atmosphere when the corresponding area is converted to another land use through burning and decay (Houghton et al., 2009). Therefore, as Cerrado is strongly affected by fire (natural and human induced) and has high rates of deforestation, it is of utmost importance to quantify the different biomass pools in this biome. Reliable estimates of biomass are necessary for the prediction of the emissions from land use change and of biomass stock in ecosystems (Alves et al., 2010). Moreover, the information on biomass amount can be used in forestry projects under the Kyoto Protocol and in the implementation of REDD (Reducing Emissions from Deforestation and Forest Degradation) initiatives (Djomo et al., 2010).

Allometric models are among the standard tools for biomass prediction (Fehrmann and Kleinn, 2006), in particular when individual tree biomass is to be estimated, because biomass cannot directly be measured nor observed in the field. An allometric model is an empirical relationship between biomass and easily measured variables, such as tree diameter at breast height that can be established by means of a regression analysis (Overman et al., 1994; Parresol, 1999; Ketterings et al., 2001). Such models are valid and should be applied only to the species or species group for which they were derived and many of such models suffer from a relatively modest number of measurements on which they are based. Hardly any mixed species models for the Cerrado can be found in the literature (Abdala et al., 1998; Rezende et al., 2006).

In our work we wanted to address and help filling some of the knowledge gaps in Cerrado biomass studies. We selected the most typical physiognomy of Cerrado, the cerrado *sensu stricto* (s.s.) – and provided estimates of above- and belowground biomass that base on allometric models derived from destructive samples taken for individual tree biomass measurements. We also provide carbon stock estimates for the cerrado s.s. remnant.

2. Material and methods

2.1. Study site

Field data were collected in October 2009 in a protected Cerrado remnant (33 ha) in Curvelo, located in the central part of the state of Minas Gerais, Brazil. The fragment is embedded in a *Eucalyptus* matrix inside an area of a privately owned company that operates in pig-iron production and *Eucalyptus* plantation. The average annual rainfall in Curvelo is around 1.200 mm, falling mostly during January and February, and the mean annual temperature is 23°C. Soils in the region have a high content of clay, low fertility and little organic matter. The soil type in the Cerrado remnant area is the red latosol. The elevation of study site is approximately 600 m. Cerrado in Curvelo is affected by human interventions since long. These interventions were over the past 4-5 decades mainly due the conversion to pasture to cash-crop agriculture and to eucalyptus monocultures (ALMG, 2004; Klink and Machado, 2005). These land-use changes lead to a heavy fragmentation of the landscape where the remnants were left at different stages of degradation.

The Cerrado remnant where this study took place can be classified according to Ribeiro and Walter (1998), as “cerrado sensu stricto típico” (cerrado s.s. in the following). This phytophisionomy is characterized by high species richness of shrubs and trees with mean height of about 3-6 m and tree cover of 20-50%. In the whole study site there was no clear evidence of any recent anthropogenic disturbance.

2.2. Forest inventory

In order to characterize the vegetation in more detail a forest inventory was carried out. The cerrado s.s. remnant of this study has a rectangular shape (Figure 1). Ten plots of 20 m x 25 m (0.05 ha) were established in a systematic grid over the forest area. The plots were separated 200 m from each other along two transect lines. The distance between each plot and the border of the remnant was 75 m. On these sample plots, for all trees with DBH > 5 cm the girth was tape measured, the tree height was visually estimated by experienced field crews in 0.5 m classes and species was identified.

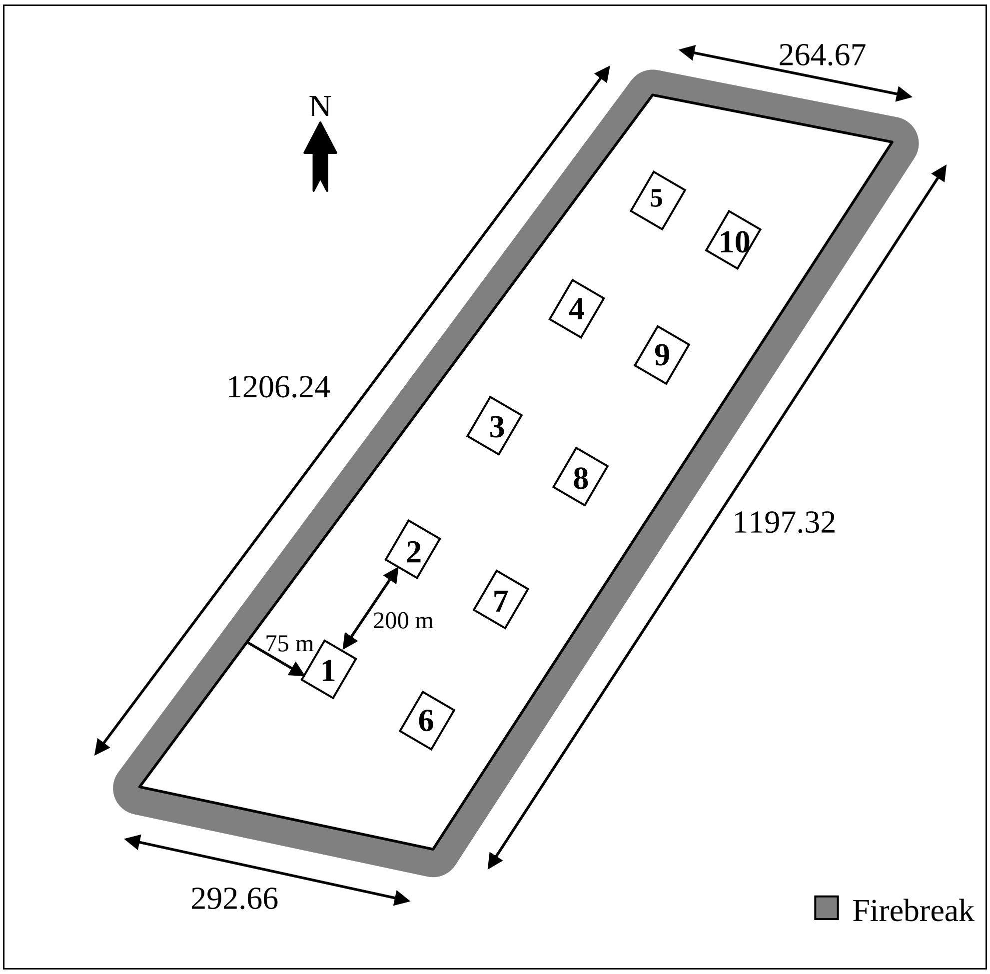

Figure 1. Plot design in the "cerrado s.s." remnant in Curvelo (MG), Brazil.

Multi-stemmed trees are common in Cerrado vegetation. In order to make the biomass comparable for all trees – single-stem and multi-stem – a pooled diameter (Eq. 1) was calculated for trees with multiple stems.

$$D_x = \sqrt{D1^2 + D2^2 + \cdots + Dn^2} \qquad (1)$$

The average height of a multiple-stem tree was calculated as a simple arithmetic mean of the heights of all stems.

2.3. Selection of sample trees

In Cerrado, as in many other tropical forest types, tree species diversity is high and the availability of prior studies that focus on individual species' biomass or tree architecture is limited. Considering that a certain minimum number of sample trees need to be biomass measured to derive a useful model, it becomes clear that feasible biomass estimation will need to start with aiming at models for larger sets of species rather than for individual species. In our case, we faced the additional issue of bureaucratic barriers. As Cerrado is one of the two recognized biodiversity hotspots in Brazil (Myers et al., 2000; Mittermeier et al., 2005), it is difficult to obtain permission for destructive sampling spread over a larger area, even for research purposes. Due to practical restrictions we needed to limit the total number of trees to be selected for destructive sampling to 120 individuals.

Selection of sample trees was prepared on the basis of data from the inventory as described above (Figure 1) where DBH, height and species was observed for all trees with DBH > 5 cm on 10 systematically arranged sample plots of 500 m^2 each. From these data, we were able to observe 47 species, from which were identified a set of 18 species that contribute with more than 75% to basal area. We used basal area as guiding variable here because basal area is known to be highly correlated to many tree variables and it can be determined with only two sources of error, (1) the measurement of diameter or girth and (2) the model assumption of a perfectly circular cross cut. The set of 18 species contains the most typical tree species for the biome Cerrado in general (Ratter et al., 2003) and for the Cerrado area in state of Minas Gerais (Brandão and Gavilanes, 1992), where this study was carried out.

The number of sample trees per species to be cut was determined proportional to the species contribution to total basal area. Trees for each species were selected proportional to basal area, according to diameter classes. Sample trees were then identified from the list of inventory sample trees in such a way that a uniform spatial distribution over the whole study site was ensured.

2.4. Biomass of the sample trees

A total number of 120 trees were harvested. The stem was cut as close to soil level as possible. The stump was marked with the code number for unambiguous identification. Disks at breast height were cut and weighed (using a balance of 5-10 kg capacity and 1-2 g division) from all felled trees. The rest of the stem and the branches were cut in appropriately sized pieces and weighed together using a standard balance of 150 kg capacity and 100 g division. For trees with multiple stems, the woody biomass of one single tree was considered as the sum of weights of each stem of this single tree.

All leaves of single trees were collected manually and fresh weight was recorded. A composite sample (~135 g) of leaves was manually collected for each individual and weighed to determine fresh weight to dry weight relation. The wood disks and samples of leaves were taken to the laboratory. Two wood samples were taken from each wood disk on opposite sides. Each wood sample was volume measured by water displacement and weighed after oven drying at 103 ± 2 ºC until weight stabilized. The basic wood density for one wood disk was calculated as an average of the two measurements per disk (Table 1). The leaf samples were dried at ~70 ºC until the weight stabilized.

The per-plot biomass was then expanded to estimate the biomass stock per-hectare in a two-step procedure: (1) biomass per plot was upscaled from the biomass m_i of the sub-set of biomass-sampled trees by using a upscaling factor (UF_i) that is a ratio between the total number of trees of a plot to the number of trees harvested in this plot; and (2) biomass per hectare was calculated by standard plot expansion; here, for inventory sample plots of 0.05 ha, the expansion factor is constantly EF = 10,000/500 = 20 for all sample plots. The estimated biomass per hectare B_i, as expanded from the inventory plot i, results then from the equation 2:

$$B_i = UF_i \times m_i \times EF \qquad (2)$$

where B_i refers to the biomass stock per hectare of the i^{th} plot (kg ha^{-1}) and UF_i and m_i refer to the upscaling factor and to the sub-sampled biomass (kg) of the i^{th} plot, respectively.

2.5. Biomass of shrubs and litter

Shrub was defined to be all woody species with DBH < 5 cm. In the center of each inventory plot, shrubs were sampled in a sub-plot of 2.0 m x 2.5 m; they were cut and the total fresh weight was determined. A random sample (wood and leaves) of about 200 g was collected from each sub-plot to determine the fresh- to dry weight relation.

