

20. Raju, B., Wu, C., Castillo, R., Okun, I., Stavros, F. and Chan, M. F., 2-Aryloxy-carbonylthiophene-3-sulfonamides: highly potent and ET_A selective endothelin receptor antagonists. *Bioorg. Med. Chem. Lett.*, 1997, **7**(16), 2093–2098.
21. Morimoto, H. *et al.*, Modifications and structure-activity relationships at the 2-position of 4-sulfonamidopyrimidine derivatives as potent endothelin antagonists. *Bioorg. Med. Chem. Lett.*, 2002, **12**(1), 81–84.
22. Wu, C. *et al.*, Endothelin antagonists: substituted mesitylcarboxamides with high potency and selectivity for ET(A) receptors-1. *J. Med. Chem.*, 1999, **42**(22), 4485–4499.
23. Wermuth, C. G., Selective optimization of side activities: another way for drug discovery. *J. Med. Chem.*, 2004, **47**(6), 1303–1314.
24. Chan, M. F. *et al.*, The discovery and structure-activity relationships of nonpeptide, low molecular weight antagonists selective for the endothelin ET(B) receptor. *Bioorg. Med. Chem.*, 1998, **6**, 2301–2316.
25. Chan, M. F. *et al.*, Halogen substitution at the isoxazole ring enhances the activity of *n*-(isoxazolyl) sulfonamide endothelin antagonists-1. *Bioorg. Med. Chem. Lett.*, 1996, **6**(20), 2393–2398.
26. Funk, O. F., Kettmann, V., Drimal, J. and Langer, T., Chemical function based pharmacophore generation of endothelin-A selective receptor antagonists. *J. Med. Chem.*, 2004, **47**(11), 2750–2760.
27. MAESTRO (version 8.5), A graphical user Interface for Schrödinger suite, developed and marketed by Schrodinger LLC, New York, USA.
28. Dixon, S. L., Smondyrev, A. M., Knoll, E. H., Rao, S. N., Shaw, D. E. and Friesner, R. A., PHASE: a new engine for pharmacophore perception, 3D QSAR model development, and 3D database screening: 1. Methodology and preliminary results. *J. Comput. Aided Mol. Des.*, 2006, **20**, 647–671.
29. Tobias, R., *An Introduction to Partial Least Squares Regression*; <http://support.sas.com/techsup/technote/ts509.pdf>; Abdi, H., *Partial Least Squares (PLS) Regression*; <http://www.utdallas.edu/~herve/Abdi-PLS-pretty.pdf>; Hasegawa, K. and Funatsu, K., *SAR QSAR Environ Res.*, 2000, **11**(3–4), 189–209.

Received 14 June 2010; revised accepted 23 March 2011

Forest dynamics and carbon stocks in Rio Doce State Park – an Atlantic rainforest hotspot

Thiago Metzker^{1,*}, Tereza C. Spósito²,
Mariana T. F. Martins², Marise B. Horta²
and Queila S. Garcia²

¹PPG-ECMVS, Ecology, Conservation and Wildlife Management and
²Department of Botany, ICB–UFMG, CP:486, CEP:31270-901,
Belo Horizonte, Minas Gerais, Brazil

Tropical forests are significant biodiversity epicentres and work as important modulators of climatic change. In natural cycles, carbon stocks are regulated by vegetation dynamics through the rates of mortality, recruitment and turnover. This study was conducted

in five permanent monitoring plots (1 ha each: total 5 ha) in the Rio Doce State Park (RDSP), the most continuous Atlantic Forest remaining in Minas Gerais, Brazil and considered one of the world's hotspots. The aboveground biomass ranged from 201 Mg/ha in the primary forest to 92 Mg/ha in the secondary forest. The recruitment rate (1.8) was higher than the mortality rate (1.1); however, the average diameter of dead trees was higher than that of the recruited trees. Notwithstanding this result, the internal diametric increment (ingrowth) in RDSP was compensated by the biomass loss of dead trees, producing positive growth in the annual biomass and increasing their carbon stocks by 1.0 Mg C/ha/yr. Interest in conservation and management of tropical forests has intensified since the 2007 IPCC results. Thus, our study provides data that will help calibrate the use of international methodologies in local projects using data previously collected with a standardized methodology.

Keywords: Aboveground biomass, carbon stock, permanent monitoring plots, tropical forest.

TROPICAL forests store millions of tonnes of carbon and account for approximately 40% of all terrestrial carbon in terrestrial vegetation¹. In natural cycles, the biomass stock ensures a balance in the carbon cycle through dynamic exchanges with the atmosphere. Forest dynamics is controlled by the balance between turnover, death and recruitment rates – essential components of net primary production (NPP)².

Recent studies suggest that turnover and growth rates of tropical forests have increased in the last few decades due to stimulation of forest growth caused by increase in CO₂ concentrations in the atmosphere^{2–6}. However, Feeley⁷ demonstrated that growth rates for forests in Panama and Malaysia have declined due to a decrease in precipitation and an increase in the minimum daily temperature.

Changes in tropical forest pattern dynamics can result in consequences for the biodiversity and economy of the planet. Biomass and biodiversity loss in forests due to burnout and deforestation, for example, affects the natural regime of the hydrologic cycle. Tropical forests play an important role in the control of rain precipitation through the release of volatile organic compounds (VOCs). VOCs function like cloud condensation nuclei and effectively control precipitation and cloud condensation formations⁸. Without this system of water replenishment, the whole hydrologic cycle can be compromised, resulting in a process of forest desertification.

