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Above- and belowground biomass in a Brazilian Cerrado

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ABSTRACT

Cerrado is a biome that occupies about 25% of the Brazilian territory and is characterized by a gradient of grassland to savanna and forest 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 South-East of Brazil in a cerrado *sensu stricto* (cerrado s.s.) with the goal to produce estimates of above- and belowground biomass 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 62,965.5 kg ha^{-1}(SE = 14.6%) and belowground biomass accounted for 37,501.8 kg ha^{-1} (SE = 23%). The best-fit equation for the estimation of individual tree aboveground biomass include DBH and wood density as explanatory variables (R^2 = 0.898; 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 (R^2 = 0.934; 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.

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 forest formations. The Cerrado is not a homogeneous vegetation type: according to Coutinho (1978) and Miranda et al. (1997), its physiognomies range from *campo* forms (grassland formation), and the typical cerrado *sensu stricto* (savanna formation with trees and shrubs up to 8–10 m high and with a grass understory) to the cerradão (forest formation with trees up to a height of 20 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 hot spot, 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

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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.

2. Materials 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 1200 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 predatory 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 remnant of this study has a rectangular shape (Fig. 1). Ten plots of 20 m × 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.

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.

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

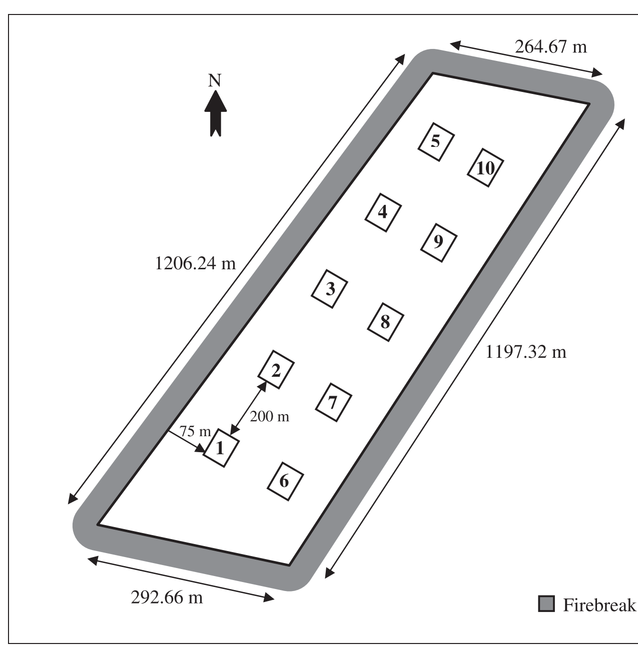

Fig. 1. Plot design in the "cerrado s.s." remnant in which this study was done.

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 hot spots 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 (Fig. 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 identify a set of 18 species (out of a total of 47 observed 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 °C 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 °C 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 Eq. (2):

$$B_i = UF_i \times m_i \times EF \tag{2}$$

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

2.5. Biomass of shrubs and litter

Shrub is 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 × 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 is 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

Table 1
Basal area *BA*, number of trees *N*, and average wood density *WD* from the Cerrado 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.	Papilionoideae	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
Piptocarpha rotundifolia (Less.) Baker	Asteraceae	0.075	19	0.46
Plathymenia reticulata Benth.	Mimosaceae	0.062	14	0.58
Pouteria torta (Mart.) Radlk.	Sapotaceae	0.098	11	0.59
Pterodon emarginatus Vogel	Papilionoideae	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.	Caesalpinioideae	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	Mimosaceae	0.126	13	0.54
Terminalia argentea Mart.	Combretaceae	0.108	17	0.67

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 °C 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 × 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 °C 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:

$$\ln B = \beta_0 + \beta_1 \ln D + \beta_3 \ln H + \beta_7 \ln WD \qquad (m_1)$$

$$\ln B = \beta_0 + \beta_5 \ln D^2H + \beta_7 \ln WD \qquad (m_2)$$

$$\ln B = \beta_0 + \beta_1 \ln D + \beta_2 (\ln D)^2 + \beta_4 (\ln D)^3 + \beta_7 \ln WD \qquad (m_3)$$

$$\ln B = \beta_0 + \beta_1 \ln D + \beta_7 \ln WD \qquad (m_4)$$

$$\ln B = \beta_0 + \beta_1 \ln D \qquad (m_5)$$

where *B* = aboveground biomass in kg; *D* = diameter at breast height in cm, *H* = total height of the tree in m and *WD* = wood density in g cm^{-3}.