Litter was defined as dead biomass forming a layer on the ground above the mineral soil and consisting of decaying leaves, twigs and wood parts. Litter was collected within a wooden frame with 1.0 m^2 area that was laid out at two opposite corners of the rectangular sample plot. The fresh weight of all material was determined while a sample of about 80 g was taken to be dried in order to determine the fresh- to dry weight relation.

Both the samples of shrubs and litter were dried at ~70 ºC in an oven until the stabilization of weight. The estimate of litter biomass per plot was then calculated as mean of the two measurements per plot.

2.6. Biomass of roots

Root biomass assessment had a different approach than the aboveground biomass. Instead of sampling the roots based on single trees, the roots biomass was determined per area. Thus, a sub-plot of 2.0 m x 2.5 m was established in the center of each inventory plot. The sub-plot was excavated to a depth of 1.0 m. All the soil inside the sub-plot passed through a sieve with mesh size of 1.0 cm. As most of the roots were too long, they could not pass through the sieve. Thus, even the roots that had a diameter smaller than 1.0 cm were collected. Live and dead roots were hand-sorted together from the material remaining in the sieve. Taproot and coarse roots were cut close to the ground and removed. All collected roots were weighed in the field. A random sample of about 300 g was taken from the total material, weighed in the field and then dried at ~70 ºC in an oven until stabilization of weight in order to determine the fresh- to dry weight relation.

2.7. Biomass modeling

For statistical analysis of single tree biomass we only considered the total aboveground part per tree that is the biomass values for stem, branches and leaves. Input variables for the biomass model were DBH (*D*), height (*H*) and wood density (*WD*). For some model formulations *D* and *H* entered the analyses also as the interaction term D^2H. Five standard models (Loetsch et al., 1973; Chave et al., 2005) were tested for prediction of aboveground biomass:

$$lnB = \beta_0 + \beta_1 lnD + \beta_3 lnH + \beta_7 lnWD + \varepsilon \qquad (m_1)$$

$$lnB = \beta_0 + \beta_5 lnD^2H + \beta_7 lnWD + \varepsilon \qquad (m_2)$$

$$lnB = \beta_0 + \beta_1 lnD + \beta_2 (lnD)^2 + \beta_4 (lnD)^3 + \beta_7 lnWD + \varepsilon \qquad (m_3)$$

$$lnB = \beta_0 + \beta_1 lnD + \beta_7 lnWD + \varepsilon \qquad (m_4)$$

$$lnB = \beta_0 + \beta_1 lnD + \varepsilon \qquad (m_5)$$

where B = aboveground biomass in kg; D = diameter at breast height in cm; H = total height of the tree in m; WD = wood density in g cm^{-3}; β_0, β_1 and β_2 = regression parameters; ε = random error.

As already mentioned before, the high species diversity of cerrado s.s. is an argument to search for simple and general approaches to model aboveground biomass. One possibility in this context is not to use single tree models to estimate biomass per tree on each sample plot, but to use stand parameters as independent variables. We tested a model with the basal area (*BA*) as an independent variable. The data used for model adjustment are total biomass and the respective total basal area of all sampled trees per plot:

$$lnB = \beta_0 + \beta_8 lnBA + \varepsilon \quad (m_6)$$

As the single tree biomass show a typical heteroscedasticity when plotted against the independent variables, we applied a log-transformation to ensure a homogenization of variances as precaution for linear regression analysis. For back transformation of model predictions to the metric scale a correction factor *CF* has to be applied in order to comply with the different distributions of log-transformed and metric values (Sprugel, 1983; Fehrmann and Kleinn, 2006):

$$CF = exp\ (SEE^2/2) \quad (3)$$

The correction factor is a number greater than one and is calculated based on the standard error of estimate (*SEE*). The more precise the estimates predicted by the model, the smaller the *SEE* and thus the correction factor.

The models were fitted to data using ordinary least squares-regression analysis. All data analyses were performed with the STATISTICA software package version 8.0 (StatSoft Inc, 2007). The significance of the models was evaluated with the *F-test* and the *t* statistic was used to test the significance of the model coefficients.

The normal probability plots of residuals and of the standard residuals versus predicted values of each tested model were examined to verify the compliance with the assumptions of least square regression. The selection of the best equation followed the criteria proposed by Draper and Smith (1998) that is logic of the sign (+/-) of the coefficient associated with a specific variable, the adjusted coefficient of determination ($\bar{R}^2$), the standard error of estimate (*SEE*), and the analysis of variance table and residual distributions.

2.8. Carbon stock

The carbon content of each compartment (bole + branches, leaves, roots, shrubs and litter) was determined in laboratory using a continuos-flow isotope ratio mass spectrometer (ANCA-GLS). The carbon stock (Eq. 4) of the different compartments was estimated using the biomass per plot (B_i) and the carbon content (T_{C_i}).

$$C_i = B_i \cdot T_{C_i} \tag{4}$$

3. Results

3.1. Species richness and tree variables

In the forest inventory of the 10 sample plots we found 47 tree species with DBH > 5 cm and tree density was estimated to be 2086 trees ha^{-1}. These 47 species belong to 40 genera and 29 families. The six most common species were *Qualea parviflora*, *Qualea grandiflora*, *Erythroxylum suberosum*, *Caryocar brasiliense*, *Eriotheca gracilipes* and *Lafoensia pacari*. Among the 18 species (Table 1) that were selected for destructive biomass measurements, there were five of the six most common species. The exception was *Caryocar brasiliense,* which is protected by federal regulations since 1987 and must not be cut (IBDF, 1987).

Table 1. Basal area *B*, number of trees *N*, and average wood density *WD* from the cerrado s.s. forest inventory (only the species that were included for destructive measurements).

Species, scientific name	**Botanical family**	**Variables [per hectare]**		
		B **(m^2)**	***N***	***WD*** **(g cm^{-3})**
Acosmium sp.	Fabaceae	0.141	29	0.65
Astronium fraxinifolium Schott ex Spreng.	Anacardiaceae	0.105	26	0.67
Byrsonima coccolobifolia Kunth	Malpighiaceae	0.116	30	0.50
Curatella americana L.	Dilleniaceae	0.147	4	0.51
Eriotheca gracilipes (K.Schum)A.Rob.	Bombacaceae	0.270	26	0.43
Erythroxylum suberosum A. St.-Hil.	Erythroxylaceae	0.537	105	0.55
Lafoensia pacari A. St.-Hil.	Lythraceae	0.126	32	0.60

Table 1. (continue)

Species, scientific name	Botanical family	Variables [per hectare]		
		B **(m^2)**	***N***	***WD*** **(g cm^{-3})**
Piptocarpha rotundifolia (Less.) Baker	Asteraceae	0.075	19	0.46
Plathymenia reticulata Benth.	Fabaceae	0.062	14	0.58
Pouteria torta (Mart.) Radlk.	Sapotaceae	0.098	11	0.59
Pterodon emarginatus Vogel	Fabaceae	0.111	9	0.68
Qualea grandiflora Mart.	Vochysiaceae	0.927	129	0.56
Qualea parviflora Mart.	Vochysiaceae	2.265	260	0.51
Sclerolobium sp.	Fabaceae	0.167	18	0.60
Solanum sp.	Solanaceae	0.270	21	0.45
Strychnos pseudoquina A. St.-Hil.	Loganiaceae	0.005	1	0.70
Stryphnodendron adstringens (Mart.) Coville	Fabaceae	0.126	13	0.54
Terminalia argentea Mart.	Combretaceae	0.108	17	0.67

The DBH, height and basal area of the all inventory sample trees are given in Table 2 and these are contrasted there to the mensurational characteristics of the sub-set of trees that was destructively sampled for biomass. Three inventory sample trees of *Caryocar brasiliense* had DBH > 30.0 cm, which explains the greater range in DBH of all inventory trees when compared to the biomass sample trees. Removing these three individuals leads to a maximum diameter of 28.0 cm that is a value similar to the maximum diameter of sample trees.

In a similar way, the range of height of all trees is also greater than the sample trees. The surveyed trees in the forest inventory have a maximum height of 7.5 m, except for one tree of *Tabebuia serratifolia* (height = 19.0 m) which was responsible for increasing the height range in this case.

Table 2. Mensurational characteristics of all inventory plot sample trees and of the sub-set selected for destructive biomass measurements.

	All inventory plot sample trees	**Sub-set of biomass sample trees**
DBH (cm)		
mean (C.V.[a])	8.74 (44.13%)	10.77 (37.68%)
range	5.0 – 43.9	5.0 – 27.6
SE%[b]	1.37	3.47
CI[c]	8.74 ± 0.234	10.77 ± 0.732
Height (m)		
mean (C.V.[a])	3.39 (28.44%)	3.86 (26.50%)
range	1.5 – 19.0	1.5 – 7.5
SE%[b]	0.88	2.44
CI[c]	3.39 ± 0.058	3.86 ± 0.184
Basal area (m^2 ha^{-1})	14.94 (127.08%)	2.41 (81.95%)
SE%[b]	3.93	7.48
CI[c]	0.01 ± 0.001	0.02 ± 0.003

[a]C.V.: coefficient of variation.
[b]SE%: relative standard error.
[c]CI: confidence interval (95% CI).

The basal area of the inventory plot sample trees corresponds to 16.1% of total basal area of the woodland remnant. The sub-set of biomass sample trees encompass the range of mensurational characteristics of the whole set of trees.

3.2. Above- and belowground biomass

The aboveground tree biomass (bole, branches and leaves) as expanded from the ten plots to per-hectare values ranged from 12.90 t ha^{-1} to 107.36 t ha^{-1}, with a mean of 62.97 t ha^{-1} and a relative standard error of 14.6% (Figure 2). The biomass of bole and branches (60.96 t ha^{-1}, 14.6%[1]) had a smaller variation than the biomass of leaves (2.00 t ha^{-1}, 20.7%).

[1] Relative Standard Error (SE%)

The biomass of leaves is comparable in all plots. Some variation is presumably related to the presence of brevideciduous/deciduous species, such as *Qualea grandiflora*, *Q. parviflora* and *Erythroxylum suberosum* (Lenza and Klink, 2006).