The Atlantic Forest, a diverse tropical forest located in the Brazilian coast and inland, has high levels of biodiversity, endemism and environmental impacts. This forest is one of the world's biodiversity hotspots⁹, and has only 8% of its original area. There are strong economic and social demands to use the remnant lands despite the effort

*For correspondence. (e-mail: thiagobio@ufmg.br)

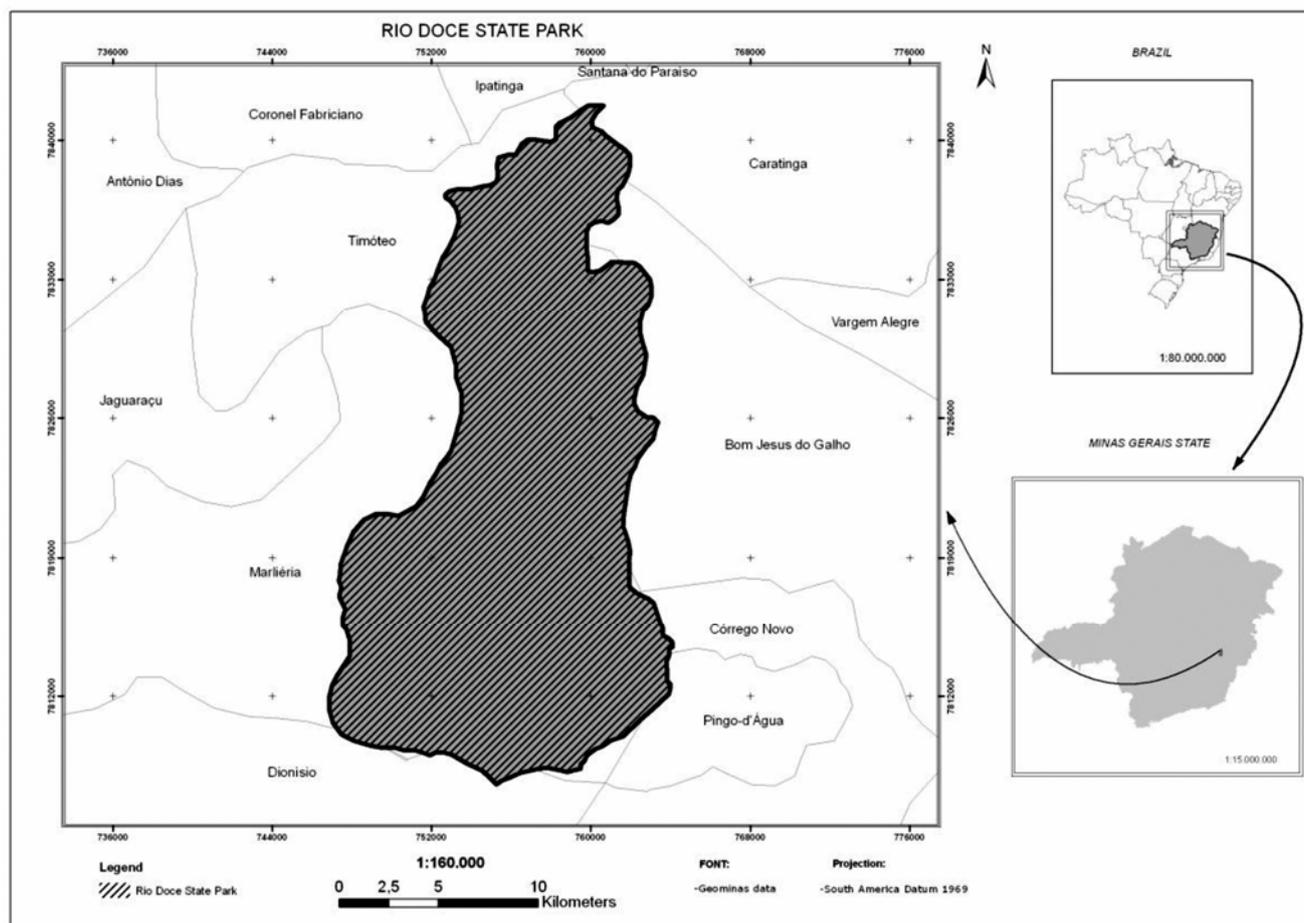


Figure 1. Location map of the Rio Doce State Park, Minas Gerais, Brazil.

to preserve forested sites¹⁰. The Atlantic Forest biome is extremely fragmented with low connectivity among areas, inserted in a matrix of urban centres, pastures and eucalyptus plantations.

The Atlantic Forest is considered one of the world's most endangered tropical forests and there is little information available about its carbon stock levels and vegetation dynamics¹¹. This is necessary to calculate primary productivity¹² and climatic modelling, to serve as a baseline for the quantification of emissions and atmospheric exchanges over time. Monitoring forest carbon stocks can also identify temporal changes in ecological patterns that occur due to the impact of factors such as pollution, deforestation, fire and increasing concentration of atmospheric CO₂. For both developed and developing countries, there is a strong need to know what happens in relation to carbon dynamics within their territories in order to implement conservation policies, as well as forest management and conservation strategies for these environments. Therefore, studies that quantify carbon stocks are important for tropical forests^{1,13}.

This communication presents the initial results related to biomass, carbon stocks, growth rates, recruitment and

mortality (using a standardized methodology) in different forest stages at the Rio Doce State Park (RDSP), Minas Gerais (MG), Brazil.

RDSP (36,000 ha) is the largest remaining continuous forest of the Atlantic Forest biome in MG (Figure 1). RDSP (19°45'03"S, 42°33'26"W) is composed of a complex mosaic of native forests in various stages of succession, with about 130 lakes interspersed among them (a lacustrine system). RDSP vegetation is classified as seasonal semi-deciduous submontane forest. Considering the landscape and the level of human intervention that has resulted in destruction throughout extensive areas of the original vegetation, RDSP assumes a position of prominence in terms of regional natural resources preservation and conservation.

According to Köppen, the climate (Aw) produces an annual average temperature of 22°C (±2.2°C) and an annual average precipitation of 1478 ± 8 mm/yr. During the rainy season from October to April, rainfall accounts for about 84.5% of the average annual precipitation. The dry season lasts about five months, from May to September, with only 134.9 mm of rainfall and 9.1% of the total annual precipitation. Soils in the RDSP are red–yellow

latosol, acidic soils with low natural fertility – a common characteristic of soils in the Park. RDSP is situated in a region with soft contours (in the form of hills), sedimentary plains and valleys, and an altitudinal range of 230–515 m.