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:

$$\ln B = \beta_0 + \beta_8 \ln BA \qquad (m_6)$$

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):

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

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 coefficient of determination (R^2), the standard error of estimate (*SEE*), and the analysis of variance table and residual distributions.

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 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.

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*

Table 2
Mensurational characteristics of all inventory plot sample trees and of the sub-set selected for destructive biomass measurements (coefficient of variation in parentheses).

	All inventory plot sample trees	Sub-set of biomass sample trees
DBH (cm)		
Mean (C.V.)	8.7 (44.1%)	10.8 (37.8%)
Range	5.0–43.9	5.0–27.6
Height (m)		
Mean (C.V.)	3.4 (28.4%)	3.8 (26.8%)
Range	1.5–19.0	1.5–7.5
Basal area (m^2 ha^{-1})	14.9 (127.1%)	2.4 (81.9%)

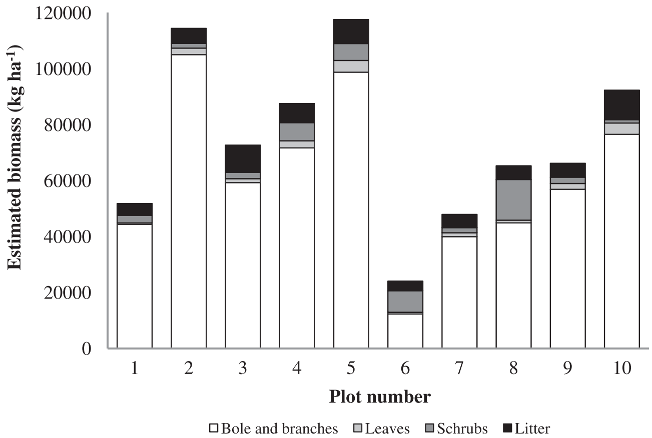

Fig. 2. Aboveground biomass of the 10 plots in the 10 sample plots.

serratifolia (height = 19.0 m) which was responsible for increasing the height range in this case.

The basal area of the inventory plot sample trees corresponds to 16.1% of total basal area of the forest 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 10 plots to per-hectare values ranged from 12,895.7 to 107,362.7 kg ha^{-1}, with a mean of 62,965.5 kg ha^{-1} and a relative standard error of 14.6% (Fig. 2). The biomass of bole and branches (60,963.0, 14.6%[2]) had a smaller variation than the biomass of leaves (2002.5, 20.7%).

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).

The estimated mean biomass of shrubs and litter is 4682.4 (28.2%) and 6316.8 (12.3%) kg ha^{-1}, respectively, so that total aboveground biomass (AGB), resulting from the AGB of trees, shrubs and litter, is estimated to be 73,964.7 kg ha^{-1}. These figures are higher than those published for the same Cerrado vegetation type, as illustrated by the comparison in Table 3.

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 15,066.9 to 102,116.7 kg ha^{-1} with an estimated mean of 37,501.8 kg 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 111,466.5 kg ha^{-1} and its composition is depicted in Fig. 3.

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 coefficient of determination R^2 was around 89% 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 R^2 and *SEE* of 0.934 and 0.224, respectively.

The best-fit single tree models for estimating aboveground biomass (*B*) along R^2 and *SEE* were m_1, m_3 and m_4. These models presented similar R^2 values (0.902, 0.901 and 0.898, respectively) and *SEE* (Table 4). The model m_3 had a similar 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 Fig. 4.

Model m_6 had the higher R^2 and *SEE* values (0.934 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.