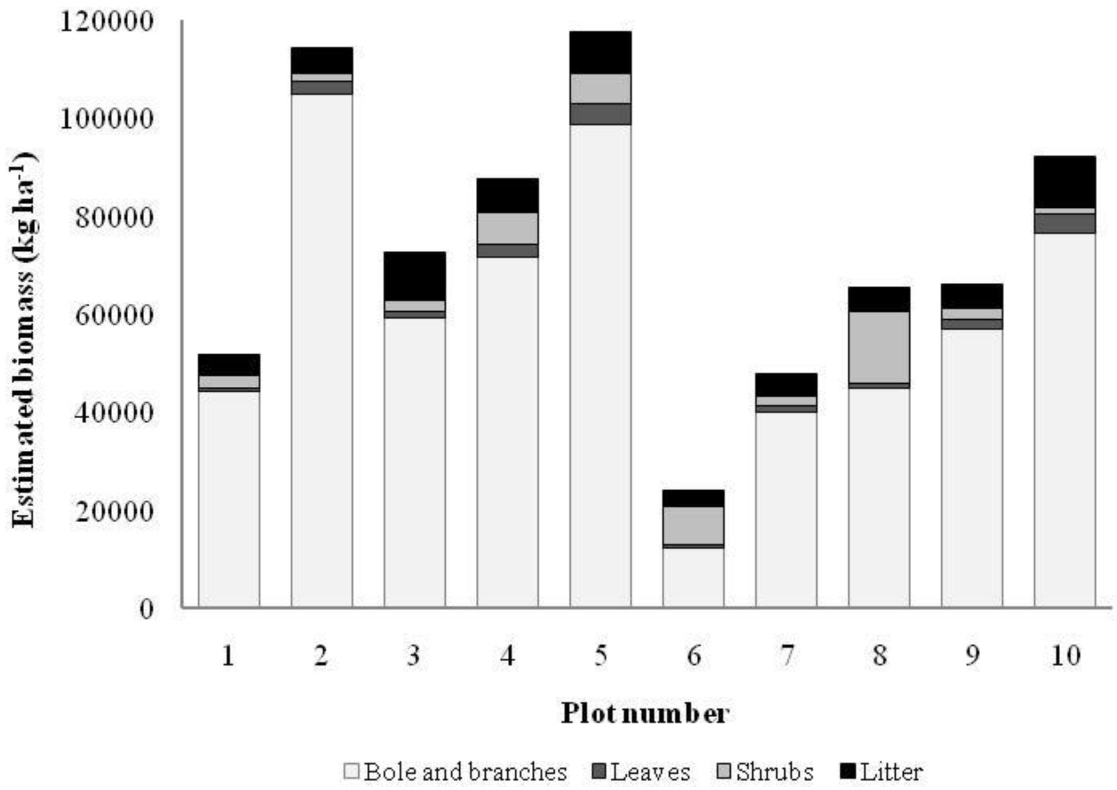

Figure 2. Aboveground biomass of the ten sample plots in a cerrado s.s. in Curvelo (MG), Brazil.

The estimated mean biomass of shrubs and litter is 4.68 t ha^{-1} (28.2%) and 6.32 t ha^{-1} (12.3%), respectively, so that total aboveground biomass (AGB), resulting from the AGB of trees, shrubs and litter, is estimated to be 73.96 t ha^{-1}. These figures are higher than those published for the same Cerrado vegetation type, as illustrated by the comparison in Table 3.

Table 3
Published figures on aboveground biomass (kg ha^{-1}) from studies in areas of cerrado s.s.

State[a]	Basal area (m^2 ha^{-1})	Tree density (tree ha^{-1})	Measurement criteria[d]	Tree biomass	Shrub biomass	Tree + shrub biomass	Grassy/woody layer	Litter	AGB	References
DF	14.5	670	C_{30} >6 cm	22,898[g]	3122[g]	26,020	5580 (±2240)[e]	5190 (±190)[e]	36,790	Abdala et al. (1998)
	8.5	1069[b]	Height >2 m (B_{30} and DBH)	6600 (±1700)[f]	6200 (±500)[f]	12,800	8200	3800 (±300)[f]	24,800 (±2500)[f]	Castro and Kauffman (1998)
	14.5	1000[c]	"	12,900 (±2500)[f]	3200 (±500)[f]	16,100	5600	3300 (±200)[f]	25,000 (±2900)[f]	
	–	2819	B_{30} ≥2 cm	–	–	14,280[g]	4680[g]	1940[g]	20,900[g]	Ottmar et al. (2001)
	–	10,776	"	–	–	21,370	6560	5450	33,380	
	–	6258	"	–	–	42,960	8090	6960	58,010	
	–	673	B_{30} ≥5 cm	12,393[g]	–	–	–	–	–	Vale et al. (2002)
	6.2	681	B_{30} ≥5 cm	9850 (±1080)[e]	–	–	–	–	–	Rezende et al. (2006)
MG	–	1054	B_{30} ≥2 cm	–	–	12,530[g]	7120[g]	1350[g]	21,000[g]	Ottmar et al. (2001)
	–	6487	All trees and shrubs in the plot	17,140[g]	2629[g]	19,769[g]	2966[g]	–	22,735[g]	Lilienfein et al. (2001)
MT	–	2267	B_{30} ≥2 cm	–	–	35,370[g]	7680[g]	4730[g]	47,780[g]	Ottmar et al. (2001)
	–	–	All trees and shrubs in the plot	12,400[g]	–	–	–	–	–	Araujo et al. (2001)
	–	–	All trees and shrubs in the plot	12,970[g]	–	–	–	–	–	Santos et al. (2002)
	–	–	"	13,830[g]	–	–	–	–	–	
	–	–	"	11,350[g]	–	–	–	–	–	
	–	–	"	11,820[g]	–	–	–	–	–	
	–	–	"	16,750[g]	–	–	–	–	–	
	–	–	"	20,570[g]	–	–	–	–	–	
	–	–	"	11,500[g]	–	–	–	–	–	
RR	–	–	B_1 ≥2 cm	–	–	9559 (±1297.7)[e]	1524.8 (416.6)[e]	442 (±150.6)[e]	–	Barbosa and Fearnside (2005)
MG	14.9	2086	DBH ≥5 cm	62,966 (14.6%)[h]	4682 (28.2%)[h]	67,648	–	6317 (12.3%)[h]	73,965	This study

[a] Federal States: Distrito Federal (DF), Minas Gerais (MG), Mato Grosso (MT) and Roraima (RR).
[b] Open scrub (*cerrado aberto*).
[c] Closed scrub (*cerrado denso*).
[d] Refers to the criteria used to define the minimum size for a tree/shrub be included in the biomass assessment: C_{30} and B_{30} refer to perimeter and diameter at 30 cm height, respectively; B_1 refers to diameter at 1 cm above the ground.
[e] Standard deviation.
[f] Standard error.
[g] No information about the precision of the estimation.
[h] Relative standard error (%).

Trees (leaves and wood), shrubs and litter accounted for an estimated 85.1%, 6.3% and 8.5% of the AGB, respectively. Only the tree biomass has considerably higher values as compared to other studies, while the biomass of shrubs and litter are within the range of magnitude reported in previous studies. Estimates of belowground biomass (BGB, down to 1 m) from the ten sub-plots ranged from 15.07 t ha^{-1} to 102.12 t ha^{-1} with an estimated mean of 37.50 t ha^{-1} (*SE%* = 23.0%). Combining all biomass components considered in this study (AGB and BGB), the total biomass for the study area was thus estimated to 111.47 t ha^{-1} and its composition is depicted in Figure 3.

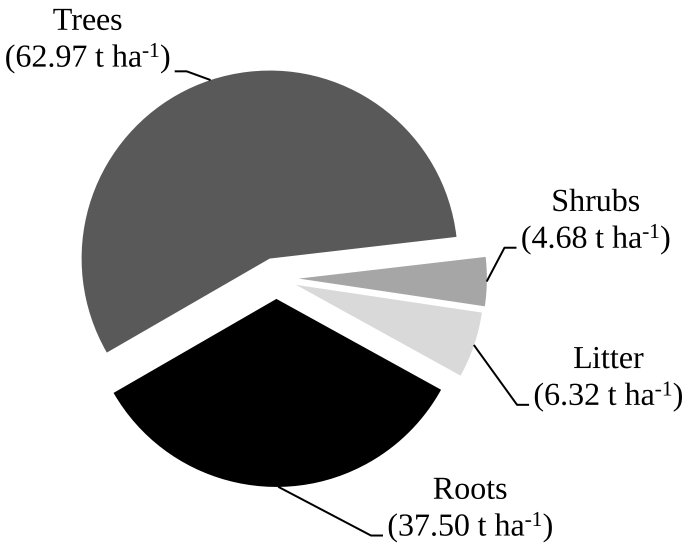

Figure 3. Composition of total biomass from the biomass components considered in this study.

From the per-hectare figures of AGB and BGB, a root-shoot ratio can be derived. In our study the ratio of BGB to AGB of individual trees resulted in a ratio close to 0.6.

3.3. Biomass models

After eliminating four extreme outliers that are probably result of inconsistent field measurements from the data, all models were tested regarding their general fit by visual interpretation. Afterwards the mentioned goodness of fit criteria were computed for all models and are given in Table 4. The total variance of the data explained by the regression of the single tree models, quantified by the adjusted coefficient of determination $\bar{R}^2$ was around 90% and the standard error of estimation (*SEE*) ranged between 0.365 and 0.394. The m_6 that was based on a stand parameter had a $\bar{R}^2$ and *SEE* of 0.926 and 0.224, respectively.

Table 4. Regression coefficients (with *p*-value of the *t*-distribution in parentheses), adjusted coefficient of determination ($\bar{R}^2$), standard error of estimation (*SEE*) and correction factor (*CF*) for the 6 compared regression models.

Model	Coefficient									$\bar{R}^2$	*SEE*	*CF*[a]
	b_0 (Intercept)	b_1 (lnD)	b_2 $(\ln D)^2$	b_3 (lnH)	b_4 $(\ln D)^3$	b_5 (D^2H)	b_6 (DH^2)	b_7 (lnWD)	b_8 (lnBA)			
m₁	-3.3369 *(<0.0001)*	2.7635 *(<0.0001)*	-	0.4059 *(0.0316)*	-	-	-	1.2439 *(<0.0001)*	-	0.899	0.365	1.069
m₂	-3.1679 *(<0.0001)*	-	-	-	-	1.1438 *(<0.0001)*	-	1.3079 *(0.0001)*	-	0.886	0.389	1.079
m₃	6.6844 *(0.2022)*	-9.9319 *(0.1501)*	5.3745 *(0.0697)*	-	-0.7273 *(0.0798)*	-	-	1.1201 *(0.0003)*	-	0.897	0.368	1.070
m₄	-3.3520 *(<0.0001)*	2.9853 *(<0.0001)*	-	-	-	-	-	1.1855 *(0.0001)*	-	0.896	0.371	1.071
m₅	-3.9336 *(<0.0001)*	2.9171 *(<0.0001)*	-	-	-	-	-	-	-	0.883	0.394	1.081
m₆	8.3724 *(<0.0001)*	-	-	-	-	-	-	-	1.1912 *(<0.0001)*	0.926	0.224	1.025

[a] Correction factor: $CF = exp\ (SEE^2/2)$

The best-fit single tree models for estimating aboveground biomass (*B*) along $\bar{R}^2$ and *SEE* were m_1, m_3 and m_4. These models presented similar $\bar{R}^2$ values (0.899, 0.897 and 0.896, respectively) and *SEE* (Table 4). The model m_3 had a similar $\bar{R}^2$ and *SEE* as the other models, but only one of the regression coefficients was significant so this equation was refused.

Following the principle of parsimony (McLeod, 1993; Burnham and Anderson, 2002), model m_4 was selected as the best single tree model for estimating the aboveground biomass as it uses only two explanatory variables (*DBH* and *WD)* and still generates results not much less precise than more complex models. The single effect of diameter on estimated AGB is plotted in Figure 4.