To collect the data, five permanent monitoring plots (PMPs) measuring 1 ha (10,000 m²) each were demarcated. The choice of locations was based on the criteria to meet the demands of homogeneity of physiognomic types, the types of soil and inclination of the land. Each PMP was divided into 25 sub-plots of 20 m × 20 m for more efficient field logistics. The area of each 1 ha plot was validated by researchers from Conservation International (Washington, DC, USA), using a high-precision GPS.

Samples included all trees, palms and lianas with a diameter-at-breast-height (DBH) ≥ 10 cm that were marked and measured. The point-of-measurement (POM) was marked at 1.30 m with a graduated pipe to prevent errors due to differing heights of the field markers¹⁴. However, for individuals with higher tabular and buttress roots, the POM was set at 50 cm above the tallest buttress. This correction is valid because it is common in forest inventories for individual trees to have DBH measured at 1.30 m. When DBH data of trees that include tabular and buttress roots are inserted into equations, the resulting biomass calculations become inflated, thus increasing the standard error of these calculations^{15–17}. POM was marked with yellow paint, and its height was recorded in the field spreadsheet.

The first census was conducted in September 2005 and the re-census in September 2006. Field measurements were carried out during the dry season to prevent any influence from the rain. In the 2006 census, all new trees, palms and lianas beyond the limit of inclusion (DBH ≥ 10 cm) were also sampled using the same methodology for marking as stated above. Individuals marked in the first census that did not exhibit vegetative activity in the subsequent census were considered dead.

An indirect method was used to estimate biomass and carbon stocks. An equation developed by Chave *et al.*¹⁸ was used to calculate dry aboveground biomass (AGB) for each tree in PMPs (Table 1). This equation consisted of three independent variables for the calculation of dry

biomass (DBH, wood density and tree height). Carbon stocks were calculated as 50% of the dry biomass. The palm biomass was calculated separately in each plot using the equation of Nascimento and Laurance¹⁹. The liana biomass was also calculated separately using the equation of Gerwing and Farias²⁰. To increase the precision of the estimates, a correction factor was applied using species-specific wood density.

The rates of mortality (*M*) and recruitment (*R*) were calculated using the equations by Sheil²¹.

A total of 2757 individuals were marked and measured in the five PMPs studied – 2584 trees (93.75%), 142 palms (5.11%) and 31 lianas (1.12%). The average number of stems totalled 517 (± 80) trees, 28 (± 35) palms and 6 (± 5) lianas per hectare. The diametric class that made the greatest contribution to the total density of the individuals was the 10–20 cm class, with 72.2% (1966) of individuals. The diametric class of large trees (DBH ≥ 30 cm) comprised 12.3% (335) of total individuals and was highest in the primary forest (Figure 2).

Tree density varied according to the forest physiognomic type. The highest density of individuals was in Lagoa Preta (LP – primary forest), with 614 (93.6%) trees, 31 (4.7%) palms and 11 (1.7%) lianas. The lowest density was found in Garapa Torta (GT – secondary forest), which contained 415 (100%) trees. The palm density was greatest in Lagoa Juquita (LJ), with 85 palms followed by LP (31), both primary forest areas. The secondary forest did not present palm tree individuals (Table 2).

Trees of greater diameter were found in plain areas of the primary forest. The largest diameter was recorded in plot LJ, belonging to an *Andradea floribunda* individual with DBH of 110 cm. In primary forests, the large lianas also had greater densities compared to those in secondary forest areas. In Lagoa Central (LC – primary forest), 12 lianas were found, whereas in GT (secondary forest) no liana was marked. However, in the secondary forest, where the gap dynamics is more intensive, the density of fine lianas was greater than in the primary forest.

The average dry AGB of trees, palms and lianas found in the five plots was 150 (± 48) Mg/ha. In primary areas, the average was 185 (± 14) Mg/ha, and in secondary forest it was 99 (± 10) Mg/ha. The contribution of trees to the total biomass was 98.3% (± 1.3). Palms contributed 0.8% (± 1) and lianas 0.9% (± 0.8). The LP plot (primary forest) had the largest value of dry biomass, with 201 Mg/ha. The lowest value was for GT (hillside secondary forest) with 92 Mg/ha (Table 3). In contrast to tree density, contribution of the individuals in the 30–40 cm diametric class to the total biomass was 19.6%. The 10–20 cm diameter class contributed 18.7% to the total biomass. The large diametric class (DBH ≥ 30 cm) was a major reservoir of the biomass in the forest system (63.4%), despite containing a smaller number of individuals.

The distribution of dry biomass had a large spatial variation within and among the plots (Figure 3). In LP

Table 1. Allometric equations used to estimate the dry vegetative biomass (kg) of trees, palms and lianas in five plots in the Rio Doce State Park (RDSP)

Type	Allometric model
Trees ^a	$\exp(-2.977 + \ln(p * DBH^2 * H))$
Palms ^b	$\exp((5.7236 + 0.9285 * \ln(DBH^2)) * 1.05001)/10^3$
Lianas ^c	$\exp(0.07 + 2.17 * \ln(DBH))$

^aChave¹⁸; ^bNascimento and Laurance¹⁹; ^cGerwing and Farias²⁰.

DBH, Diameter at breast height; H, Total height, and *p*, Wood mean density for the RDSP species (in/g/cm³).

