

Brazil's Amazonian forest carbon: the key to Southern Amazonia's significance for global climate

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Received: 15 June 2015 / Accepted: 8 June 2016 / Published online: 11 July 2016
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Abstract Southern Amazonia is the first region of Brazil's Amazon area to be exposed to intensive conversion to agriculture and ranching. This conversion emits greenhouse gases from the carbon stock in the biomass and soils of the previous vegetation. Quantifying these carbon stocks is the first step in quantifying the impact on global warming from this conversion. This review is limited to information on Brazilian Amazonia's carbon stocks. It indicates large amounts of carbon at risk of emission in both biomass and soils, as well as considerable uncertainty in estimates. Reducing uncertainty is a priority for research but the existence of uncertainty must not be used as an excuse for delaying measures to contain deforestation. The magnitude of carbon stocks is proportional to greenhouse gas emissions per hectare of deforestation and consequently to impact on global climate.

Keywords Carbon · Biomass · Amazonia · Soil carbon · Greenhouse gas emissions · Brazil

Introduction

Brazilian Amazonia (Fig. 1) contains a large stock of carbon that could be released to the atmosphere as greenhouse gases as a result of land use and land-use

change (e.g., Fearnside et al. 2009). Carbon stock is the starting point for quantifying the climatic impacts of land-use change, both within the southern Amazonia subregion and in Brazilian Amazonia as a whole. Information specific to southern Amazonia is available for several key factors, such as the aboveground volume of the trees measured in the RADAMBRASIL surveys (Brazil, Projeto RADAMBRASIL 1973–1982), and soil carbon (e.g., Moraes et al. 1995). For various other carbon stocks, estimates depend on data from other parts of Amazonia, such as belowground biomass, dead biomass (necromass), non-tree components, and secondary forest biomass. The present review is limited to information on forest carbon stocks. These stocks are proportional to the amount of greenhouse gas emission when forests are converted to other uses (e.g., Fearnside 2016), and the emissions are therefore proportional to impact on global climate (IPCC 2013).

The importance of studies in southern Amazonia extends far beyond the limits of this subregion. Land-use changes in southern Amazonia represent processes that can be expected to expand to other parts of Amazonia if the trends seen over the past years continue (Fearnside 2008a, 2015). Southern Amazonia is the first portion of the region to face intense and large-scale deforestation and forest degradation (e.g., Egler et al. 2013) (Fig. 2); it serves therefore as a bellwether for what spread of these processes would bring to other parts of Amazonia if current trends continue. The amounts of carbon involved are uncertain, and improvement in estimates is a high priority to provide the information needed as a basis for public policies affecting the future course of development in Amazonia. Despite uncertainty, knowledge is amply sufficient to justify actions to avoid deforestation.

Electronic supplementary material The online version of this article (doi:10.1007/s10113-016-1007-2) contains supplementary material, which is available to authorized users.

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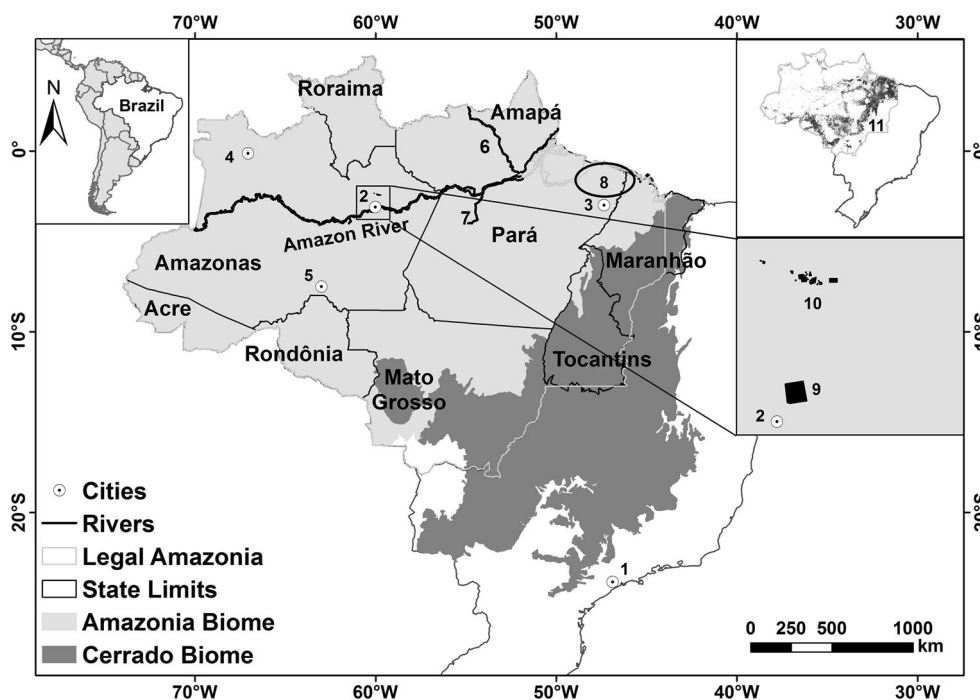


Fig. 1 Brazil and Brazilian Amazonia with locations mentioned in the text. Cities: (1) São Paulo, (2) Manaus, (3) Paragominas, (4) São Gabriel da Cachoeira, (5) Humaitá; Other: (6) Jari River, (7) Curuá-Una River, (8) Zona Bragantina, (9) Ducke Reserve, (10) Biological Dynamics of Forest Fragments Project (BDFFP), (11) arc of deforestation. “Southern Amazonia” refers to the states of Rondônia, Mato Grosso, Tocantins, Maranhão, and the southern half of Pará. “Legal Amazonia” is an administrative region in Brazil

encompassing all or part of nine states; 26 % of Legal Amazonia is *cerrado* (savanna) rather than forest. Brazil also officially divides its territory into biomes, based on the predominant original vegetation. The “Amazonia biome,” represents Amazonian forest, although it includes some enclaves of non-forest vegetation. The term “Brazilian Amazonia” is used when the distinction between Legal Amazonia and the Amazonia biome is not necessary

Development in biomass estimation to date

Primary forest aboveground live biomass

Improving ground-based measurements

Forest biomass is a key factor in determining the magnitude of greenhouse gas emission from tropical deforestation, as the carbon stock is directly proportional to the biomass. Improvements in biomass stock estimates continue to be made through remote sensing, through better interpretation of existing forest surveys and through on-the-ground studies.