Model m_6 had the higher $\bar{R}^2$ and *SEE* values (0.926 and 0.224), representing an option for aboveground biomass prediction when only stand parameters, like basal area, are available. As model m_6 was adjusted based on per plot values (n=10) and not based on single tree variables (n=116) like in case of the other models, this fact should be carefully considered while comparing the performance.

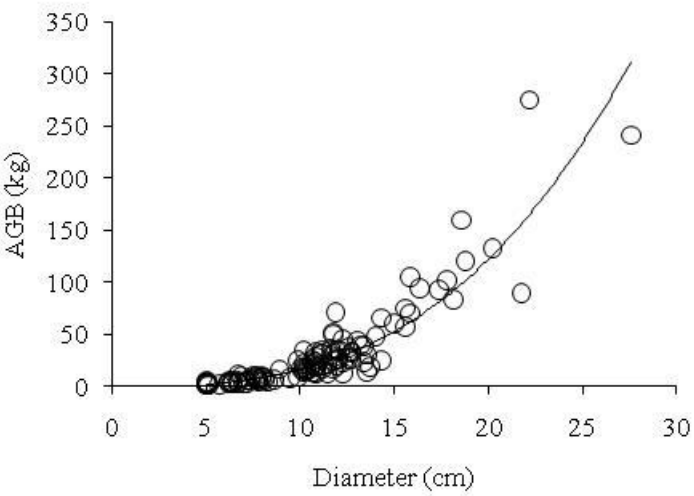

Figure 4. Relation between single tree aboveground biomass (AGB) and tree diameter (n=116).

3.4. Carbon stock

The carbon content and carbon stock of each compartment (bole + branches, leaves, roots, shrubs and litter) is given in Table 5.

Table 5. Carbon content (%) and carbon stock (tC ha^{-1}) of the compartments analysed in the cerrado s.s. remnant in Curvelo (MG), Brazil.

	Tree		Roots	Shrubs	Litter
	Bole + branches	**Leaves**			
Carbon content (%)					
Mean (SE%[a])	48.74 (1.5%)	46.42 (2.7%)	48.55 (0.8%)	48.97 (1.9%)	48.86 (1.4%)
Range	43.30 – 50.79	39.11 – 50.35	47.20 – 50.70	43.90 – 52.50	44.40 – 51.95
CI[b]	48.74 ± 1.607	46.42 ± 2.817	48.55 ± 0.925	48.97 ± 2.097	48.86 ± 1.548
Carbon stock (tC ha^{-1})					
Mean (SE%[a])	29.80 (14.8%)	0.96 (22.3%)	18.16 (22.6%)	2.35 (29.1%)	3.09 (12.7%)
Range	6.04 – 52.79	0.19 – 2.11	7.13 – 48.20	0.61 – 7.45	1.67 – 5.47
CI[b]	29.80 ± 18.842	0.96 ± 0.697	18.16 ± 9.267	2.35 ± 1.548	3.09 ± 0.884

[a]SE%: relative standard error.
[b]CI: confidence interval (95% CI).

Considering all the compartments, the mean carbon content is 48%. The total estimated carbon stock for the cerrado s.s. remnant is 54.36 tC ha^{-1}.

4. Discussion

The overall goal of this study was to estimate biomass density of cerrado s.s. and to relate the estimates with those of existing studies for the same biome. One of the core findings of this case study is that the AGB stock of the actual study site (73.96 t ha^{-1}) is relatively large in comparison to other studies published for cerrado s.s. elsewhere in Brazil (Table 3). The main difference was thereby found in the tree and tree + shrub biomass pool that are significantly larger than in other studies performed using direct measurements in the Distrito Federal (Abdala et al., 1998; Castro and Kauffman, 1998; Vale et al., 2002; Rezende et al., 2006), in Mato Grosso (Araujo et al., 2001; Santos et al., 2002), in Minas Gerais (Lilienfein et al., 2001) and in Roraima (Barbosa and Fearnside, 2005). These estimates are on average about only one fifth of the values estimated in this study (trees = 62.97 t ha^{-1}, trees + shrubs = 67.65 t ha^{-1}).

Indirect estimations of biomass for trees and shrubs in the cerrado s.s. were perfomed by Ottmar et al. (2001) based on stereo photos and with an allometric equation proposed by Abdala et al. (1998). Also in this study the authors found a biomass of trees and shrubs that was significantly larger than in most of the other mentioned results, ranging from 12.53 t ha^{-1} to 42.96 t ha^{-1}, with an average of 25.30 t ha^{-1}. Contrary to the estimated tree biomass, our results for the shrub and litter pool are in the range of values reported by other studies (4.68 t ha^{-1} and 6.32 t ha^{-1}, respectively).

Caution, however, must be taken in the direct comparison of our estimates with those reported in other studies, as different measurement criteria and methodologies had been used. Especially when comparing the estimated regression coefficients of the biomass models we have applied, it should be noted that these refer to DBH (and for multiple stems to the pooled diameter) as independent variable, while other studies used a base diameter. Further, the basal area (14.9 m^2 ha^{-1}) and tree density (2,086 tree ha^{-1}) for the actual study site are slightly higher as compared to others (see Table 3). The studied cerrado s.s. remnant is a protected area with restricted access. This situation possibly enabled a higher biomass accumulation, compared to areas that are not state-declared protected areas.

Beyond the influence of different methodological approaches and the differences of study sites, the relatively high AGB estimated in this study may also be related to the selection of sample trees. In our study 18 species that are among the most common and widespread woody species for the Cerrado region (Ratter et al., 2003) and contributed with 75% to the basal area, were destructively sampled. However 25% of the individuals found in the inventory plots were not sampled because of their relatively small contribution to basal area. In case that those unobserved trees have a significant different biomass, the exclusion of them might be a source of an estimation bias.

Regarding the belowground biomass the estimates obtained here (37.50 t ha^{-1}) are about half of the estimated AGB. There are only few published studies which assessed the belowground biomass in cerrado s.s. Abdala et al. (1998) collected samples of roots in a cerrado s.s. in Distrito Federal using soil monoliths (until a depth of 6.2 m) and tanks (depth of 1 m) and found an average belowground biomass of 41.10 t ha^{-1}. Castro and Kauffman (1998) assessed the above- and belowground biomass in three different physiognomies of Cerrado in Distrito Federal. The roots biomass was sampled using soil monoliths until a depth of 1 m and for the 1 m to 2 m layer samples were extracted using an augur. The authors observed for the two different variants of cerrado s.s. (open and close canopy) a root biomass of 46.60 t ha^{-1} and 52.90 t ha^{-1}, respectively. Based on a different methodology, Lilienfein et al. (2001) estimated above- and belowground biomass in a cerrado s.s. in Uberlândia, Minas Gerais, and found a root biomass (until 2 m depth) of 30.36 t ha^{-1}. The belowground biomass estimated in our study is comparable to these three studies, despite the differences in the methodological approaches.

Most of the studies that assess the belowground biomass focus on the upper layers, due to the inherent difficult of measuring root system, not only in Cerrado, but in any other forest ecosystem (Sanford and Cuevas, 1996; Vogt et al., 1998). As some Cerrado woody species can develop a very deep root system (Rawitscher, 1948; Sarmiento, 1983), which is associated with the deep ground water levels (Jackson et al., 1999; Meinzer et al., 1999; Oliveira et al., 2005), more detailed information about the belowground biomass pool is, therefore, required if the carbon stocks of these systems shall be estimated completely. Zobel and Zobel (2002) addressed the challenges of such studies, emphasizing that they must be tackled despite the practical difficulties if progress in precision of biomass estimation shall be achieved.

The biomass allocation to roots and shoots for the cerrado s.s. remnant was different than expected: more biomass was allocated to shoots than to the roots (root-shoot ratio = 0.6). Other studies under similar conditions found a root-shoot ratio that varies between 1.0 to 2.9 (Abdala et al., 1998; Castro and Kauffman, 1998; Lilienfein et al., 2001).

Considering studies in other savannas around the world, the root-shoot ratio ranges between 0.6 and 2.5, with a median of 0.642 (Grace et al., 2006; Mokany et al., 2006). Our study is within the root-shoot ratio range for savannas ecosystems, despite of being smaller than other studies in the cerrado s.s. The belowground biomass was slighter smaller than in the other cerrado s.s. studies probably due to soil physical stresses (mechanical impedance, water content) and nutrient availability (Bengough et al., 2006). The high aboveground biomass comparing to other studies is the major reason for the small value of the root-shoot ratio.

To our knowledge only few studies developed single tree allometric equations for aboveground biomass estimation for cerrado s.s. (Abdala et al., 1998; Barbosa and Fearnside, 2005; Rezende et al., 2006; Scolforo et al., 2008). These studies focused on areas in the central part of Brazil and in the open savannas of Roraima. Our study and the one developed by Scolforo et al. (2008), seems to be the only ones that recently developed single tree allometric equations for biomass estimation in a cerrado s.s. in the southeast of the country. Based on our data model, m_4 was identified as the best one to predict the aboveground biomass based on DBH and wood density as independent variables. DBH is the commonest and best predictor for biomass in allometric models due to the strong relation with biomass. Moreover, this variable is relatively easy to measure and available in standard forest inventories (Ter-Mikaelian and Korzukhin, 1997; Zianis and Mencuccini, 2004; Segura and Kanninen, 2005). Wood density is a variable that reflects aspects related to the forest structure, like diameter growth rates, life history strategy and succession state of the area (Fearnside, 1997; Baker et al., 2004). Further this variable has a certain discriminatory power in regard to the distinction between different tree species (Návar, 2009). This is particular important in biomes like Cerrado which are characterized by high species diversity and scarce tree biomass estimations. More comprehensive biomass equations can be used in different sites (respecting the range of validity of the equation). Unfortunately, there is still a lack of information about wood density values for Cerrado tree species. Some studies were developed in disjunctive Cerrado areas in the north part of Brazil (e.g. Barbosa and Fearnside, 2004; Nogueira et al., 2007). However there are few or no data about wood density for trees in the core area of Cerrado (Central Brazil Plateau). Our study gives a modest contribution to fill this information gap by providing direct wood density measurements for 18 species (Table 1).

Model m_1 has the best goodness of fit statistics for our dataset. Nevertheless due to the controversy associated to the inclusion of tree height in allometric models for estimating biomass, the model m_4 was preferred. The measurement of the height is often less accurate than DBH, time-consuming and costly to assess. Furthermore, as tree height measurements are not always performed in field inventories, especially in historical ones, its inclusion in allometric biomass models may limit their application (Chave et al., 2005; Montagu et al., 2005; Wang, 2006; Fehrmann and Kleinn, 2006). Beside of the issues related to height measurement, the selection of model m_4 was also motivated by its simplicity. The DBH and WD can be measured easily and accurately and are very relevant variables for biomass estimation. Thereby, m_4 equation is the most parsimonious and adequate statistical model among the ones tested.