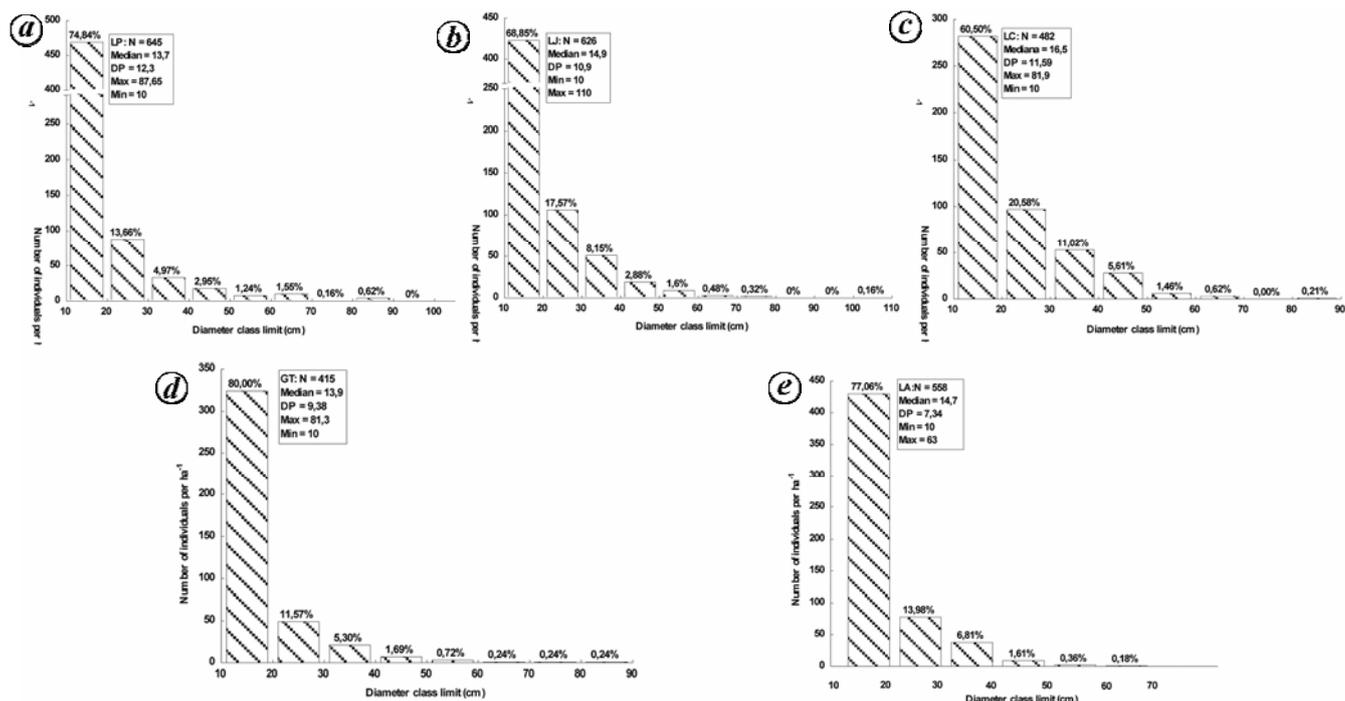


Figure 2. Diametric distribution of stems (trees and palms) in the five permanent monitoring plots (PMPs) studied in the RDSP. (a) Lagoa Preta, (b) Lagoa do Juquita, (c) Lagoa Central, (d) Garapa Torta and (e) Lagoa do Aníbal. Distributions are ‘inverted J’ curves, all with positive asymmetry to the right of unimodal trend.

Table 2. Physiognomy and topography of each permanent monitoring plot (PMP). The density of trees, palms and lianas is measured as the number of individuals in the 1 ha plot. The aboveground biomass (AGB) and total carbon stocks were calculated using the equation by Chave *et al.*¹⁸

PMP	Physiognomy	Topography	N	AGB trees	Per-centage	N	AGB palms	Per-centage	N	AGB lianas	Per-centage	Total AGB	Carbon stocks
LP	Primary forest	Plain	614	194.1	98.0	31	1.3	0.7	11	2.6	1.3	198	99
LJ	Primary forest	Plain	541	174	97.0	85	4.4	2.5	5	1	0.6	179.4	89.7
LC	Primary forest	Hillside	456	166.6	97.2	26	1.1	0.6	12	3.7	2.2	171.4	85.7
LA	Secondary forest	Hillside	558	105.8	99.4	0	0	0.0	3	0.6	0.6	106.4	53.2
GT	Secondary forest	Hillside	415	88.5	100.0	0	0	0.0	0	0	0.0	88.5	44.2
Mean	–	–	516.8	145.8	98.3	28.4	1.3	0.8	6.2	1.5	0.9	148.7	74.4
SD	–	–	80.3	45.9	1.3	34.7	1.8	1.0	5.2	1.5	0.8	48.2	24.1

Data are in Mg/ha; LP, Lagoa Preta; LJ, Lagoa do Juquita; LC, Lagoa Central; LA, Lagoa do Aníbal; GT, Garapa Torta.

sub-plots, the biomass values varied from 2 to 41 Mg (amplitude of 39 Mg), whereas in LA biomass varied from 2 to 11 Mg (amplitude of 9 Mg). In LP, stem densities in the sub-plots were not significantly correlated to the dry biomass ($N = 25$, $r^2 = -0.035$, $P > 0.05$), whereas in LJ this relationship was significant ($N = 25$, $r^2 = 0.402$, $P < 0.05$). In other plots (LC, GT and LA), the correlation between stem density and dry biomass was also significant with a homogeneous distribution of biomass among the individuals. Across all plots, a tendency for greater values of AGB in the plain areas was verified (Figure 3). In LP and LJ (plain topography), the biomass was heterogeneously distributed due to greater variation among biomass values. The areas of hillside forest had lower biomass values in sub-plots with more homogeneous dis-

tributions. Although not significant ($P = 0.08$, $r^2 = 0.264$), a relationship between the biomass values and the inclination of the PMP was found, suggesting an inversely proportional trend.