Where detailed forest volume and biomass estimates have been made for closely spaced plots in a single forest type, such as the 65 1-ha plots in the botanical survey of the Biological Dynamics of Forest Fragments Project (BDFFP) near Manaus, the wide variance in biomass at the level of 1-ha plots is evident. In this case, the coefficient of variation (CV) was 13.2 %, with mean aboveground live biomass of $356 \pm 47 \text{ Mg ha}^{-1}$ for all trees, based on measurements for trees $\geq 10 \text{ cm DBH}$ (diameter at breast height: diameter at 1.3 m above the ground or above any

buttresses) with a 12 % correction for small trees (Laurance et al. 1999). In 72 1-ha plots in the Ducke Reserve, also near Manaus, the CV was 12.8 %, with mean aboveground live biomass for trees $\geq 1 \text{ cm DBH}$, which allows as few as three 1-ha plots to provide an estimate with a mean value within 10 % of the true mean (considering a 95 % confidence interval), indicating the priority for surveys at widely spaced locations, each with only a small numbers of plots (Nascimento and Laurance 2002). Note that plots smaller than 1 ha, which are not uncommon in forest biomass studies, would have higher variance (Clark and Clark 2000).

Quantifying local variation represents a different problem from quantifying large-scale variation, which is driven by different factors. To improve large-scale assessment of aboveground biomass, the key challenge is to sample well over the vast spatial extent of the region, not to replicate mainly locally. Clearly, a large sample size is needed for this purpose.

Progress has been made in improving allometric equations for interpreting existing forest surveys, such as RADAMBRASIL. Particularly important are improvements for the forests in the “arc of deforestation,” or the

crescent-shaped strip along the southern and eastern edges of the Amazon forest biome where deforestation activity has been concentrated since 1970 (Fig. 2). Previously, the volume of wood in trees and the conversion to biomass in all of Amazonia were calculated based on measurements taken in the Manaus area in central Amazonia (e.g., Higuchi et al. 1998). However, new measurements in Southern Amazonia's arc of deforestation indicate 13.6 % lower biomass there than that calculated using the parameter values from central Amazonia (Nogueira et al. 2007). Trees in the arc of deforestation have significantly lower wood density than those in central Amazonia, not only from the species composition of the forest but also with lower basic density of wood for individuals from the same species (Nogueira et al. 2007). "Basic" density is the oven-dry weight divided by the wet volume, which is the most appropriate density measure for converting forest volume data to biomass (Fearnside 1997b). Part of the difference comes from lower wood density as a result of greater pore volume, which leads to higher water content: the wood in the arc of deforestation has 3–4 % higher water content as compared to wood in central Amazonia, meaning that some of what was previously being counted as biomass was actually water (Nogueira et al. 2008b). In addition, trees in the arc of deforestation are shorter for individuals of any given diameter, resulting in further overestimation of biomass (by 3.6–11.0 %) when central Amazonian allometric equations are applied to these forests (Nogueira et al. 2008c). The importance of tree height extends to biomass estimates throughout the tropics, and incorporation of this parameter in allometric equations for forest biomass lowers estimated pantropical deforestation emissions by 13 % as compared to using equations based solely on diameter (Feldpausch et al. 2011, 2012; see also: Chave et al. 2014). Wood density of tropical trees and its effect on biomass have been extensively reviewed by Chave et al. (2006).

One important factor with little data is the multiplier used to represent the biomass of tree crowns (the "biomass expansion factor," or BEF). Most existing estimates of Amazonian biomass have used values for this parameter derived from early unpublished data from Venezuela by Jean-Pierre Veillon (after Brown and Lugo 1992). However, weighing the entire aboveground portion of 267 trees in the arc of deforestation showed that the values from Venezuela overestimated this component by 6 %, resulting in overestimates of total aboveground live biomass by percentages ranging from 3.6 to 11.0 % for forest types in the arc of deforestation (Nogueira et al. 2008a). The Venezuelan data by Veillon have been essential to many studies of Amazonian forests, but doubts concerning how the trees were measured have proved impossible to resolve: see the dispute between Clark (2002) and Phillips et al. (2002). One solution has been to remove these data from

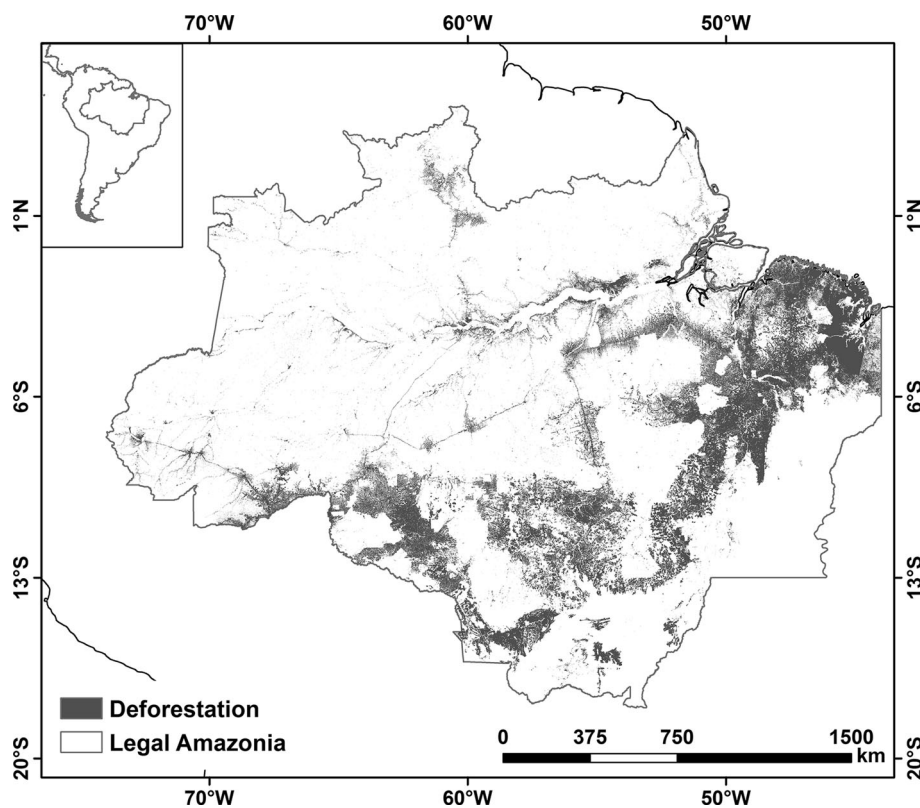
analyses of Amazonian forest dynamics (Lewis et al. 2004). Nevertheless, aside from the BEF measurement by Nogueira et al. (2008a), Veillon's estimate reported by Brown and Lugo (1992) is the only other known value for this important biomass parameter. Estimates of BEF are needed to represent the range of forest types in Amazonia. A promising possibility is use of airborne and ground-based LiDAR, which are able to measure the dimensions of branches in the crowns of standing Amazonian trees (e.g., Figueiredo 2014).