Model m_6 represents a more general approach than single tree models, and is based on the relation between total basal area of all sampled trees per plot and the resulting total biomass that was estimated. Such approaches might be in particular useful for forest types in which the application of allometric models on single tree level is difficult and estimates of stand characteristics, like basal area per hectare are easier to obtain.

Few studies focused on the quantification of carbon stock in Cerrado areas. Carbon content values for different compartments in Cerrado are also scantily available. Most of the research have concentrated only in the soil pool (e.g. Lardy et al., 2002; Carvalho et al., 2010), while little information is available for other compartments. More comprehensive approaches are needed for a better understanding of the processes of carbon sequestration and storage in the Cerrado biome.

5. Conclusions

In this work the above- and belowground biomass in a cerrado s.s. in the southeast of Brazil were estimated using destructive measurements. The aboveground biomass was higher than other studies developed in the same physiognomy, whereas the belowground biomass pool was among the range of these studies. Nonetheless, the lack of a standardized sampling protocol hampers meaningful comparisons among studies.

We would like to reiterate the relevance of the cerrado s.s. (and the Cerrado biome as a whole) as a pool of biodiversity and carbon reservoir. Despite of its importance, the Cerrado biome has been systematically deforested to give place to agriculture and cattle raising activities.

However we expect that with the advance of climate change negotiations, especially in issues related to REDD, more importance will be given to Cerrado. Therefore, studies focusing on the biomass and carbon storage quantification in different Cerrado physiognomies are of great importance.

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CAPÍTULO 2

ABOVE- AND BELOWGROUND BIOMASS AND CARBON ESTIMATES FOR CLONAL EUCALYPTUS TREES IN SOUTHEASTERN BRAZIL

Resumo

No Brasil os plantios de eucalipto abrangem mais de 4 milhões de hectares. Esses povoamentos representam uma alternativa economicamente viável de curto prazo para sequestrar o carbono da atmosfera. Apesar do potencial de plantios florestais com espécies de rápido crescimento de estocar carbono na biomassa, nota-se a falta de estudos que incluam estimativas precisas da quantidade de carbono nesses povoamentos. Em vista disso, o presente estudo objetivou a determinação do teor de carbono no tronco, galhos, folhas e raízes de um plantio clonal de *Eucalyptus grandis* (espaçamento 3 x 3 m) com 5,5 anos no sudeste do Brasil. Equações alométricas para estimar a quantidade total de carbono e biomassa também foram desenvolvidas e estimativas do estoque de carbono no povoamento foram geradas. Inicialmente selecionaram-se 23 árvores-amostra para a determinação da biomassa pelo método destrutivo. As raízes de 9 das 23 árvores-amostra foram parcialmente excavadas para a estimação da biomassa abaixo do solo em nível de árvore individual. O teor de carbono do tronco, galhos, folhas e raízes foi determinado em laboratório. Dois modelos usando as variáveis independentes *DAP*, altura (*H*) e DAP^2H foram testados. Como o teor de carbono na biomassa geralmente não está disponível, os dois modelos anteriores também foram testados para a estimação da biomassa arbórea acima do solo. O teor de carbono médio do tronco, galhos, folhas e raízes foi de 44,6%, 43,0%, 46,1% and 37,8%, respectivamente. As equações de melhor ajuste para estimar a quantidade total de carbono e biomassa apresentavam o DAP^2H como variável independente. O teor de carbono do tronco, galhos, folhas e raízes foi menor do que o valor genérico comumente usado (50%). Isso destaca a importância de se determinar o teor de carbono em laboratório ao invés de se usar um valor padrão. A razão raiz-parte aérea foi relativamente estável (*C.V.* = 27,5%) provavelmente devido ao fato da sub-amostra ser composta por clones. O estoque de carbono total para o povoamento de eucalipto foi estimado em 73,38 tC ha^{-1}, valor semelhante ao encontrado em outros povoamentos.

Palavras-chave: Eucalipto, Brasil, teor de carbono, equação alométrica.

Abstract

Eucalyptus plantations cover more than 4 million hectares in Brazil. These plantations represent a short term and cost efficient alternative for sequestrating the carbon from the atmosphere. Despite the potential of forest plantations with fast growing species to store carbon in the biomass, there is a lack of studies including precise estimates of the amount of carbon in these plantations. In our study we determined the carbon content in stem, branches, leaves and roots of a 5.5-year-old clonal *Eucalyptus urograndis* plantation (planting spacing 3 x 3 m) in the Southeast of Brazil. We also developed allometric equations to estimate the total amount of carbon and total biomass and generated an estimate of carbon stock in the stand level. Altogether 23 sample trees were selected for aboveground biomass assessment. The roots of 9 of the 23 sampled trees were partially excavated to assess the belowground biomass in a single-tree level. The carbon content of stem, branches, leaves and roots was determined in laboratory. Two models with *DBH*, *H* and DBH^2H were tested. As the carbon content of the biomass sometimes is not available, we also tested the two previous models for the estimation of the tree aboveground biomass. The average carbon content of stem, branches, leaves and roots was 44.6%, 43.0%, 46.1% and 37.8%, respectively. The best-fit allometric equations to estimate the total amount of carbon and total biomass had DBH^2H as independent variable. The carbon content of stem, branches, leaves and roots was smaller than the generic value commonly used (50%). This highlights the importance of determining the carbon content in laboratory instead of using a default value. The root-to-shoot ratio was relatively stable (*C.V.* = 27.5%) probably because the sub-sample was composed by clones. Total stand carbon stock in the Eucalyptus plantation was estimated to be 73.38 tC ha^{-1}, being within the carbon stock range for Eucalyptus plantations.

Keywords: Eucalyptus, Brazil, carbon content, allometric equation.

1. Introduction

Eucalyptus plantations occupy more than 20 million hectares worldwide. They are widely spread, especially in tropical regions (Iglesias and Wistermann, 2008; Laclau et al., 2010). In Brazil, *Eucalyptus* plantations cover more than 4 million hectares and are mainly used to produce pulpwood and renewable charcoal required by the siderurgic industry (ABRAF, 2010).

Different fast-growing and well-adapted *Eucalyptus* cultivars have been developed through natural and artificial hybridization (Wei and Xu, 2002). One of these is the hybrid clone *E. urophylla* S.T. Blake and *E. grandis* Hill ex Maiden, which is known as *urograndis*. This clone is widely distributed in tropical and subtropical regions, being the most favored for pulp production and for solid wood (Rockwood et al., 2008). Most of the *urograndis* plantations are situated in the Congo basin (Bouillet et al., 2002; Matondo et al., 2005), in Brazil (Silvério et al., 2007) and in China (Zhou et al., 2008).

Since the beginning of the discussions about climate change, forests were considered important for mitigating the greenhouse effect (Schlamadinger et al., 2007). Forest plantations, especially with fast growing species, such as *Eucalyptus* and its cultivars, represent a short term and cost efficient alternative for sequestrating the carbon which would otherwise be emitted to the atmosphere (Madeira et al., 2002; Stern, 2007).

Brazil, within this context, assumes a privileged position as one of the few countries in the world with appropriate climate and technological conditions for forest production (Stape et al., 2001; Gonçalves et al., 2008). However, to assess the Brazilian potential of carbon storage in forest plantations, it is essential to have reliable estimates of biomass.

Biomass estimation of forest trees has been subject to research for a long time (Fehrmann and Kleinn, 2006). A common approach to estimating biomass is the use of regression analysis and the development of allometric equations (Parresol, 1999). Usually allometric equations are developed using three basic sources of information: dry samples of different tree compartments, bulk density and volume of the wood. Based on this data one obtains the total dry mass which is usually related to DBH and height of the tree by an allometric relationship (Henry et al., 2010).

Most of the allometric equations for forest plantations were developed to estimate the aboveground biomass. However, there still is a lack of studies including precise estimates of the amount of carbon in the various forest compartments, such as the roots, leaves and branches. According to Kauffman et al. (2009), the understanding of the dynamic development of carbon sinks and sources is important in establishing strategies related to the *Clean Development Mechanism* (CDM) and in planning future actions related to the *Reducing Emissions from Deforestation and Forest Degradation* (REDD).

In this study, allometric equations for estimating the total amount of carbon and the biomass of a commercial Eucalyptus plantation are developed. The amount of carbon in roots' biomass is also assessed through destructive procedures and an estimate of carbon stock in the stand level is generated.

2. Material and Methods

This section briefly introduces the study area and presents the methods of data gathering and analysis applied in this study.

2.1. Study Area

This study was conducted in a *Eucalyptus* plantation owned by the company *Plantar S.A.* The plantation is located near the municipality of Curvelo, in the central part of Minas Gerais, Brazil (Figure 1). The climate in the region is subtropical, with a marked dry season from April to October. January and February are the months with the highest precipitation. The average annual rainfall is between 1.100 mm and 1.200 mm. The hottest month has an average temperature of 26ºC and the coldest one of 21ºC.

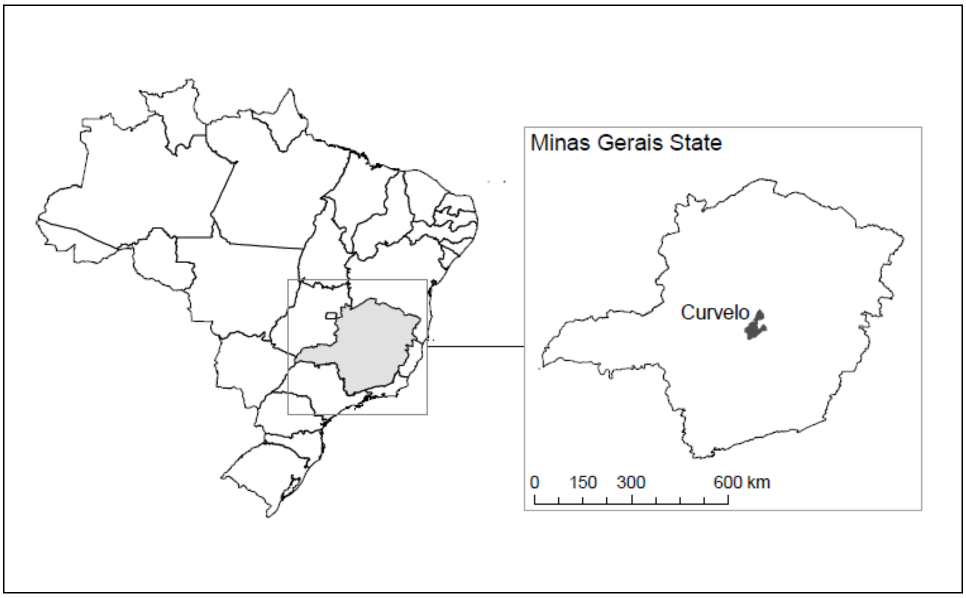


Figure 1. Location of the studied area, southeastern Brazil.

The soil in the study area is the red latosol, which is characterized by high clay content, low levels of organic matter and low fertility. The topography of the study site is flat and the elevation is approximately 600 m.