The global median of the diametric increment was 0.1 cm/yr. Many individuals had negative increments, thus producing a small bimodality trend in the distribution curve. Positive growth (≥ 0.1 cm) was found in 59.7% of individuals, whereas 3.3% showed no growth and 6.9% had negative growth (≤ -0.1 cm). In general, average diametric growth varied between PMPs (Figure 4). The GT plot exhibited the greatest growth rate (0.3 cm/yr), whereas the LA plot did not exhibit any growth during the study period. The values of growth in each plot also varied between the diametric classes: for

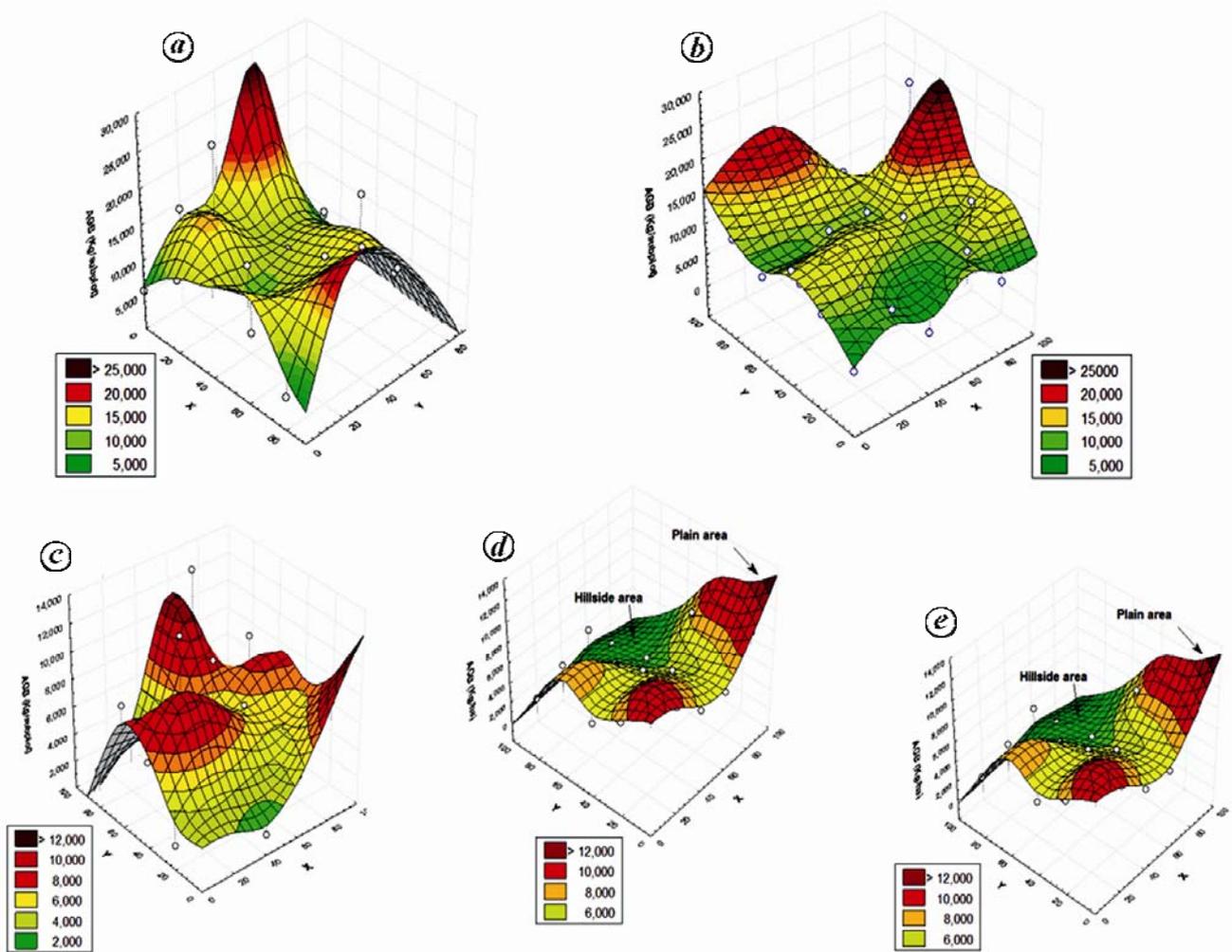


Figure 3. Spatial distribution of dry aboveground biomass (trees + palms) in 25 sub-plots in each PMP. *a*, Lagoa Preta; *b*, Lagoa do Juquita; *c*, Garapa Torta; *d*, Lagoa do Aníbal; *e*, Lagoa Central. *a*, *b*, Plain primary forest; *c*, *d*, Hillside secondary forest, and *e*, Hillside primary forest.

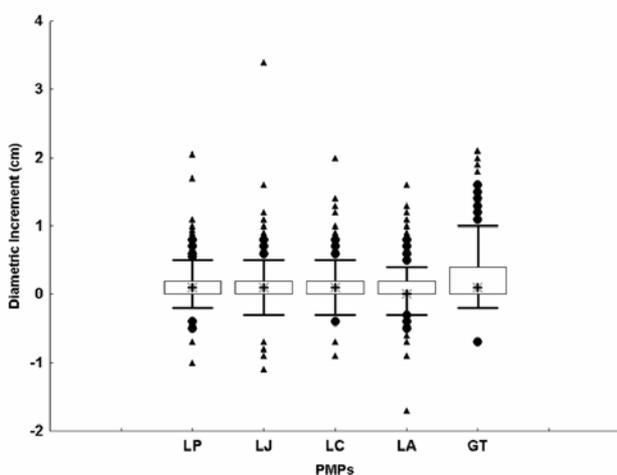


Figure 4. Box plot of the distributions of diameter increments from September 2005 to September 2006 in the five plots used in this study. LP, Lagoa Preta; LJ, Lagoa do Juquita; LC, Lagoa Central; LA, Lagoa do Aníbal and GT, Garapa Torta.

individuals larger than 40 cm, DBH increased by 0.2 cm/yr. The diametric class of 80–90 cm in LP grew 0.5 cm/yr.

The average rates of mortality and recruitment of the plots were 1.1 (± 0.3) and 1.8% (± 0.9) respectively (Table 3). The highest mortality rate was 1.6% (9 individuals) in LP and the highest recruitment rate was 2.9% (12 individuals) in GT. Although recruitment rates were greater, the average diameter of dead trees (18.6 ± 6 cm) was larger than that of recruitment trees (10.1 ± 0.1 cm). In the five plots, the dead biomass was 2.2 Mg/ha (± 1.9), whereas the recruitment biomass was only 0.51 Mg/ha (± 0.2), indicating that recruitment does not necessarily imply a biomass increase in the community.