Since the RADAMBRASIL surveys do not include small trees, the biomass in these trees must be estimated by multiplying the biomass in the larger trees by a multiplier derived as the ratio between small- and large-tree biomass from sites where both have been measured. Small trees are divided into two diameter groups, each with a separate multiplier. The first multiplier represents trees with diameters between 10 cm and the lower limit of the forest volume surveys, such as the 31.8-cm DBH lower limit for RADAMBRASIL data. Early estimates mistakenly omitted the 30- to 31.8-cm DBH range (see: Fearnside 1992). Aside from this problem, new data from the arc of deforestation indicate that the volume expansion factor (VEF) used for tree boles in this diameter range (e.g., from Brown and Lugo 1992) underestimates this component by 25 % in the arc of deforestation (Nogueira et al. 2008a).

The second small-tree multiplier represents biomass in trees <10 cm DBH. Again, a value from Venezuela (12 % of aboveground live biomass: Jordan and Uhl 1978) has been widely used in Brazilian Amazonia. Now, measurements in 72 1-ha plots located >1000 m from a forest edge and spread over a 64-km² area in the Ducke Reserve, near Manaus, indicate that trees ≥ 1 cm and <10 cm DBH represent only 6.1 ± 1.8 % of aboveground live biomass in living trees, including palms (de Castilho et al. 2006), while in 56 1-ha plots located >300 m from the nearest forest-pasture edge spread over a 1000-km² area in the BDFFP reserves, also near Manaus, this percentage is 5.4 % (Nascimento and Laurance 2002). In terms of total live aboveground biomass, these estimates represent a reduction of approximately 5.5 % as compared to those using the values from Venezuela.

Lianas and other non-tree life forms have been omitted from a number of Amazonian biomass studies, and studies often fail to report what components are included. Standardization for non-tree components, together with trees <10 cm DBH, removes almost all of the difference between aboveground live biomass estimates by Fearnside (1997a), Houghton et al. (2001) and Malhi et al. (2006) (see review in: Malhi et al. 2006, pp. 1120–1121). The importance of lianas, palms, bamboo, and other non-tree components varies greatly in different parts of the region (Online resources: Table S1).

Fig. 2 Deforestation by 2014 (PRODES data from Brazil, INPE 2015). The curved band of heavy deforestation on the eastern and southern edges of the forest is known as the “arc of deforestation”



Biomass studies of Brazilian savanna woodlands (mostly *cerrado*), including those in Amazonia, have recently been reviewed by de Miranda et al. (2014). These authors review 26 studies at 170 sites and emphasize the contrast between the amount of available data and what has been used in global carbon computations, pointing out that the estimate by Saatchi et al. (2011) used only one study at two savanna woodland sites in Brazil. For Brazil as a whole, the review by de Miranda et al. (2014) calculates an average aboveground carbon stock of $37.4 \text{ Mg C ha}^{-1}$ in savanna woodlands classified as “forestland” (34.4 % of the total savanna woodland area), and $11.5 \text{ Mg C ha}^{-1}$ in those classified as “shrublands” (65.6 % of the area), giving a weighted average of $20.4 \text{ Mg C ha}^{-1}$. For grasslands, aboveground biomass averaged 7.2 Mg C ha^{-1} [i.e., roughly 3.6 Mg C ha^{-1}].

Improving interpretation of aboveground biomass data

Measurement of biomass density (biomass per hectare) in tropical forests from satellites is still unsatisfactory. Remote sensing has advantages over strictly ground-based estimates by providing “wall-to-wall” coverage of the entire region and by reflecting biomass of the current state of the forest, including its degradation from logging, windthrows, fires, and other disturbances. The reliability of remote sensing estimates is generally limited by the

number, representativeness, and reliability (especially as related to very small plot sizes) of ground-based measurements used to calibrate the remotely sensed data.

The limitation of a minuscule number of ground locations is evident for satellite studies, as well as for studies based on interpolation between ground-based plots (Table 1). Here, “distinct locations” refer to sites reported with nonidentical geographical coordinates (those reported with identical coordinates are lumped in calculating the “plot area”). The representativeness of these samples is even less than that implied by the number of “distinct locations,” since many of these are highly clustered (Fig. 3). The limited representativeness is critical in assessing an area roughly the size of Western Europe with a diverse array of forest types.

Table 1 and Fig. 3 show the contrast in terms of the amount and representativeness of ground-level information between different studies. Studies making use of the RADAMBRASIL surveys have a great advantage in terms of ground data (e.g., Nogueira et al. 2008a, 2015). This is also true of earlier interpretations of this dataset based on fewer plots and a more coarse-scale vegetation map (Fearnside 1994, 1997a). The RADAMBRASIL surveys were carried out from the late 1950s to the early 1970s using side-looking airborne radar imagery combined with 1-ha ground plots at approximately 3000 points, often reached by helicopter (de Lima 2008). The 1:–250,000 and

Table 1 Numbers of sample plots for “primary” forests in Brazilian Amazonia used in regional biomass estimates

Study type	References	Plot area ≥1 ha	Plot area <1 ha	Plot area unknown	Total distinct locations	Note
Studies based on interpolation between ground-based plots	Houghton et al. (2001)	16	7	5	28	a
	Malhi et al. (2006)	44	0	0	44	
Studies based on satellite imagery calibrated from ground-based plots	Saatchi et al. (2007)	28	20	5	53	a,b
	Saatchi et al. (2011)	63	28	5	96	a,b
	Baccini et al. (2012)	0	?	0	?	c
Studies based on vegetation map (from airborne radar and direct observation) and biomass by vegetation type from ground-based plots	Nogueira et al. (2008a, b, c)	2879	0	0	2879	
	Nogueira et al. (2015)	2317	0	0	2317	

