Supplementary Online Material

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

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Table S1: Non-tree components of live biomass

Component	Location	Forest type	Component dry biomass (Mg ha^{-1})	Percent of aboveground live biomass	Reference
Lianas					
	Manaus, Amazonas, ZF-2	Dense *terra firme*	7.2±6.7[a]	1.77	da Silva 2007, p. 55
	Paragominas, Pará	Dense *terra firme*	35	13.57	Gerwing 2002, p. 136
	Manaus, Amazonas, PDBFF (Forest interior plots in 1997-1999)	Dense *terra firme*	7.7 ± 2.3	2.2[c]	Laurance et al. 2014a
	Manaus, Amazonas, PDBFF (Forest interior plots in 2012)	Dense *terra firme*	8.0 ± 2.2	2.2[c]	Laurance et al. 2014a
	Manaus, Amazonas, PDBFF (Forest edge plots in 1997-1999)	Dense *terra firme*	8.1±0.3	2.3[c]	Laurance et al. 2014b
	Manaus, Amazonas, PDBFF (Forest edge plots in 2012)	Dense terra firme	9.7±0.3	2.7[c]	Laurance et al. 2014b
	Brasil Novo, Pará, Km 50	Dense *terra firme*	32.2	12.26	Fearnside et al. 1999
	Belo Monte Dam, Pará	Dense riparian	2.81	1.51	Revilla Cardenas 1987, p. 51
	Belo Monte Dam, Pará	Dense *terra firme*	2.87	2.28	Revilla Cardenas 1987, p. 34
	Samuel Dam, Rondônia	Open *terra firme*	4.59	1.18	Revilla Cardenas 1986, p. 39
	Samuel Dam, Rondônia	*Mata de baixio* [bottomland forest]	10.77	2.97	Revilla Cardenas 1986, p. 39
	Babaquara [Altamira] Dam, Pará	Dense riparian	9.74	3.28	Revilla Cardenas 1988, p. 76
	Babaquara [Altamira] Dam, Pará	Dense *terra firme*	9.02	4.55	Revilla Cardenas 1988, p. 77
	Manaus, Amazonas, Egler Reserve	Dense *terra firme*	21.85	6.12	Klinge et al. 1975
	Manaus, Amazonas, Ducke Reserve	Dense *terra firme*	7.2	2.2	Nogueira 2006, p. 17 (mean of 3 estimates)
	Rondônia	Dense *terra firme*	0.6	0.2	Cummings et al. 2002
	Rondônia	Open *terra firme*	0.6	0.2	Cummings et al. 2002
	Manaus, Tarumã settlement	Dense *terra firme*	6.30	2.06	Nogueira 2006, p. 17
	Manaus, Amazonas, PDBFF (Fazenda Dimona)	Dense *terra firme*	8.10	3.32	Fearnside et al. 1993
	Manaus, Amazonas, PDBFF	Dense *terra*	8.30	2.55	Nascimento and

		firme			Laurance 2002
	Rondônia	Ecotone forest / savanna	0.5	0.2	Cummings et al. 2002
Palms					
	Manaus, Amazonas, ZF-2	Dense *terra firme*	11.8±17.8[a]	2.31	da Silva 2007, p. 55
	Brasil Novo, Pará, Km 50	Dense *terra firme*	10.6	4.04	Fearnside et al. 1999
	Manaus, Amazonas, Egler Reserve	Dense *terra firme*	12.5	3.5	Klinge et al. 1975
	Fazenda Dimona, Amazonas	Dense *terra firme*	8.1	2.1	Fearnside et al. 1993
	Fazenda Dimona, Amazonas	Dense *terra firme*	10.8	4.08	Fearnside et al. 2001
	Jari Project, Pará	Dense *terra firme*	5.0	1.3	Russell 1983
	PDBFF reserves, Manaus, Amazonas	Dense *terra firme*	1.3	0.4	Nascimento and Laurance 2002
	Rondônia	Open *terra firme*	16.8	5.4	Cummings et al. 2002
	Manaus, Amazonas, Ducke Reserve	Dense *terra firme*	2.1	0.7	de Castilho et al. 2006
	Rondônia	Ecotone forest / savanna	37.9	14.0	Cummings et al. 2002
Seedlings[c] & understory					
	Manaus, Amazonas, Ducke Reserve	Dense *terra firme*	19.4	6.4	de Castilho et al. 2006
	Manaus, Amazonas, ZF-2	Dense *terra firme*	1.8	2.9	da Silva 2007
	PDBFF reserves, Manaus, Amazonas	Dense *terra firme*	21.1	6.5	Nascimento and Laurance 2002
	Samuel Dam, Rondônia	Dense *terra firme*	13.0[d]	3.3[d]	Revilla Cardenas 1986
	Belo Monte Dam, Pará	Open *terra firme*	5.6[d]	3.0[d]	Revilla Cardenas 1987
	Babaquara [Altamira] Dam, Pará	Dense riparian	9.6[d]	3.2[d]	Revilla Cardenas 1988, p. 77
	Babaquara [Altamira] Dam, Pará	Dense *terra firme*	9.2[d]	4.6[d]	Revilla Cardenas 1988, p. 77
	Samuel Dam, Rondônia	Open *terra firme*	2.6[d]	0.7[d]	Revilla Cardenas, 1986
	Paragominas, Pará	Dense *terra firme*	16.0	6.2	Gerwing 2002
	Rondônia	Open *terra firme*	14.1	5.9	Cummings et al. 2002