Nevertheless, over the period of study, the balance of the changes in AGB remained positive, indicating an increment of AGB in the forest community (Table 3). The average increase in AGB was 2 Mg/ha (± 1.4) of dry biomass. The plot that had the largest increase in biomass

RESEARCH COMMUNICATIONS

Table 3. AGB (Mg/ha), change in carbon stocks (Mg/ha/yr), number of recruits and dead individuals in five PMPs

PMP	<i>N</i>	Total AGB Year I	<i>M</i> (%)	<i>N</i> Dead	<i>R</i> (%)	<i>N</i> recruits	Total AGB Year II	AGB change	Carbon stocks change
LP	656	198.0	1.6	9	1.7	11	201.0	3.0	1.5
LJ	631	179.4	1.3	8	1.0	6	179.8	0.4	0.2
LC	493	171.4	0.8	4	2.3	11	174.0	2.6	1.3
LA	558	106.4	1.1	6	0.9	5	107.0	0.6	0.3
GT	415	88.5	1.0	4	2.9	12	92.0	3.5	1.7
Mean	550.4	148.7	1.1	6.2	1.8	9	150.8	2.0	1.0
SD	98.9	48.2	0.3	2.3	0.9	3.2	48.1	1.4	0.7

M, Mortality rate and *R*, Recruitment rate. All individuals (trees, palms and lianas) were included.

was GT (secondary forest), with 3.5 Mg/ha, followed by LP (primary forest), which increased to 3 Mg/ha (Table 3). Regarding carbon stocks, PMPs absorbed 1 Mg C/ha/yr (± 0.7), indicating that RDSP community had positive growth in carbon storage.

This work has initiated a rigorous study of forest dynamics and biomass monitoring of the Atlantic Forest biome using a standardized methodology. The plots that were evaluated illustrate the heterogeneous mosaic in the Atlantic Forest of the RDSP, which is representative of other forest fragments found in this Brazilian biome.

The average tree density found in the primary forest in RDSP (635 ± 12) is larger than that of the secondary forest (486 ± 101). In two tropical forest areas in French Guyana, an average of approximately 500 trees/ha has been found²². The density of individuals in PMPs in Central Amazonia varied from 325 (± 51) (ref. 19) to 518 (ref. 23). Vieira *et al.*²⁴ have registered densities of 460, 466 and 626 in Rio Branco (Acre), Santarém (Pará) and Manaus (Amazon) respectively. However, the average density of palms (58 ± 38) and lianas (8 ± 4) in RDSP was lower compared to other studies in primary tropical forests. In Costa Rica, density values have been found for palms and lianas totalling 120/ha and 10/ha respectively¹⁵.

For LP (644 stems) and LJ (626 stems), the plain topography and lesser degree of impact must have been the determinants for the occurrence of the high values for stem density. The lower values of density and dry biomass for GT (415 stems) can be attributed to the hillside topography (which makes it difficult to set seedlings), as well as the fire that occurred in this area in 1967.

The values of AGB varied significantly among plots, depending on the differences in the successional stage, the density of trees and the topography of each plot. The differences in AGB demonstrate the heterogeneous spatial distribution of biomass in natural forests. The existence of a high density of large trees in primary forests results in higher AGB values in these areas. Larger trees (DBH ≥ 30) are considered important carbon sinks in tropical forests¹⁵.

AGB values found in RDSP are low compared to the average values found for Amazonia²⁴ and Costa Rica¹⁵. In a compilation of 59 Amazonian forest plots, Baker *et al.*³ found values of dry biomass that ranged from 117 Mg/ha

(in Chore 1, Bolivia) up to 392 Mg/ha (Jarí, Brazil). Vieira *et al.*²⁴ quantified biomasses of 360 Mg/ha in Manaus, 190 Mg/ha in Rio Branco and 281 Mg/ha in Santarém. Malhi *et al.*²⁵ registered values of 200–350 Mg/ha in 227 monitoring plots. In Costa Rica, Clark and Clark¹⁵ found values varying from 161 to 186 Mg/ha. In one of the few studies carried out in the Atlantic Forest biome, Jesus and Rolim²⁶ found an average of 290 (± 117) Mg/ha in the Tabuleiro Forest in Espírito Santo. However, comparison with results from different studies must be done with caution since many factors such as buttress diameter, estimates at different heights and choice of allometric equation can influence estimates of biomass¹⁴.

In LP (primary forest), the biomass did not correlate with the density of the individuals in the plot, whereas in the other four PMPs, this correlation was significant. This result can be partially explained by the significant variation in AGB values in LP sub-plots (amplitude 39) and the high number of large trees in this PMP. In the secondary forest plots, this relationship was highly significant due to the fact that AGB values are more homogeneously distributed among individuals.

Factors such as water (rainfall), light and nutrients can also influence the rate of tree growth²⁷. The global diameter increment in RDSP was 0.1 cm/yr. This value is similar to that found in Central Amazonia²⁸ and lower than those of tropical forest studies in southern Brazil²⁹ and Costa Rica¹⁵. Chambers *et al.*²⁸ have shown that trees in Central Amazonia grow slowly, with a diameter increment of only 0.11 cm/yr. In the 21-yr study of mixed ombrophilous forest (advanced secondary forest) in Paraná, Schaaf *et al.*²⁹ found growth rate of 0.2 cm/yr.

In the RDSP, the large trees have higher rates of diametric growth. Whereas some argue that young trees have larger diameter increments, this is not always the case because young individuals spend more time and resources to maintain their presence in the community. According to Schaaf *et al.*²⁹, 'young' trees can be, 'old' chronologically, because they can remain in this condition for years. However, larger trees have a competitive advantage in capturing sunlight and nutrients because their crowns are more established in the canopy²⁹. Their ability to capture greater amounts of solar energy enables them to invest more energy in biomass increment.

The GT plot had the highest recruitment and increment rates. This is related to the presence of a large number of pioneer species. As a secondary forest (many gaps), a greater amount of light enters the interior and generates ambient conditions of luminosity, as well as fluctuations of temperature, which are favourable to seed germination among pioneer species. This plot also had high mortality rate in the lower diametric classes, reflecting that regeneration processes occurring after disturbances create more opportunity for the recruitment of pioneering species. This pattern has also been described by some authors who have observed high mortality rates in lower diametric classes in tropical forest areas under regeneration³⁰.