^a Includes five studies with unknown sample areas (all small areas or line intersect sampling studies that are not area based)

^b Includes one study with location unknown

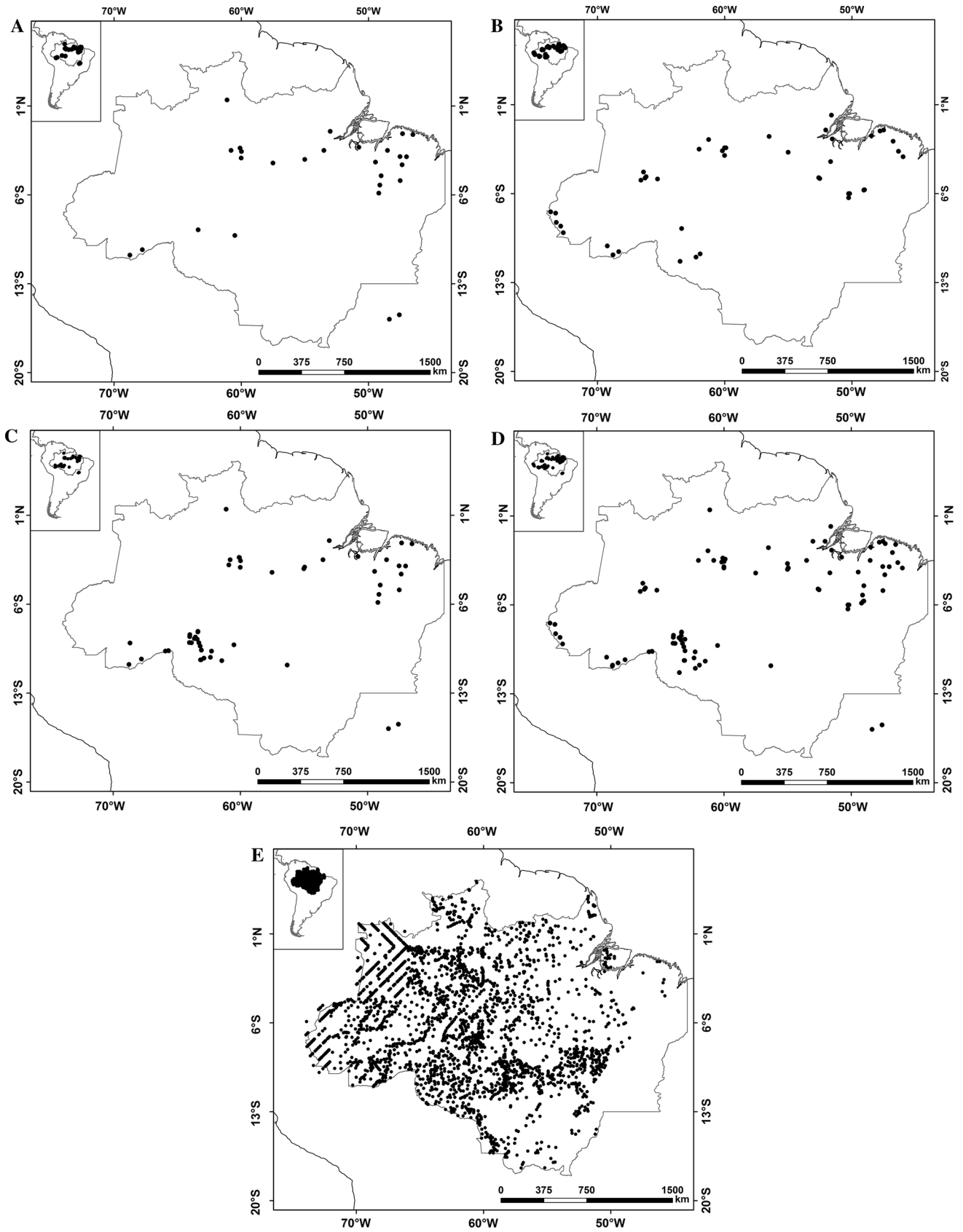
^c Baccini et al. (2012) do not report the countries or locations of their 283 0.16-ha plots distributed throughout the African, Asian, and Latin American tropics

1:1,000,000 scale RADAMBRASIL vegetation maps were developed through extensive on-the-ground and airborne observation and through visual interpretation of the high-resolution radar imagery (Brazil, Projeto RADAMBRASIL 1973–1983). Use of the RADAMBRASIL surveys has been daunting to many research groups: the reports are a vast labyrinth of over 50,000 pages, written in Portuguese and historically with limited availability at any single location. However, ignoring this enormous body of work represents a loss that is not easily compensated for by applying more sophisticated remote sensing interpretation to a small set of ground-based plots.

Saatchi et al. (2007) used tree-diameter data to derive statistical relationships between the biomass at ground-based sites and a variety of spectral characteristics. The resulting relationships were then applied to the imagery from the region as a whole to estimate the biomass in each pixel. The analysis associated aboveground live biomass in the plots with a set of 19 metrics derived from satellite data for 1 km² pixels at the plot locations. Of the 15 metrics, 9 were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS): 4 for Normalized Difference Vegetation Index (NDVI), 4 for Leaf Area Index (LAI), and 1 for percent tree cover. The remaining metrics were derived from different kinds of radar: 4 metrics were derived from the Quick Scatterometer (QuikSCAT): measures of backscatter; 4 metrics were derived from Japan Earth Resources Satellite (JERS-1) data: 2 for backscatter and 2 for the coefficient of variation of the texture measure; 2 metrics were derived from Shuttle Radar Topography

Mission (SRTM) data: mean elevation and “ruggedness factor.”