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 (73,964.7 kg 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 = 62,965.5 kg ha^{-1}, trees + shrubs = 67,647.9 kg ha^{-1}).

Indirect estimations of biomass for trees and shrubs in the cerrado s.s. were performed 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 12,530 to 42,960 kg ha^{-1}, with an average of 25,302 kg 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 (4682.4 and 6316.8 kg 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 (2086 tree ha^{-1}) for the actual study site are slightly higher as compared to others (see Table 3).

[2] Relative standard error (SE%).

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 (%).

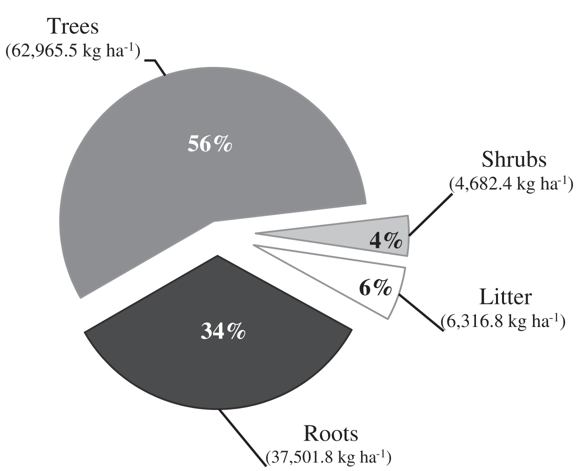

Fig. 3. Composition of total biomass from the biomass components considered in this study.

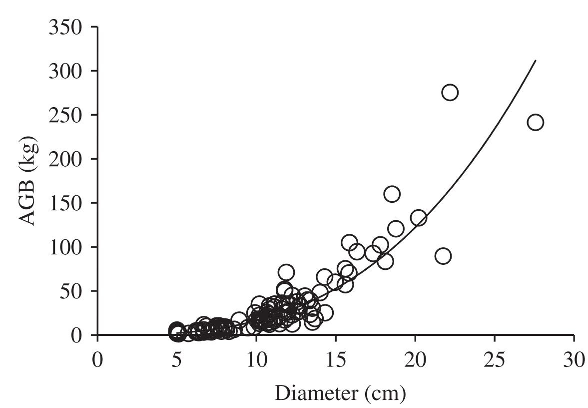

Fig. 4. Relation between single tree aboveground biomass (AGB) and tree diameter (n = 116).

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 (37,501.8 kg ha^{-1}) are about half of the estimated AGB. There are only few published studies which assessed the belowground

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

Model	Coefficient									R^2	*SEE*	CF^a
	b_0 (Intercept)	b_1 (ln *D*)	b_2 (ln *D*)^2	b_3 (ln *H*)	b_4 (ln *D*)^3	b_5 (D^2H)	b_6 (DH^2)	b_7 (ln *WD*)	b_8 (ln *BA*)			
m_1	−3.3369 (*<0.0001*)	2.7635 (*<0.0001*)	–	0.4059 (*0.0316*)	–	–	–	1.2439 (*<0.0001*)	–	0.902	0.365	1.069
m_2	−3.1679 (*<0.0001*)	–	–	–	–	1.1438 (*<0.0001*)	–	1.3079 (*0.0001*)	–	0.888	0.389	1.079
m_3	6.6844 (*0.2022*)	−9.9319 (*0.1501*)	5.3745 (*0.0697*)	–	−0.7273 (*0.0798*)	–	–	1.1201 (*0.0003*)	–	0.901	0.368	1.070
m_4	−3.3520 (*<0.0001*)	2.9853 (*<0.0001*)	–	–	–	–	–	1.1855 (*0.0001*)	–	0.898	0.371	1.071
m_5	−3.9336 (*<0.0001*)	2.9171 (*<0.0001*)	–	–	–	–	–	–	–	0.884	0.394	1.081
m_6	8.3724 (*<0.0001*)	–	–	–	–	–	–	–	1.1912 (*<0.0001*)	0.934	0.224	1.025

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

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 41,100 kg 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 1–2 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 46,600 and 52,900 kg 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 30,360 kg 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 and 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.

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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