The rates of mortality and recruitment found in RDSP plots are within the values found for tropical forests. In RDSP, the recruitment rate was greater than the mortality rate, indicating a positive balance for recruitment. False perceptions are common in the everyday analysis of this dynamics. Recruitment and mortality are determined basically by the density of individuals, which is essentially a question of available space²⁹. However, when analysing new recruits and dead trees in terms of their biomass, the value of dead biomass is significantly greater than that of the recruited biomass. Recruits have lower diameter than dead trees. In RDSP the internal diametric increment (ingrowth) compensated for the biomass loss of dead trees, producing positive growth in annual biomass.

Based on the analysis of growth rate, mortality and recruitment in RDSP plots, the changes in the carbon stocks and AGB were positive. Despite the high biomass of the dead trees, the internal growth of the community compensated for these losses and the carbon stocks increased at a rate of 1 Mg C/ha/yr. For Amazonia, Phillips *et al.*³¹ found an average increase of 0.97 Mg/ha/yr of carbon, based on 97 permanent plots. Higuchi *et al.*³² found values of carbon increment in Manaus (Central Amazonia) to be 1.2 Mg C/ha/yr. These values indicate that RDSP community, with an increase of 1.0 Mg C/ha/yr, is in a growth phase and will continue until its maximum capacity of support³².

Due to the great complexity of patterns in forest dynamics and the relationship between forests and the atmosphere, long-term conservation research must be prioritized. The use of standardized methodology in repeated annual censuses of all individuals in PMPs is the most robust way to monitor changes in the biomass and dynamics of tropical forests³³. AGB and carbon stocks data presented here can be used for forest restoration projects in the Atlantic Forest biome, where conservation and forest management activities can maximize the benefits provided by native forests. Furthermore, at both local and regional levels, our data should be used to subsidize fundraising through projects that aim to recover native forests (e.g. projects of landscape connectivity and ecological corridors in priority eco-regions), since it is possible to estimate the potential carbon sequestered by

vegetation that will be recovered in the landscape. Carbon stocks estimates are converted into financial resources (through values of Chicago Climate Exchange or European Climate Exchange), which together with other funds, enable the development of local and regional policies for native forest reforestation.

The Payment for Environmental Services (PES) may be another way to encourage the conservation of standing forests. In addition to maintaining biodiversity, protecting soil function and conserving water, forests should be valued for their capacity to sequester atmospheric carbon (CO₂). The average value of carbon stocks for each hectare generated by the PES can be used by policy-makers as incentives for families of local communities to support forest conservation. These are examples of how forest carbon studies can be applied and how the relationships between monitoring change in carbon stocks and ecosystem benefits can support conservation efforts.

Both the initiatives presented here can use international mechanisms such as the clean development mechanism or reduce emissions for deforestation and degradation to assist in fundraising, but with a powerful differential: calibrating the calculation methodologies with highly reliable data, collected locally, using a standardized methodology.

1. Malhi, Y. and Grace, J., Tropical forests and atmospheric carbon dioxide. *Trends Ecol. Evol.*, 2000, **15**, 332–337.
2. Phillips, O. L. *et al.*, Patterns and process in Amazonian tree turnover, 1976 a 2001. *Philos. Trans. R. Soc. London, Ser. B*, 2004, **359**, 381–407.
3. Baker, T. *et al.*, Increasing biomass in Amazonian forest plots. *Philos. Trans. R. Soc. London, Ser. B*, 2004, **359**, 353–365.
4. Lewis, S. L. *et al.*, Concerted changes in tropical forest structure and dynamics: evidence from 50 South American long-term plots. *Philos. Trans. R. Soc. London, Ser. B*, 2004, **359**, 421–436.
5. Lewis, S. L., Tropical forests and the changing earth system. *Philos. Trans. R. Soc. London, Ser. B*, 2006, **361**, 439–450.
6. Phillips, O. L. *et al.*, Drought sensitivity of the Amazon rainforest. *Science*, 2009, **323**, 1344–1347.
7. Feeley, K. J. *et al.*, Decelerating growth in tropical forest trees. *Ecol. Lett.*, 2007, **10**, 461–469.
8. Artaxo, P. *et al.*, Química atmosférica na Amazônia: a floresta e as emissões de queimadas controlando a composição da atmosfera amazônica. *Acta Amazônica*, 2005, **35**, 185–196.
9. Mittermeier, R. A. *et al.*, *Hotspots Revisited*, CEMEX, Conservation International, Washington, DC and Agrupacion Sierra Madre, Mexico, 2004, p. 392.
10. Spósito, T. C. and Stehmann, J. R., Heterogeneidade florística e estrutural de remanescentes florestais da Área de Proteção Ambiental ao sul da Região Metropolitana de Belo Horizonte (APA Sul-RMBH), Minas Gerais, Brasil. *Acta Bot. Bras.*, 2006, **20**, 347–362.
11. Vieira, S. A. *et al.*, Estimation of biomass and carbon stocks: the case of Atlantic Rain Forest. *Biota Neotrop. J.*, 2008, **8**, 21–29.
12. Keeling, H. C. and Phillips, O. L., The global relationship between forest productivity and biomass. *Global Ecol. Biogeogr.*, 2007, **16**, 618–631.
13. Malhi, Y. *et al.*, An international network to monitor the structure, composition and dynamics of Amazonian forests (RAINFOR). *J. Veg. Sci.*, 2002, **13**, 439–450.