The Saatchi et al. (2007) study's restriction to only 53 distinct locations for ground-based information on primary forests in Brazil, with almost half having a sample area <1 ha or unknown, is particularly limiting. Saatchi et al. (2011) increased the ground data to 96 distinct locations in Brazilian Amazonia's primary forests. The analysis used space-borne LiDAR (Light Detection and Ranging) from the US National Aeronautics and Space Agency (NASA) Geoscience Laser Altimeter System (GLAS) on the Cloud and Land Elevation Satellite (ICESat), together with optical data from MODIS imagery and radar data from the Global Quick Scatterometer (OSCAT). Baccini et al. (2012) used space-borne LiDAR from GLAS together with ICESat and MODIS imagery. All of these studies represent advances in interpretation of remote sensing data, but remain limited by their datasets for ground truth. Mitchard et al. (2014) contrasted the spatial results of the Saatchi et al. (2011) and Baccini et al. (2012) remote sensing studies, as well as the geographical information system (GIS) analyses derived directly from plot data by Houghton et al. (2001), Malhi et al. (2006) and their own analysis of RAINFOR (Amazon Forest Inventory Network) plots (e.g., Phillips et al. 2009). The results show major differences between all of the resulting maps, including those with largely overlapping ground-based datasets. Expanding the network of ground-based inventories is essential. The way forward will require using remote sensing data together with ground-based measurements, with progress needed in both areas.



◀ **Fig. 3** Distribution of “distinct locations” of plots used in different biomass studies (see Table 1). A = Houghton et al. (2001). B = Malhi et al. (2006). C = Saatchi et al. (2007). D = Saatchi et al. (2011). E = Nogueira et al. (2008a)

Belowground biomass

Belowground biomass (Online resources: Table S2) remains one of the areas of greatest uncertainty in biomass and emissions estimates. The response to high uncertainty of belowground estimates of simply ignoring this component by counting only aboveground biomass leads to misleading estimates. On the strength of being “uncertain,” belowground biomass and change in this stock were ignored in Brazil's first national inventory under the United Nations Framework Convention on Climate Change (UNFCCC), better known as the “climate convention” (Brazil, MCT 2004, p. 146). Uncertain as estimates for this component may be, effectively using a value of zero rather than the best available estimates introduces an obvious error into overall estimates of Amazonian carbon stocks and greenhouse gas emissions from deforestation (see: Fearnside 2013a).

Belowground biomass was included in Brazil's second national inventory by assuming that Amazonian forests have 27.1 % of their biomass in this component (Brazil, MCT 2010, p. 235). This is based on a measurement at a single site located in an upland (*terra firme*) forest (IBGE code: Db; Brazil, IBGE 2012) near Manaus (da Silva 2007). Roots >2 mm in diameter were separated and weighed in 11 quadrats each measuring 10 × 10 m (0.11 ha total); of these, 2 quadrats were excavated to 1.5 m depth and 9 to 1.0 m depth (da Silva 2007, pp. 32–34). Taproots were pulled mechanically from soil below the excavation limit, using levers tied to the stumps. Trunks, branches, and leaves from 131 trees (DBH ≥ 5 cm) in the quadrats were weighed, and the aboveground and belowground biomasses totaled for each tree.

Fearnside (1994) calculated a mean of 23.7 % for this parameter based on estimates for Manaus (33.4 %), Jari (19.8 %) and Paragominas (15.2 %), which were derived from existing studies (Klinge et al. 1975; Klinge and Rodrigues 1973; Russell 1983, p. 29; Uhl et al. 1988, p. 670; see Supplementary Online Material, Table S2), complemented by information on underground boles from D.C. Nepstad (Pers. Comm.; see: Fearnside 1994, p. 111). In a global review of root biomass, Cairns et al. (1997) found tropical forests (including secondary forests) to have a mean root/shoot ratio of 0.24 ± 0.14 ($n = 39$), this mean corresponding to 19.4 % belowground.

Roots of an ecotone (“contact”) (IBGE code: LO) between forested shade-loving *campinarana* (woody

oligotrophic vegetation of swampy and sandy areas) and rain forest near São Gabriel da Cachoeira, Amazonas were weighed by Lima et al. (2012). This forest had an aboveground live biomass of 222.3 ± 21.1 Mg ha⁻¹, and a belowground biomass of 30.7 ± 20 Mg ha⁻¹, yielding a root:shoot ratio of 0.138 (i.e., roots represented 12.4 % of the total aboveground + belowground biomass). For three types of treed savannas in Roraima, Barbosa et al. (2012) found the corresponding percentages to range from 7.5 to 16.7 % for roots ≥ 2 mm in diameter.

The review by de Miranda et al. (2014) of savanna woodlands in Brazil as a whole calculates an average carbon stock in belowground biomass of 8.4 Mg C ha⁻¹ in savanna woodlands classified as “forestland” (root/shoot ratio of 0.22, or 18.3 % belowground). Belowground biomass carbon stock in savanna woodlands classified as “shrublands” is calculated at 15.8 Mg C ha⁻¹ (root/shoot ratio of 1.37, or 57.9 % belowground). The weighted average by area for belowground biomass carbon in “forestland” and “shrubland” savanna woodlands is 13.3 Mg C ha⁻¹, and the root/shoot ratio is 0.65, or 35.6 % belowground. For grasslands, belowground biomass averaged 16.7 Mg ha⁻¹ [i.e., roughly 8 Mg C ha⁻¹], and the root/shoot ratio averaged 2.3, or 70.0 % belowground. The importance of including roots is evident.

Necromass (dead biomass)

Necromass, or dead biomass, is also important to greenhouse gas emissions from deforestation. This is often omitted from estimates of deforestation emissions on the strength of the linguistic fine point of necromass not being considered as “biomass” (e.g., Brazil, MCT 2004, p. 136; note: Brazil, MCT 2010, p. 235 included a 3 % adjustment for litter). The carbon contained in necromass is also released by deforestation, and each ton causes just as much climatic damage as a ton of carbon coming from live biomass. Necromass in undisturbed forests has been measured at an increasing number of sites (Online resources: Table S3). The stock of necromass varies across the Amazon region as a whole (including areas outside of Brazil), with the highest stocks being found in the north-eastern corner of the region and the lowest in the north-western corner (Chao et al. 2008, 2009). At this scale, there is a significant positive relationship between aboveground live biomass and necromass stock (Chao et al. 2009). However, an extensive survey of necromass on a north-south transect from the Manaus area to Humaitá found no relation to aboveground live biomass, differences in necromass stocks being explained instead by soil quality and other limitations on site quality for tree growth (Martins et al. 2014). In a pantropical review, Palace et al. (2012) found that undisturbed forests had a peak of

necromass in the middle range of aboveground live biomass values, with less necromass in both high- and low-biomass forests.