The study was started in 2008 in a plantation compartment covering an area of 31 ha in total. The site was planted with a *Eucalyptus* hybrid clone of *E. urophylla* S.T. Blake and *E. grandis* Hill ex Maiden. At that stage the age of the plantation was 5.5 years. The initial planting spacing was 3 m x 3 m. The average tree height at that age was 26.3 m and the average tree diameter at breast height (DBH) of the stand was 15.7 cm.

2.2. Data Collection

Altogether 23 sample trees were selected for above- and belowground biomass assessment. The selection of the sample trees was based on the diameter distribution of the *Eucalyptus* plantation.

The sample trees were used to develop allometric equations for estimating the aboveground amount of carbon in the biomass of stem, branches and leaves. The roots of 9 of the 23 sampled trees were partially excavated to assess the belowground biomass and carbon content of this compartment on single-tree level (Table 1).

The DBH, total height and commercial height (the stem height up to a diameter of 3 cm) were measured for each sampled tree (Table 1). The volume (inside and outside bark) of each stem section was calculated using Smalian's formula (Loetsch, 1973). The stem diameters with bark and the bark thicknesses were recorded at stem heights of 0.3 m, 0.7 m, 1.3 m and thereafter in 2 m intervals, up to the 3 cm diameter limit.

Table 1. Identification of the 23 sample trees.

Tree Nº	DBH (cm)	Total Height (m)	Commercial Height (m)	Volume inside bark (m^3)	Volume outside bark (m^3)	Root sample tree
1	10.0	18.0	15.1	0.061	0.052	
2	11.2	20.2	17.5	0.095	0.079	
3	11.8	21.7	19.2	0.109	0.096	
4	12.1	23.2	20.9	0.135	0.118	
5	12.3	23.1	21.0	0.137	0.117	
6	12.8	22.9	20.6	0.141	0.125	X
7	13.0	23.6	20.8	0.140	0.125	X

Table 1. (continue)

Tree Nº	DBH (cm)	Total Height (m)	Commercial Height (m)	Volume inside bark (m^3)	Volume outside bark (m^3)	Root sample tree
8	13.3	24.0	22.0	0.164	0.140	
9	13.4	23.7	21.6	0.161	0.141	X
10	13.7	24.2	22.2	0.178	0.151	
11	15.0	25.7	23.8	0.218	0.188	X
12	15.3	24.9	23.4	0.241	0.218	X
13	15.3	25.3	23.5	0.232	0.206	X
14	16.5	25.8	24.0	0.245	0.215	
15	17.2	26.7	24.8	0.286	0.249	
16	17.2	27.1	25.2	0.306	0.271	
17	17.3	26.9	25.1	0.299	0.265	
18	17.4	27.0	25.3	0.297	0.258	
19	17.8	26.6	14.2	0.296	0.257	X
20	17.8	26.5	24.9	0.334	0.297	X
21	18.3	27.0	25.2	0.309	0.265	X
22	18.5	27.1	25.3	0.326	0.287	
23	18.7	27.3	25.6	0.347	0.301	

Each sample tree was felled and the stem up to commercial height was divided into five sections of equal length. Stem discs (outside bark) approximately 2.5 cm thick, were cut at both ends of the sections. An additional disc was cut at breast height (1.3m). The basic density of wood and bark, and the carbon content of wood in each one of these stem discs were assessed in the laboratory.

All the leaves of each sample tree were collected manually and the fresh weight was recorded. A sample of the fresh leaves was taken to the laboratory to determine dryweight/freshweight ratio, following Vital (1984). The leaf samples were dried at 70 ± 2ºC until the dry weight stabilized.

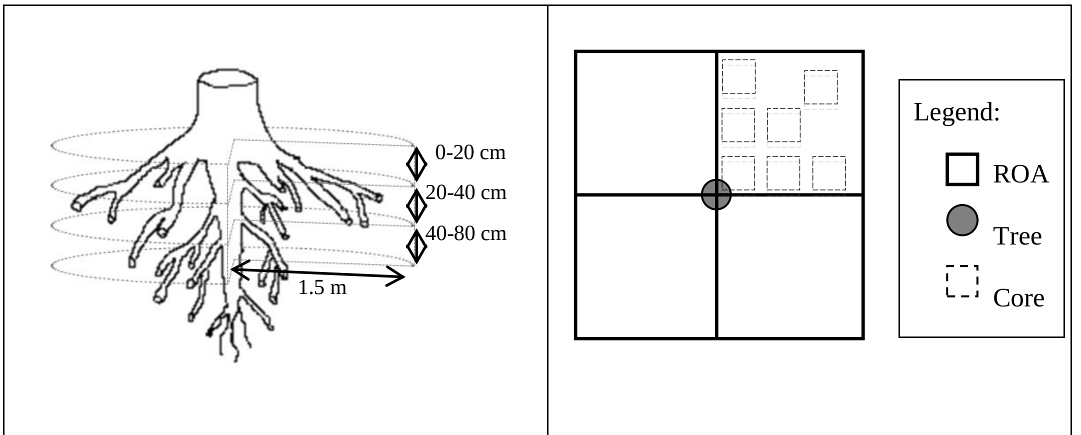
Similarly, the dry and green branches were removed and weighed separately. The stem tip was classified as a branch when its diameter was smaller than 3 cm. Samples of dry and green branches of known weight were collected to determine dryweight/freshweight ratio in the laboratory. They were dried at 103 ± 2ºC until the dry weight stabilized.

Nine sample trees belonging to three different diameter classes were selected for the root assessments. The root material was assessed in three different layers (0 cm – 20 cm, 20 cm – 40 cm and 40 cm – 80 cm). The specific area assigned to each root sample tree is based on the systematic 3 m spacing between planting rows and in the depth of each layer.

Thus, for the first two layers this volume would be of 1.8 m^3 $(3 \cdot 3 \cdot 0.2)$ and for the third layer of 3.6 m^3 $(3 \cdot 3 \cdot 0.4)$. Therefore, it was assumed that all the roots of the sample trees were located within a 3 m radius extending from the tree position (Figure 2).

This "root occupation area" (ROA) was divided into four quadrants. In one of these quadrants, 7 vertical cores, each measuring 40 x 40 cm with a depth of 80 cm (divided in three layers), were used to excavate all the root material, including one-quarter of the tap root, within the ROA of each of the nine root sample trees. For each layer we calculated the volume of each vertical core: for the first two layers (0 cm – 20 cm and 20 cm – 40 cm), the volume is the same (0.032 m^3), as they have the same depth (20 cm). For the 40 cm – 80 cm layer the volume was 0.064 m^3. A total surface area of 1.12m^2 $(7 \cdot 0.16\ m^2)$, or about one-half of the quadrant surface of 2.25 m^2 $(9/4)$ was sampled. All the material was weighed in the field. A root sample was oven-dried at 103 ± 2ºC to determine dryweight/freshweight ratio in the laboratory.

The dry weight of the roots in each layer was upscaled to the ROA considering the specific area assigned to each root sample and the sum of the volume of the seven vertical cores. For example, for the first layer (0 cm – 20 cm), the dry weight of the roots was calculated as follows: $[(1.8 \cdot weight)/(7 \cdot 0.032)]$. The weight of the taproot was estimated by multiplying its sampled weight by the factor 4. The sum of the dry weights obtained in each layer with the estimated weight of the taproot gave the total dry weight of roots of one sample tree.



Root sampling: side view | Root sampling: top view and legend

Figure 2. Schematic representation of root sampling.

The root/shoot ratio (R/S) was calculated for each one of the nine trees, considering the aboveground biomass as the sum of biomass of stem, bark, branches and leaves.

2.3. Biomass and carbon content of the 23 sample trees

The biomass ratios (Br_i) of the branches, leaves and roots of sample trees were calculated as follows (c.f. FAO, 1997):

$$Br_i = \frac{Dw_i}{Fw_i} \tag{1}$$

where Dw_i and Fw_i refer to the sampled dry and fresh weights (kg) of the ith compartment respectively. These ratios were multiplied with the total fresh weights (kg) of the whole compartment per tree obtained in the field (F_i), to give the biomass in the field (B_i):

$$B_i = F_i \cdot Br_i \tag{2}$$

The total biomass of the stem and bark (B_i) was calculated by multiplying the stem and bark volume with the average basic density of the wood (*BDW*) and bark (*BDB*), following Pretzsch (2009):

$$B_i = V_i \cdot (BDW or BDB) \tag{3}$$

where V_i refers to volume of wood or bark (m^3), and *BDW* and *BDB* are the basic density of wood or bark (kg m^{-3}), respectively.

The above- and belowground biomass of each sampled component was converted to carbon using the carbon content, which was obtained in the laboratory using a continuos-flow isotope ratio mass spectrometer (ANCA-GLS).

2.4. Data analysis

Allometric equations were adjusted to estimate the total amount of carbon (stem+bark+branches+leaves) of the 23 sample trees. As the carbon content of the bark was not available due to technical issues, we calculated an average carbon content for the bark using the data of the other compartments (stem, branches and leaves).

As in many situations the carbon content of the biomass is not available, we decided to also adjust an equation to estimate the tree aboveground biomass using the previous equations. The tree aboveground biomass (stem+branches+bark+leaves) and the *DBH* and *H* of the 23 sample trees were used in the model adjustment. The following equations were fitted to the field data (Soares et al., 2006):

$$Y_1 = \beta_{01} \cdot DBH^{\beta_{11}} \cdot H^{\beta_{21}} \cdot \varepsilon \tag{m$_1$}$$

$$Y_2 = \beta_{02} \cdot (DBH^2 \cdot H)^{\beta_{12}} \cdot \varepsilon \tag{m$_2$}$$

where Y_j refers to the total amount of carbon or biomass (kg) of the jth model; H refers to the height (m); β_0, β_1 and β_2 refer to parameters of the jth model and ε refers to random error.

A non-linear ordinary least squares-regression analysis was used to fit the models to the data. The significance of the models and the models coefficients were evaluated using the *F-test* and the *t* statistic, respectively. All the analyses were conducted using the STATISTICA software package version 8.0 (StatSoft Inc, 2007).

To select the best model the following evaluation criteria were used: a) logic of the sign (+/-) associated with a specific parameter; b) distribution of residuals; c) bias ($\bar{E}$), which tests the systematic deviation of the model from the observations; d) root mean square error (*RMSE*), which analyses the accuracy of the estimates; e) model efficiency (*MEF*), which shows the proportion of the total variance that is explained by the model, adjusted for the number of model parameters and the number of observations. These criteria were calculated as follows (Álvarez-González et al., 2010):

$$\bar{E} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \tag{4}$$

$$RMSE = \pm\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p}} \tag{5}$$

$$MEF = 1 - \frac{(n-1)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \tag{6}$$

where y_i, $\hat{y}_i$ and $\bar{y}_i$ are the observed, predicted and mean values of the dependent variable, respectively; n is the total number of observations used to fit the function; and p is the number of model parameters.

2.5. Carbon stock estimates in the stand level

The best fit allometric equation derived from the 23 sample trees to estimate the total amount of carbon was used to predict the aboveground tree carbon stock on the stand level. The raw data were divided in four diameter size classes and the tree density and the average height ($\bar{H}$) of each size class were calculated.