	Rondônia	Ecotone forest / savanna	11.4	4.2	Cummings et al. 2002
	Jari Project, Pará	Dense *terra firme*	9.61	2.5	Russell 1983
Other					
	Manaus, Amazonas, Egler Reserve	Dense *terra firme*	0.75	0.21	Klinge et al. 1975

[a]Assumes same water content as weighted average for above-ground components of trees: 40.62% (da Silva 2007, p. 66).

[b]Based on mean above-ground live biomass of 356 ±47 Mg ha^{-1} (Laurance et al. 1999).

[c]"Seedlings" < 1 cm DBH.

[d]includes root-mat.

Table S2: Belowground biomass of Amazon forests

Forest type	Location	Biomass (Mg ha^{-1})				Carbon (MgC ha^{-1})		Root:shoot ratio		Reference
Description		Belowground between trees	Belowground deep roots[a]	Approximate total belowground	Aboveground live	Belowground	Aboveground live	Biomass	Carbon	
Dense *terra firme*	Manaus, Amazonas (ZF-02 road)	62.2[b]			461.6 [b]	28.41	223.88	0.135	0.127	da Silva 2007
Contact Woody oligotrophic vegetation (*Campinaran*a) of swampy & sandy areas / *terra firme*	São Gabriel da Cachoeira, Amazonas	30.7 ± 20			222.3 ± 21.1			0.138		Lima et al. 2012
Dense *terra firme*	Jari, Pará	56.96	34	91	368.91			0.23		Russell 1983, p. 29
Dense *terra firme*	Manaus, Amazonas, Egler Reserve	122.5	74	196	357			0.50		Klinge et al. 1975
Dense *terra firme*	Paragominas, Pará	45	23	68	336			0.18		Uhl et al. 1988; see Fearnside 1994

[a]"belowground bole" calculated as 50% and roots below 1-m depth as 10% with respect to estimates between trees to 1-m depth. This is based on preliminary results from Paragominas and Porto Trombetas, Pará (D.C. Nepstad, pers. comm.; see: Fearnside 1994).
[b]Weighted mean water content:aboveground= 40.62% below-ground=45.42% (calculated from da Silva 2007, pp. 55 & 66).

Table S3: Estimates of necromass > 10 cm in diameter in “undisturbed” forests in Brazilian Amazonia

Location	Forest type	IBGE code	Necromass (Mg ha^{-1} dry weight)	Area surveyed	Minimum diameter (cm)	Reference
Tapajós National Forest, Pará	Dense *terra firme*		50.7 ± 1.1	6000 m of line transects.	2	Keller et al 2004
Tapajós National Forest, Pará	Dense *terra firme*		58.4 ± 0.9	5.5 ha	2	Palace et al 2007
Juruena, Mato Grosso	Open *terra firme*		44.9 ± 0.2	6 ha	2	Palace et al 2007
Juruena, Mato Grosso	Open *terra firme*		33.7	8 ha	2	Pauletto 2006
Paragomians, Pará (Caxuí)	Dense *terra firme*		55.2 ± 4.7	5930 m of line transects	2	Keller et al 2004
Rio Moju, Pará	Dense *terra firme*		57.4 Mg ha^{-1}	6000 m of line transects.	10	Cruz Filho 2005
BDFFP[a] reserves, Manaus, Amazonas	Dense *terra firme*		25.5 ± 7.1	20 ha	10	Nascimento and Laurance 2006
BDFFP[a] reserves, Manaus, Amazonas	Dense *terra firme*		31.6±12.36	6 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
Ducke Reserve, Manaus, Amazonas	Dense *terra firme*		34.05±20.09	9 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 34 [M01], Amazonas	60%¨flooded; 40% *terra firme*		15.12±5.56	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 100 [M02],	20% secondary forest; 80% *terra*		14.42±5.98	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers.