Necromass stocks increase in forests subject to disturbances such as extreme climatic events, fire, and logging. Calculations based on observed long-term increases in tree mortality rates in the RAINFOR network of 321 permanent plots indicate that approximately 3.8 PgC has been left in necromass in Amazonian forests since 1983, or a 30 % increase in these stocks (Brienen et al. 2015, p. 346). Increases in this magnitude should be directly observable, but monitoring of necromass is rare. The RAINFOR plots are exposed to droughts, but not to logging and fire. Understory fires are increasingly common in Amazonia, resulting in substantial transfers from living to dead biomass pools (e.g., Balch et al. 2008; Barlow et al. 2003; Haugaasen et al. 2003; Vasconcelos et al. 2013). Logging has a similar effect, in addition to increasing the risk of fire (e.g., Barlow and Peres 2006; Berenguer et al. 2014; Gerwing 2002; Keller et al. 2004). A recent study in Malaysia has drawn attention to the worldwide underestimation of tropical forest emissions by ignoring necromass (Pfeifer et al. 2015).

Implications of biomass uncertainties

The large areas of annual deforestation, with most deforestation occurring in the relatively poorly studied arc of deforestation, mean that small percentage differences in biomass estimates for this part of the region translate into large amounts of greenhouse gas emission. For example, just the adjustment for lower wood density in the arc of deforestation resulted in a $23.4\text{--}24.4 \times 10^6$ Mg CO₂-equivalent C year⁻¹ reduction in the estimated emission for 1990, when 13.8×10^3 km² was deforested in the Brazilian Legal Amazon (Nogueira et al. 2007). This is approximately double the current annual emission of metropolitan São Paulo (e.g., COPPE 2005). The biomass map of Brazilian Amazonia incorporating these improvements (Nogueira et al. 2008a) provides the basis of recent emissions estimates for the region (Aguiar et al. 2012).

Future prospects for measuring primary forest biomass

Technology is advancing rapidly in areas that can provide greatly improved estimates of forest biomass. LiDAR (light detection and ranging) is able to produce accurate three-dimensional representations of individual trees, including branches and irregularities, thus allowing much greater accuracy in quantifying the volume of wood present in aboveground biomass. LiDAR can measure the morphology of the crowns from airborne platforms, including

pilotless aircraft (drones), while instruments recording data from a sequence of points on the ground can produce composite images of the trunks that are more accurate than manual measurements even for traditional parameters such as diameter at breast height (DBH). Airborne LiDAR transects arranged in a top-down sampling design have produced promising results in Colombian Amazonia (Asner et al. 2012).

Radar backscatter is another avenue for improving biomass estimates (Saatchi et al. 2011; Woodhouse et al. 2012). This can be used from satellites and is advancing as a means of estimating tropical forest biomass. Space-borne LiDAR is also advancing as a biomass estimation technique (Goetz et al. 2009). However, the major spatial inconsistencies between the Saatchi and Baccini maps that both used space-borne LiDAR indicate the need for further progress in interpreting LiDAR data (Saatchi et al. 2011; Baccini et al. 2012; see: Mitchard et al. 2014).

For forest monitoring on the ground, prospects are improved by the recent discovery from the RAINFOR plot series, where only 1 % of tree species account for 50 % of Amazon forest biomass due to “hyperdominance” (Fauset et al. 2015). This raises the possibility of significant gains in understanding of biomass and associated biogeochemical processes by concentrating research on these species.

Secondary forest

The rate of secondary forest regrowth varies widely depending on the age of the stand, initial soil quality, and the land-use history of the site (especially use as pasture), among other factors (Online resources: Table S4). Realistic estimates of carbon uptake at a regional level are therefore highly dependent on appropriate weighting of the data on growth rates in accord with the spatial extent of secondary forests of each type. Particularly critical is the dichotomy between those derived from degraded cattle pasture versus slash-and-burn agriculture (Fearnside 1996; Fearnside and Guimarães 1996). Since secondary forests grow much more slowly in abandoned pasture than in shifting cultivation fallows, the fact that most existing studies of tropical secondary forests have been done in shifting cultivation fallows whereas the vast majority of deforested areas in Brazilian Amazonia is pasture means that calculating carbon uptake at a regional level requires care in either making separate calculations for each land-use history or properly weighting the growth rates by the proportion of each. Studies in the easily measured but highly atypical secondary forests surrounding the BDFFP reserves north of Manaus have indicated higher growth rates than in areas with typical use histories. The areas around the BDFFP reserves were abandoned prematurely as a result of

cessation of subsidies for the ranches rather than because of the more common circumstance where a decrease in pasture productivity motivates abandonment to secondary succession (see: Fearnside 2013a).

Estimates of the extent of secondary forest in deforested portions of Brazilian Amazonia are presented in the Online Resources (Table S5). The very low values used in Brazil's second communication to the Climate Convention are unexplained (Brazil, MCT 2010, p. 242). Not all of the variation in values is the result of differences in methodology: a real reduction has occurred in the percentage of the deforested area that is in degraded pasture and secondary forest in recent years as compared to the 1980s (see: Fearnside 2013a).

Although many estimates are not explicit in defining "secondary forest," the estimates in Table S5 can all be assumed to refer to relatively recent stands, that is, since the modern age of deforestation began with the opening of the Transamazon Highway in 1970. They do not include "old" secondary forest ("*capoeirões*") in the Zona Bragantina of Pará and in Maranhão, many of which have been recovering since the "rubber boom" in the late nineteenth and early twentieth centuries when these areas were cleared to produce manioc and other agriculture products. These areas are considered as "deforested" in INPE's PRODES data (Brazil, INPE 2015). The area of "old" secondary forest was estimated at $71.3 \times 10^3 \text{ km}^2$ in 1990 (Fearnside 2000a), and most of it has since been recleared.