14. Clark, D. A. *et al.*, Measuring net primary production in forests: Concepts and field methods. *Ecol. Appl.*, 2001, **11**, 356–370.
15. Clark, D. B. and Clark, D. A., Landscape-scale variation in forest structure and biomass in a tropical rainforest. *Forest Ecol. Manage.*, 2000, **137**, 185–198.
16. Clark, D. A., Are tropical forests an important carbon sink? Reanalysis of the long-term plot data. *Ecol. Appl.*, 2002, **12**, 3–7.
17. Chave, J. *et al.*, Error propagation and scaling for tropical forest biomass estimates. *Philos. Trans. R. Soc. London, Ser. B*, 2004, **359**, 409–420.
18. Chave, J. *et al.*, Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 2005, **145**, 87–99.
19. Nascimento, H. E. and Laurance, W. F., Total aboveground biomass in central Amazonian rainforest: a landscape-scale study. *For. Ecol. Manage.*, 2002, **168**, 311–321.
20. Gerwing, J. J. and Farias, D. L., Integrating liana abundance and forest stature into an estimate of aboveground biomass for an eastern Amazonian forest. *J. Trop. Ecol.*, 2000, **16**, 327–336.
21. Sheil, D., Evaluating turnover in tropical forests. *Science*, 1995, **268**, 894.
22. Chave, J. *et al.*, Estimation of biomass in a neotropical forest of French Guiana: spatial and temporal variability. *J. Trop. Ecol.*, 2001, **17**, 79–96.
23. Castilho, C. V. *et al.*, Variation in aboveground tree live biomass in a central Amazonian Forest: Effects of soil and topography. *For. Ecol. Manage.*, 2006, **234**, 85–96.
24. Vieira, S. A. *et al.*, Forest structure and carbon dynamics in Amazonian tropical rainforests. *Oecologia*, 2004, **140**, 468–479.
25. Malhi, Y. *et al.*, The regional variation of aboveground live biomass in old-growth Amazonian forests. *Global Change Biol.*, 2006, **12**, 1–32.
26. Jesus, R. M. and Rolim, S. G., Fitossociologia da Floresta Atlântica de Tabuleiro em Linhares (ES). *Bol. Téc. SIF*, 2005, **19**, 1–149.
27. Baker, T. *et al.*, Variation in tropical growth rates: combined effects of functional group composition and resource availability. *Urban Fischer Verlag*, 2003, **6**, 21–36.
28. Chambers, J. Q. *et al.*, Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. *For. Ecol. Manage.*, 2001, **152**, 73–84.
29. Schaaf, L. B. *et al.*, Incremento diamétrico e em área basal no período 1979–2000 de espécies arbóreas de uma floresta ombrófila mista localizada no sul do Paraná. *Floresta*, 2005, **35**, 271–290.
30. Oliveira-Filho, A. T. *et al.*, Effects of past disturbance and edges on tree community structure and dynamics within a fragment of tropical semideciduous forest in south-eastern Brazil over a five-year period (1987–1992). *Plant Ecol.*, 1997, **131**, 45–66.
31. Phillips, O. L. *et al.*, Changes in the carbon balance of tropical forest: evidence from long-term plots. *Science*, 1998, **282**, 439–442.
32. Higuchi, N. *et al.*, Dinâmica e balanço do carbono da vegetação primária da Amazônia Central. *Floresta*, 2004, **34**, 295–304.
33. Team Network, *Vegetation Protocol Implementation Manual, vol. 1.5: Tropical Ecology, Assessment and Monitoring Network*, Center for Applied Biodiversity Science, Conservation International, 2009, p. 75.

ACKNOWLEDGEMENTS. We thank the anonymous reviewer for providing useful suggestions that helped improve the manuscript. We also thank the UFMG, ECMVS, CAPES, USF&WS, Departamento de Botânica – Laboratório de Sistemática Vegetal, CNPQ (PELD-PROCESS: 520031/98-9), IEF (Instituto Estadual de Florestas) and TEAM (Tropical Ecology Assessment Monitoring Initiative) for their support during the field data collections. We also thank Marcus Vinícius (Management), Geraldo Adriano dos Santos (Canela), Marquinhos (Salão Dourado), Tião, Naná and the whole community of the Rio Doce State Park.

Received 2 August 2010; revised accepted 12 April 2011

Live tree biomass and carbon variation along an altitudinal gradient in moist temperate valley slopes of the Garhwal Himalaya (India)

Sumeet Gairola, C. M. Sharma*, S. K. Ghildiyal and Sarvesh Suyal

Department of Botany, HNB Garhwal University, Post Box No. 51, Srinagar Garhwal 246 174, India

The carbon (C) stored in the living biomass of trees is typically the largest C pool of the forest ecosystem which is directly impacted by deforestation and degradation. The relationships between diversity, biomass and C stocks at varied altitudes can have crucial implications for the management and conservation of C sinks. The study was undertaken in moist temperate Mandal-Chopta forest of Chamoli District, Garhwal Himalaya, Uttarakhand, India with the following objectives: (1) to assess live tree biomass and C stocks along an altitudinal gradient; (2) to assess relationship of live tree C density (TCD) with altitude, species richness, diversity and density, and (3) to compare values of live tree biomass and C density of the present study with the earlier reported values in forests of other parts of Garhwal Himalaya, Uttarakhand and India. The total live tree biomass density (TBD) varied from 215.5 to 468.2 Mg ha⁻¹ and TCD varied from 107.8 to 234.1 Mg C ha⁻¹. The average values of TBD and TCD for the study area were 356.8 ± 83.0 Mg ha⁻¹ and 178.4 ± 41.5 Mg C ha⁻¹ respectively. Comparative assessment of the data suggests that these values are similar to the earlier recorded values of C and biomass density for other forests of Garhwal Himalaya and Uttarakhand, but are higher than those reported from most of the other parts of the country. The stem density showed positive correlation with species richness (0.852) and diversity (0.749). No correlation between TCD and diversity was observed. However, statistically significant positive correlation of TCD with altitude (0.579) was observed, which could be attributed to dominance of large conifers and hardwoods at higher altitudes compared to lower altitudes.

Keywords: Altitude, carbon stocks, live tree biomass, tree density and diversity.

FORESTS are natural storehouses of biomass and carbon (C). They sequester and store more C than any other terrestrial ecosystem and are an important natural ‘brake’ on climate change¹. Forests fix, store and emit C by photosynthesis, respiration, decomposition and disturbances through a series of stages in the life cycle from regeneration to harvest². Forest vegetation represents a major pool in the global C cycle and alone contains over

*For correspondence. (e-mail: sharmacmin@gmail.com)