The diameter center class and the average height of each size class were used as independent variables in the allometric equation derived from the 23 sample trees. The amount of carbon obtained per size class was multiplied by the tree density in order to obtain an estimate of the stand aboveground tree carbon stock.

The carbon stock of the roots was estimated based on the field estimates of carbon content and biomass. However, for the roots the raw data was divided in three diameter size classes. The diameter center class and the tree density of each size was calculated. The average amount of carbon obtained for each size class was multiplied by the tree density to estimate the belowground tree carbon stock on the stand level.

3. Results

This section presents the biomass and carbon content above- and belowground of the 23 sample trees, the fitted allometric equations and the estimates of carbon stock in the stand level for an Eucalyptus plantation.

3.1. Biomass and carbon content of the 23 sample trees

The aboveground biomass and the carbon content in different compartments of the 23 sample trees are given in Table 2.

Table 2. Aboveground biomass (kg) and carbon content (%) of sample trees of a Eucalyptus plantation in Curvelo (MG), Brazil.

Tree Nº	BDW ($kg\ m^{-3}$)	BDB ($kg\ m^{-3}$)	Biomass (kg)					Carbon content (%)		
			Stem	Bark	Branches	Leaves	Total	Stem	Branches	Leaves
1	513	346	26.8	3.2	4.3	0.8	35.1	45.00	41.50	45.40
2	525	346	41.7	5.4	5.9	1.2	54.2	44.30	42.25	44.70
3	437	295	42.0	4.0	4.4	1.0	51.4	43.60	42.92	46.03
4	450	317	53.1	5.4	4.1	1.5	64.1	44.50	41.10	46.90
5	480	339	56.1	6.9	3.1	1.7	67.9	44.43	43.15	45.30
6	455	347	56.9	5.6	4.1	1.5	68.1	44.80	42.75	39.10
7	465	326	57.9	5.0	3.7	1.5	68.2	44.40	42.35	46.50
8	474	328	66.5	7.7	3.8	2.2	80.1	45.20	41.35	47.55
9	466	353	65.7	7.1	6.6	1.4	80.7	43.60	43.90	44.80
10	474	344	71.5	9.2	6.3	2.3	89.3	45.50	42.85	43.30
11	468	335	88.1	10.0	7.5	3.5	109.1	44.90	43.50	48.30
12	458	349	99.7	8.2	7.4	3.8	119.2	44.30	43.00	47.20
13	476	347	97.8	9.0	8.7	3.3	118.8	44.30	44.50	47.60
14	458	316	98.7	9.4	9.1	3.9	121.1	44.70	43.15	45.10
15	480	355	119.4	13.3	8.2	5.3	146.1	44.10	44.20	44.60
16	476	342	129.0	12.0	8.6	5.8	155.4	44.90	42.85	47.90
17	480	360	127.1	12.4	8.5	4.9	152.9	44.50	42.55	47.00
18	481	345	124.2	13.2	9.0	5.5	151.8	44.90	43.60	48.00
19	477	343	122.5	13.6	9.0	6.0	151.1	45.10	41.25	46.40
20	495	342	146.8	12.9	8.9	5.2	173.8	44.10	44.70	47.20
21	485	341	128.6	15.0	8.5	5.4	157.5	44.80	43.75	46.80
22	480	326	137.8	12.8	8.7	7.0	166.3	44.50	41.25	47.80
23	489	343	147.5	15.5	8.6	7.1	178.7	45.50	44.15	46.90
Mean (±*C.V.*[a])	**476 (4.0%)**	**338 (4.3%)**	**91.5 (41.2%)**	**9.4 (39.4%)**	**6.8 (31.4%)**	**3.6 (58.3%)**	**111.3 (40.5%)**	**44.61 (1.1%)**	**42.89 (2.5%)**	**46.10 (4.4%)**
SE%[b]	**0.84**	**0.90**	**8.58**	**8.21**	**6.54**	**12.16**	**8.45**	**0.24**	**0.53**	**0.91**
CI[c]	**476 ± 8.240**	**338 ± 6.348**	**91.5 ± 16.298**	**9.4 ± 1.605**	**6.8 ± 0.927**	**3.6 ± 0.896**	**111.3 ± 19.520**	**44.61 ± 0.002**	**42.89 ± 0.005**	**46.10 ± 0.009**

[a]C.V.: coefficient of variation.
[b]SE%: relative standard error.
[c]CI: confidence interval (95% CI).

The percentage contribution of each compartment (stem, bark, branches and leaves) to the total tree aboveground biomass is showed in Figure 3.

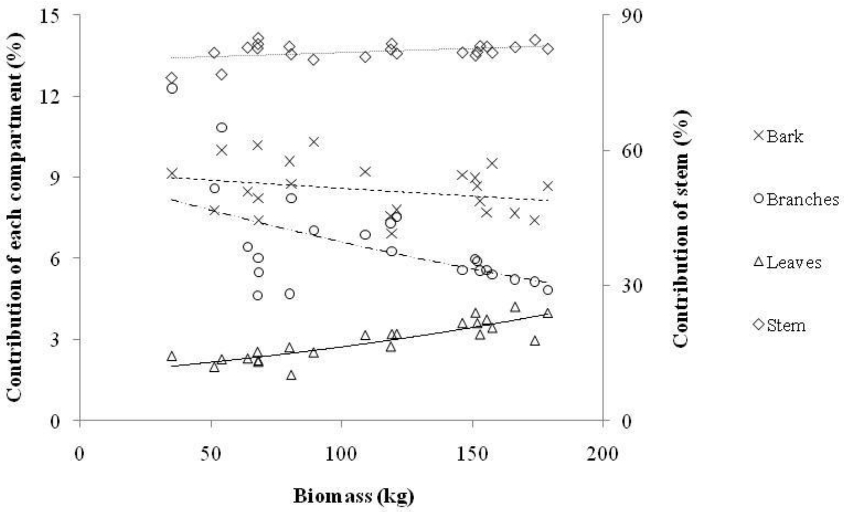


Figure 3. Percentage contribution of stem, bark, branches and leaves to the total tree aboveground biomass of a Eucalyptus plantation in Curvelo (MG), Brazil.

The stem is the compartment that highly contributed with the tree aboveground biomass (82%), followed by bark (8%), branches (7%) and leaves (3%). Nonetheless, the carbon content follows a different pattern. The leaves have a higher average carbon content (46.10%), followed by the stem (44.61%) and branches (42.89%).

3.2. Allometric equations

The allometric equations were fit to the data using *DBH*, *H* and the combined variable DBH^2H as explanatory variables. The parameter estimates of each allometric equation tested, as well as the standard error for each parameter (*SE*), bias ($\bar{E}$), root mean square error (*RMSE*) and model efficiency (*MEF*), are given in Table 3.

Table 3. Estimated regression coefficients and their standard errors (±*SE*), model bias ($\bar{E}$), root mean square error (±*RMSE*) and model efficiency (*MEF*) of the tested allometric models.

Total carbon amount						
Model	**Parameter**	**Estimate**	**SE**	**$\bar{E}$**	**RMSE**	**MEF**
m_1	b_{01}	0.0067	0.0093	-0.0095	3.0150	0.9789
	b_{11}	1.8605	0.3168			
	b_{21}	1.1865	0.6784			
m_2	b_{02}	0.0102	0.0034	-0.0211	2.9492	0.9798
	b_{12}	0.9776	0.0374			

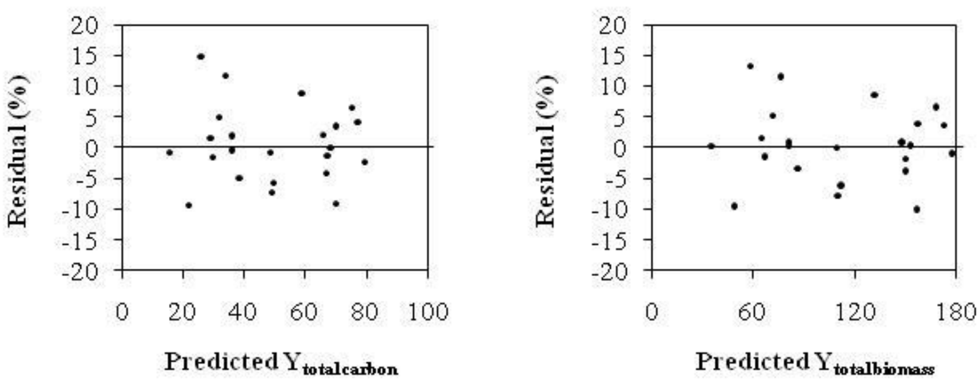
Table 3. (continue)

Total tree aboveground biomass						
Model	**Parameter**	**Estimate**	**SE**	**$\bar{E}$**	**RMSE**	**MEF**
m_1	b_{01}	0.0192	0.0268	-0.0385	6.8405	0.9770
	b_{11}	1.8766	0.3191			
	b_{21}	1.0980	0.6814			
m_2	b_{02}	0.0249	0.0083	-0.0545	6.6816	0.9781
	b_{12}	0.9679	0.0377			

The equations to estimate the total carbon amount and total tree aboveground biomass generally fit the data well. The *MEF* ranged from 0.9770 to 0.9798. The *RMSE* varied between 2.9492 and 6.8405 and $\bar{E}$ between -0.0545 and -0.0095.

From the set of regression models for predicting the total amount of carbon, equation m_2 was chosen. This equation used the combination of *DBH* and *H* as independent variables in the form DBH^2H. Although $\bar{E}$ is slightly higher than equation m_1, in equation m_2 all the variables are significant (α=0.05) and *MEF* and *RMSE* were the highest and lowest, respectively. Similarly, equation m_2 was the best equation to predict the total tree aboveground biomass. The equation fit the data well (*MEF* = 0.9781; *RMSE* = 6.6816), albeit $\bar{E}$ is higher (-0.0545) than equation m_1.

The scatter plots showing the residuals of the selected equations for predicting the total amount of carbon (m_2) and tree aboveground biomass (m_2) are given in Figure 4.



(A) (B)

Figure 4. Residual plots of the selected allometric equations to estimate the total amount of carbon (A) and total biomass (B) of the trees evaluated.

Scatterplots of the residuals revealed the absence of any apparent pattern and showed no trends of increasing variance (heteroscedasticity).

3.3. Belowground biomass and carbon content of the nine sample trees selected for the root assessment

The carbon content and root/shoot ratio (R/S) of the nine sub-sample trees are given in Table 4.

Table 4. Biomass (kg), carbon content (%) and R/S of the nine sub-sample trees selected for the roots assessment in a Eucalyptus plantation in Curvelo (MG), Brazil.