Brazil's first national inventory of greenhouse gas emissions claimed that secondary forests in Amazonia were absorbing $34.9 \times 10^6 \text{ Mg C year}^{-1}$ over the 1988–1994 period (Brazil, MCT 2004, p. 147). The assumptions that underlie this high estimate have been contested (Fearnside and Laurance 2004). Recent measurements of secondary forest growth rates have confirmed slower growth than was assumed (e.g., Wandelli and Fearnside 2015). Brazil's second national inventory implies net annual accumulation of 8951.4 Gg C ($9.0 \times 10^6 \text{ Mg C year}^{-1}$) over the 1994–2002 period (Online resources: Table S6). The average age of secondary forests in the inventory is 4 years, and the growth rates presumed are $10.1 \text{ Mg C year}^{-1}$, a rate 2.7 times that measured for regrowth after slash-and-burn agriculture and 4.4 times higher than that measured after use as cattle pasture (Wandelli and Fearnside 2015, p. 147). Weighted by the areas of secondary forest derived from pasture (91.4 %) and agriculture (8.6 %), the inventory growth rates average 4.1 times greater than similarly weighted rates measured in Amazonian secondary forests with these two use histories under typical conditions. Even in atypically favorable conditions, growth rates do not approach those assumed in the official estimate.

Secondary forests are a significant factor in the accounts for Brazil's national emissions. The absolute value of the

overestimate in the second national inventory is $6.8 \times 10^6 - \text{Mg C year}^{-1}$ (Wandelli and Fearnside 2015), which is equivalent to 8.3 % of the country's fossil fuel emissions in 2005 (Brazil, MCT 2010, p. 270). This unreported land-use change emission approaches the scale of the fossil fuel emission from metropolitan São Paulo, which represents 10 % of Brazil's population and presumed fossil fuel emission. São Paulo, with a population of over 20 million, is much larger than any metropolitan area in either Europe or the USA.

Soil carbon

Forest carbon is contained both in the biomass and in the soil. In the 1970s, the RADAMBRASIL project collected soil profiles at approximately 3000 points scattered (unevenly) throughout Brazilian Amazonia (Brazil, Projeto RADAMBRASIL 1973–1983). These data have been analyzed by Moraes et al. (1995), with weighting by the area of the different soil types in order to generate an estimate of the soil carbon stock in the top 1 m of soil under the original vegetation in the $5 \times 10^6 \text{ km}^2$ Brazilian Legal Amazon region. The total is 47 PgC (PgC = petagrams of carbon = 10^{15} gC = gigatons of carbon = billion Mg C), or an average of 94 Mg C ha^{-1} . Uncertainty is high with the standard error equal to 24.5 % of the mean (Cerri et al. 2000, p. 38). Various improvements are needed to obtain more reliable estimates of regional stocks of soil carbon (Sombroek et al. 2000). The top 20 cm contains 21 PgC (or 42 Mg C ha^{-1}), which represents 45 % of the carbon in the top meter of soil (Moraes et al. 1995).

Soil carbon is not limited to the top 1 m that is included in the Moraes et al. (1995) estimate. Trumbore et al. (1995) have studied soil carbon stocks to 8 m depth at Paragominas, Pará. The layers between 1 and 8 m depth there contain 155 Mg C ha^{-1} , or 152 % of the stock at the same site in the 0–1 m depth range. Assuming proportionality for the remainder of the region, the deep soil contains an additional 71 PgC, making the total stock to 8 m 276 Mg C ha^{-1} , or 138 PgC in Legal Amazonia.

The stability of the soil carbon is critical to changes when forest is cleared or undergoes other disturbances. Carbon stability affects both the total (equilibrium) carbon stock and the rate of change (i.e., the stocks in the transient states as the new equilibrium is approached). Trumbore et al. (1990, p. 411) estimated a labile (hydrolysable) soil carbon stock of 54 Mg C ha^{-1} and a refractory (non-hydrolysable) soil carbon stock of 106 Mg C ha^{-1} in the top 60 cm of a typical Amazonian Ultisol from the Curuá-Una River area in Pará studied by (Sombroek 1966, p. 244). The 60–150 cm layer contained an additional 36 Mg C ha^{-1} of labile and 40 Mg C ha^{-1} of refractory carbon. The so-called refractory soil carbon belongs to a "slow-turnover" carbon pool that is

often assumed to have no turnover at all. However, this pool does, in fact, turn over at an appreciable rate, even in the deep soil, and could therefore represent substantial carbon emissions because of the slow pool's great size in Brazilian Amazonia. Trumbore et al. (1995, p. 527) estimated a turnover time of <25 years for the entire soil carbon pool from 0 to 8 m depth under pasture.

The classic division of soil organic matter into categories as “labile” versus “recalcitrant” or “fast turnover” versus “slow turnover” has been criticized as hiding important properties of what is really a continuum (Lehmann and Kleber 2015). The soil contains a mixture of organic molecules of different sizes and with different properties relevant to their rate of oxidation, such as their association with soil minerals that can protect the organic molecules from the action of microorganisms. The molecular composition of organic matter varies with its source and is summarized in indices of organic matter “quality,” reflecting the ease with which it is decomposed. Among the factors affecting the amount and activity of soil microbiota is the soil's humidity and the interactions of humidity with temperature. All of these are important areas for research in modeling carbon release from soils (Lehmann and Kleber 2015). Climate change is expected to affect both temperature and humidity, with longer and more severe droughts together with higher temperatures in Amazonia, especially southern Amazonia (Fu et al. 2013; Marengo and Espinoza 2016). Slow-turnover soil organic matter is more sensitive to release under warming than is fast turnover organic matter (Conant et al. 2008; Craine et al. 2010; Davidson and Janssens 2006). In Amazonian soils, the fast turnover organic matter is concentrated near the soil surface (de Marques et al. 2015), which is where increases in soil temperature are greatest when forests are cleared, and this would also be the layer undergoing the greatest effects of climate change. After deforestation, changes in soil organic matter depend heavily on management, with a variety of techniques resulting in enhanced organic matter retention (e.g., Fujisaki et al. 2015; Maia et al. 2009, 2010; Perrin et al. 2014). Nevertheless, the dominant land use in Brazilian Amazonia continues to be cattle pasture with minimal management (Fearnside 2005). Conversion of forest to pasture results in soil compaction, thereby increasing bulk density and the mass of soil (and carbon) that will be found in samples to any given depth; valid comparisons of soil carbon stocks in pasture versus forest therefore require comparisons on the basis of equal mass of soil rather than equal volume, and these indicate substantial losses of soil carbon under typically managed pastures (Fearnside and Barbosa 1998).

Increase in temperature through global warming could destabilize a part of the soil carbon pool. Temperature increases have a greater effect on speeding release of slow

carbon pools than on labile carbon (Bellamy et al. 2005). This is because the sensitivity of reaction rates to changes in temperature (the Arrhenius function) is greater for reactants with higher activation energies, that is, for those that are less reactive or more recalcitrant (Davidson and Janssens 2006). The amounts of carbon involved make release a significant concern both for deforestation impacts (Fearnside and Barbosa 1998) and as a possible impact of global warming, contributing to a positive feedback mechanism (Davidson and Janssens 2006; Fearnside 2010; Schulze and Freibauer 2005; Townsend et al. 1992).

Environmental services

Maintenance of the carbon stocks in Amazonia avoids global warming and therefore provides a valuable environmental service. Amazon forest also recycles an enormous amount of water: annual evapotranspiration is estimated to total $8.4 \times 10^{12} \text{ m}^3$, which is more than the Amazon River's annual discharge to the Atlantic Ocean of $6.6 \times 10^{12} \text{ m}^3$ (Salati 2001). Approximately, $3.4 \times 10^{12} \text{ m}^3$ is transported as water vapor to other regions (Fearnside 2004), about half of this making the “curve” to the south from Amazonia (Correia et al. 2006). Brazil's Southeastern region (including São Paulo) and neighboring countries are major recipients of this transport (Arraut et al. 2012). The La Plata Basin is estimated to depend on water–vapor transport from Amazonia for 70 % of its annual total precipitation (van der Ent et al. 2010), and this water source is especially dominant in the Austral summer (Zemp et al. 2014). Water transport therefore represents a second important category of environmental service. A third is maintenance of biodiversity, with multiple utilitarian and non-utilitarian values (Fearnside 1999). The value of these environmental services represents a potential alternative basis for sustaining the rural population in Amazonia by maintaining the forest rather than destroying it (Fearnside 1997c, 2008b). The value of the forest for avoiding global warming is the closest to providing appreciable monetary flows, but the institutional mechanisms by which this goal could be achieved are still the subject of ongoing unresolved controversies (Fearnside 2012, 2013b). The magnitude of Amazonia's carbon stocks provides a powerful reason for resolving these controversies without delay.

Beyond the numbers: Amazon biomass in policy decisions

Policy decisions are made in the context of negotiations, either formal or informal. Academic discussions of biomass numbers provide one of the inputs to decisions on

mitigating global warming and on Amazonian conservation and development priorities. Understanding the significance of the numbers requires acknowledging other components of these decisions, which potentially affect billions of dollars in monetary flows and the direction of development policy in Amazonia.

While levels of uncertainty have a place in rational choices among mitigation options (Fearnside 1995, 2000b), they also play an important role in negotiated accords that try to balance the divergent interests of the parties involved. A question such as the role of deforestation in global greenhouse gas emissions is composed of various components, such as the rate of deforestation (or amount of avoided deforestation) and the biomass of the forest being cleared. Unrealistic estimates for different components may be proposed by two sides with biases in opposite directions. Unrealistic estimates for different components may be accepted in the interests of achieving agreement, but with the final result being perceived as reasonable because the biases cancel each other out. A classic case was the estimate of 1.6 Pg of carbon (Gt C) as the global annual emission from land-use change used in the IPCC's First Assessment Report (Watson et al. 1990, p. 11). The number was agreed in a Beijing hotel room at 3:00 am local time in a discussion between Robert Watson and Gylvan Meira Filho. Key elements were a value included in the calculation of Amazon forest biomass (Brown and Lugo 1984) that was about half the level of modern estimates and a value for the rate of Amazonian deforestation by Norman Myers (e.g., Myers 1989, 1991) that was about double the currently accepted rates for the period (see Fearnside 1990, 1994, for reviews of controversies on biomass and deforestation rates at the time). The Beijing hotel room accord has been described by both parties in public fora (personal observation). Such informal understandings hold a danger if subsequent revisions change one unrealistic component but not the component or components that offset its bias. It is not only important that the final result be realistic, but also that it be so for the right reasons (Fearnside 2001).

Although there are no comparable firsthand accounts, a similar sort of informal understanding between parties appears to apply today to the Amazon forest biomass assumed in calculating carbon benefits from avoiding deforestation. The Amazon Fund (*Fundo Amazônia*) was established in 2008 to receive money from other countries for purposes of avoiding deforestation and emissions in Brazil, especially the US\$1 billion offered by Norway for payment through 2015 based on progress in reducing emissions. The reductions in emissions calculated by the fund assume that net emission from Amazonian deforestation is 100 Mg C ha⁻¹. This value was deliberately chosen to be conservative (Brazil, MMA 2008, p. 8), and

high uncertainty in biomass estimates due to lack of data for parts of Amazonia was presented as a justification for assuming the low value. In this author's opinion, adopting an explicitly conservative value may be thought of as a sort of "gentlemen's agreement," where the underestimate of per hectare emission reductions that is implicit in the fund's calculations will offset the overestimate implicit in accepting the claim that all of the decline in deforestation since the high rates that prevailed in the 1996–2005 baseline period is additional to what would have occurred in the absence of governance measures. In fact, a substantial part of the slowing of deforestation is not additional because slower deforestation is explained by lower commodity prices rather than by government measures for the period up to 2008, which represents most of the total decline through 2015 (data in: Assunção et al. 2015; see: Fearnside 2016; Fearnside et al. 2014). In 2014, Brazil reevaluated biomass estimates for calculating the emissions benefit of each hectare of avoided deforestation in Amazonia (e.g., Brazil, MMA 2014a, b). Since the revised net emission per hectare is, on average, higher than the assumed 100 Mg C, the result is a shrinking of the amount of real emissions reduction obtained from the available funds.

Conclusions

1. Vegetation in southern Amazonia and throughout the Amazon region has very substantial carbon stocks that can be released as greenhouse gases upon conversion to other uses.
2. Carbon stock estimates are subject to considerable uncertainty, indicating that further research should be done but not that there should be any delay in actions to contain deforestation and reduce emissions.
3. The global warming impact of land-use conversions reflects the benefit of avoiding these conversions in favor of development based on environmental services.

Acknowledgments I thank Conselho Nacional do Desenvolvimento Científico e Tecnológico (CNPq: Proc. 304020/2010-9; 573810/2008-7), Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM: Proc. 708565) and Instituto Nacional de Pesquisas da Amazônia (INPA: PRJ15.125) for financial support. The section on soil carbon is translated and adapted from Fearnside (2010). Two reviewers contributed helpful comments.

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