Tree Nº	Roots		R/S
	Biomass (kg)	Carbon content (%)	
6	13.54	34.60	0.20
7	6.95	37.10	0.10
9	17.39	31.30	0.22
11	27.33	44.70	0.25
12	15.50	42.40	0.13
13	18.71	40.60	0.16
19	20.94	36.80	0.14
20	28.11	35.30	0.16
21	24.49	37.80	0.16
Mean (C.V.[a])	**19.22 (35.66%)**	**37.84 (10.93%)**	**0.17 (27.47%)**
SE%[b]	**11.89**	**3.64**	**9.16**
CI[c]	**19.22 ± 5.268**	**37.84 ± 0.032**	**0.17 ± 0.035**

[a]C.V.: coefficient of variation.
[b]SE%: relative standard error.
[c]CI: confidence interval (95% CI).

Average R/S and carbon content for all root material of the nine sub-sample trees was 0.17 and 37.84%, respectively. The biomass of roots ranged from 6.95 kg to 28.11 kg, with a mean of 19.22 kg.

3.4. Above- and belowground carbon stock in the stand level

The estimated carbon stock of the Eucalyptus plantation was obtained considering the carbon stored in the aboveground (stem, bark, branches and leaves) and belowground (roots) part of the trees. Table 5 shows the carbon stock in the aboveground tree biomass of the Eucalyptus plantation.

Table 5. Aboveground carbon stock on the stand level for an Eucalyptus plantation.

Diameter size class (cm)	Center class (cm)	Tree density (tree ha^{-1})	$\overline{H}$ (m)	Carbon stock (tC ha^{-1})
10.00 ¬ 12.49	11.25	32	21.88	0.76
12.50 ¬ 14.99	13.75	187	23.98	7.16
15.00 ¬ 17.49	16.25	736	25.46	41.43
17.50 ¬ 20.00	18.75	181	26.89	14.22
			Total	**63.57**

Considering the contribution of each tree compartment in the aboveground biomass (Figure 3), the carbon stock for the stem, bark, branches and leaves accounted for 52.12, 5.09, 4.45 and 1.91 tC ha^{-1}, respectively. The belowground carbon stock is given in Table 6.

Table 6. Belowground carbon stock on the stand level for an Eucalyptus plantation.

Diameter size class (cm)	Center class (cm)	Tree density (tree ha^{-1})	Carbon stock (tC ha^{-1})
10.50 ¬ 13.49	12.00	58	0.25
13.50 ¬ 16.49	15.00	613	5.39
16.50 ¬ 19.50	18.00	465	4.17
		Total	**9.81**

Total stand carbon stock in the Eucalyptus plantation was estimated to be 73.38 tC ha^{-1}. From this total, the above- and the belowground carbon stock represented 87% and 13%, respectively.

4. Discussion

The first part of this study focused on the assessment of tree aboveground biomass and carbon content of *Eucalyptus urograndis* clones to support the development of allometric equations to estimate the total amount of carbon and total aboveground biomass. The average carbon content determined in our study (Table 2) for the tree compartments stem, branches and leaves was 44.6%, 43.0% and 46.1%, respectively.

Stape et al. (2008) estimated the carbon budget for a 4-aged Eucalyptus hybrid (*E. grandis x urophylla*) in Bahia using a carbon content of 50% for foliage and 45% for stem and branch wood. Gifford (2000a) determined the carbon content for 15 different species of Eucalyptus that are native of eastern Australian. The author found an average carbon content for leaves, branches and wood of 52.9%, 46.8% and 49.8%, respectively. IPCC (2006) recommends that in the absence of specific carbon content values, a default carbon content of 47% should be used to estimate the carbon fraction in the aboveground forest biomass.

Our values of carbon content are slightly different from other studies, probably due to differences of species/clone, site and other environmental conditions. However further comparisons are hampered by the scarce number of studies that quantified the carbon content in laboratory. Most of the studies that aim the estimation of carbon stock in plantations (e.g. Miehle et al., 2006; Horner et al., 2010; Soares and Oliveira, 2002) use a generic value of 50% to estimate the carbon content in biomass.

The indiscriminate use of this value may have serious implications, especially under the Kyoto Protocol. Lamlom and Savidge (2003) argue the use of 50% as a generic value for carbon content in biomass is an oversimplification as may lead to an under- or overestimation of carbon credits allocation in projects that are based on the use of forest resources.

Regarding the carbon content distribution, we observed a higher average carbon content for the leaves (46.1%), followed by the stem (44.6%) and branches (43.0%). Gifford (2000a) also found this carbon content distribution pattern for different species of Eucalyptus in Australia: leaves (52.9%), wood (49.8%) and branches (46.8%). Schumacher and Witschoreck (2004) obtained similar results for the carbon content distribution of *Eucalyptus* sp. in Brazil: leaves > stem > branches.

For the biomass distribution, in our study we found the stem was the tree compartment that highly contributed with the tree aboveground biomass (82%), followed by bark (8%), branches (7%) and leaves (3%). Paixão et al. (2006) assessed the biomass and carbon stock in a 6-year-old *Eucalyptus grandis* plantation (planting spacing 3 x 2 m). The authors observed a similar pattern of biomass distribution: stem (81.8%), bark (8.1%), branches (7.7%) and leaves (2.6%). Soares and Oliveira (2002) estimated the carbon stock in the aboveground part of an *Eucalyptus grandis* plantation with 6.4 years old and found a slightly different biomass distribution: stem (83.2%) > branches (6.9%) > bark (6.6%) > leaves (2.5%).

Our values are comparable to these studies, despite the different species. However, other studies that quantified the biomass for *Eucalyptus grandis* and *Eucalyptus urophylla* in similar planting spacings, but with ages varying from 4 to 7 years, found different percentages of biomass contribution. These studies observed for each tree compartment a mean of 70.4% for the stem, 11.8% for bark, 10.6% for branches and 7.2% for leaves (Assis, 1999; Ferreira, 1984; Ladeira, 2001). The difference in biomass allocation between these studies and ours is probably related with the site characteristics, species, age and stand management practices.

The allometric equations were fit to the data using the amount of carbon as a dependent variable. The use of this variable instead of biomass was an attempt to allow the estimation of the total amount of carbon based solely on easy measureable variables such as *DBH* and height. Nonetheless this was only possible because we determined the carbon content of almost all the samples in this study.

The combination of *DBH* and *H* (*DBH^2H*) was a better predictor for the total amount of carbon and total biomass, than the use of single variables. This is consistent with previous studies in which the composite variable DBH^2H is pointed as a well predictor for biomass (and thus carbon) equations (Rance et al., 2011; Mello and Gonçalves, 2008; Zewdie et al., 2009).

The belowground biomass (roots) was also assessed and its carbon content estimated. The R/S ratio was relatively stable (*C.V.* = 27.5%) probably because the sub-sample was composed by clones. Beside the absence of genetic variation, all the individuals of the sub-sample had the same age (5.5 years) and presented a low variability of *DBH* (*C.V.* = 17.8%). However it is worthy to mention the R/S estimated in this study is valid only for trees and sites with similar conditions, as R/S depends on many factors such as nutrient and water availability, spacing, age, species and climatic zone (Barton and Montagu, 2006).

The carbon content of the roots (37.8%) was smaller than other studies. Gifford (2000b) found an average carbon content of 49.3% for coarse roots of Eucalyptus that are native of Australia. Stape et al. (2008) used a carbon content of 42% for roots (< 2mm) for an Eucalyptus hybrid (*E. grandis x urophylla*) in Brazil. IPCC (2003) suggests the use of a default value of 50%. As in the case of aboveground biomass, there are not many studies that quantified the carbon content of roots, being very common the use of 50% as a general value. This is not recommended as already mentioned before.

The estimates of tree carbon stock in the stand level for the above- and belowground parts were 63.57 and 9.81 tC ha^{-1}, respectively. Schumacher and Witschoreck (2004) assessed the carbon stock of *Eucalyptus* sp. in different ages in the state of Rio Grande do Sul. The authors observed an aboveground carbon stock at 4 and 6 years of 16.25 tC ha^{-1} and 72.02 tC ha^{-1}, respectively. For the belowground part, the carbon stock at 4 years old was 2.3 tC ha^{-1} and at 6 years old 8.9 tC ha^{-1}. Paixão et al. (2006) found a carbon stock of 47.7 tC ha^{-1} in the tree aboveground part and of 14.71 tC ha^{-1} for the roots in an 6-year old *Eucalyptus grandis* plantation. Our study is within the carbon stock range for Eucalyptus plantations.

5. Conclusion

We determined the carbon content in stem, branches, leaves and roots of a clonal Eucalyptus plantation. Allometric equations to estimate the total aboveground amount of carbon and biomass were developed and estimates of the carbon stock in the stand level were generated.

The carbon content of stem, branches, leaves and roots was smaller than the generic value commonly used (50%). This highlights the importance of determining the carbon content in laboratory instead of using a default value. A high proportion of the aboveground biomass is allocated in the stem, followed by bark, branches and leaves. The percentages of biomass distribution are similar to other studies.

To predict the aboveground biomass the composite variable DBH^2H performed better than the use of single variables (*DBH* and *H*). The estimates of tree carbon stock on the stand level for the above- and belowground tree parts were 63.57 and 9.81 tC ha^{-1}, respectively. Our estimates of carbon stock are within the range for Eucalyptus plantations.

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CONCLUSÕES GERAIS

Com base nos resultados obtidos neste estudo, as seguintes conclusões gerais podem ser apresentadas:

- No fragmento de cerrado *sensu stricto* verificou-se que a biomassa média acima do solo (tronco, galhos e folhas) e a biomassa média abaixo do solo corresponderam a 62,97 t ha^{-1} e 37,50 t ha^{-1}, respectivamente.

- A melhor equação para estimar a biomassa acima do solo de árvores individuais no fragmento de cerrado *sensu stricto* foi aquela com as variáveis independentes DAP e densidade básica da madeira ($\bar{R}^2$ = 0,896; $S_{y.x}$ = 0,371).

- No nível de povoamento, a equação testada com a área basal como variável independente apresentou um bom ajuste ($\bar{R}^2$ = 0,926; $S_{y.x}$ = 0,224).

- O teor de carbono médio para o tronco+galhos, folhas, raízes, arbustos e serapilheira do fragmento de cerrado *sensu stricto* foi de 48%.

- O estoque de carbono total estimado para o fragmento de cerrado *sensu stricto* foi de 54,36 tC ha^{-1}.

- No plantio de eucalipto o teor médio de carbono para o tronco, galhos, folhas e raízes foi de 44,6%, 43,0%, 46,1% e 37,8%, respectivamente.

- O teor de carbono do caule, galhos, folhas e raízes do plantio de eucalipto foi menor do que o valor genérico comumente usado (50%). Isso destaca a importância de se determinar o teor de carbono em laboratório em vez de usar um valor padrão.

- O estoque de carbono total no plantio de eucalipto foi estimado em 73,38 tC ha^{-1}, estando dentro da faixa encontrada em outros estudos.

- As equações de melhor ajuste para se estimar a quantidade total de carbono e biomassa no plantio de eucalipto apresentavam DBH^2H como variável independente.

- Os resultados encontrados para o fragmento de cerrado *sensu stricto* e o plantio de eucalipto podem ser usados por desenvolvedores de projetos florestais e REDD+ para embasar as estimativas de biomassa e estoque de carbono de seus projetos.