Amazonas	*firme*					Comm.
BR-319 Highway km 220 [M04], Amazonas	*Terra firme*		16.65±5.07	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 260 [M05] Amazonas	*Terra firme*		16.03±10.16	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 300 [M06], Amazonas	20% swamp; 80% *terra firme*		30.21±10.96	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 350 [M07], Amazonas	20% swamp; 80% *terra firme*		32.60±18.16	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 400 [M08], Amazonas	*Terra firme*		29.59±14.05	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 450 [M09], Amazonas	20% secondary forest; 80% *terra firme*		24.88±6.33	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 520 [M10], Amazonas	*Terra firme*		35.97±5.30	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm.
BR-319 Highway km 640 [M11], Amazonas	40% *terra firme*; 60% alluvial terrace		12.63±3.08	2.5 ha	10	Martins et al 2014 & D.L. Martins, Pers. Comm
Ducke Reserve, Manaus, Amazonas	Dense *terra firme*		9.5 fallen only	2.5 ha	10	Martius and Bandeira 1998
BIONTE (ZF-2 road), Manaus, Amazonas	Dense *terra firme*		29.7±12.2	3 ha for wood > 20 cm diameter;	10	Summers 1998

				0.75 há for wood 10-20 cm diameter		
Rondônia (7 sites)	Dense *terra firme*		30.5±6.9	5.25 ha	2.5	Cummings et al 2002
Rondônia (8 sites)	Open *terra firme*		32.4±5.2 10,1±0.9 litter[b]	6 ha	2.5	Cummings et al 2002
Rondônia (4 sites)	Forest/savanna ecotone		20.8±6.6	3 ha	2.5	Cummings et al 2002
BDFFP[a] reserves, Manaus, Amazonas	Dense *terra firme*		21.0	21 ha	10	Chambers et al 2000
Samuel Dam, Rondônia	Open *terra firme*		30 fallen trunks 10 litter	Coarse 1 ha Litter 7.25 m^2	Litter < 2	Brown et al 1995
Paragominas, Pará	Dense *terra firme*		51.5±16.2 fallen coarse 4.1±0.2 litter	120 m transects	~0	Uhl and Kauffman 1990
Tapajós National Forest, Pará	Dense *terra firme*		86.6±13.4	19.75 ha	Standing= 10; fallen=2	Rice et al 2004
Lago Cobra, Amazonas	*Várzea* forest		6.62 fallen (fine+coarse) 10.96[b] standing	1425 m^2	~0	Martius 1997
Viruá National Park, Roraima	Open-canopy rainforest submontane	As	5.93±5.49	1000 m^2	10	Silva et al 2016
Viruá National Park, Roraima	Open-canopy rainforest on	Ab	8.30±4.45	1250 m^2	10	Silva et al 2016

	non-flooding lowlands					
Viruá National Park, Roraima	Contact between *campinarana* and rainforest	LO	9.52±4.45	1000 m^2	10	Silva et al 2016
Viruá National Park, Roraima	Mosaic Treed *campinarana* and Forested *campinarana*	La + Ld	4.50±2.92	1750 m^2	10	Silva et al 2016
Viruá National Park, Roraima	Mosaic Shrubby *campinarana* and Treed *campinarana*	Lb + La	0.77±0.65	1500 m^2	10	Silva et al 2016

[a]BDFFP = Biological Dynamics of Forest Fragments Project (INPA and Smithsonian Institution).

[b]Density of fallen wood 6.62 Mg ha^{-1}/ 33.0 m^3 ha^{-1} = 0.195 Mg m^{-3} applied to total estimated dead volume of 90 m^3 ha^{-1} = 17.58 Mg ha^{-1}. Standing dead is therefore 17.58 – 6.62 = 10.96 17.58 Mg ha^{-1}.

Table S4. Secondary forest growth rates

Location	Secondary forest age (yr)	Aboveground live biomass growth rate (Mg ha^{-1} yr^{-1})	Previous land use	Minimum DBH considered (cm)	Reference	Note
Brazilian Amazon biome		8.7	Various		Brazil, MCT 2004, p. 147	a
Brazilian Amazon biome	8.5	8.5	Various		Brazil, MCT 2010, p. 239	b
Paragominas, Pará	8	5.4	Pasture "Moderate use"	0	Uhl et al. 1988	
Brasil Novo, Pará	2-7	4.5	3-12 yrs pasture	0	Fearnside and Guimarães 1996	
Manaus, Amazonas	19	7.1	4 yrs pasture	1	Wandelli and Fearnside 2015	
Manaus, Amazonas	20	4.5	5 yrs pasture	1	Wandelli and Fearnside 2015	
Manaus, Amazonas	21	3.4	8 yrs pasture	1	Wandelli and Fearnside 2015	
Manaus, Amazonas	< 1 - 5	4.4	9-12 yrs pasture	1	Feldspausch et al. 2007	
Manaus, Amazonas	6 - 10	5.7	3-14 yrs pasture	1	Feldspausch et al. 2007	
Manaus, Amazonas	11 - 14	9.9	3-9 yrs pasture	1	Feldspausch et al. 2007	
Landsat scene 232/067 in southwest Rondônia	13 – 16	8.4	Various		Helme et al. 2009	c
Cacaulandia, Rondônia	2	2.7 (2.1-3.3)	2 yrs agriculture; 2 burns	5	Alves et al. 1997	
Cacaulandia, Rondônia	3	10.5 (8.8-12.2)	1 yr agriculture, 3 yrs pasture	5	Alves et al. 1997	
Cacaulandia, Rondônia	5	8.3 (7.2-9.3)	2 yrs agriculture	5	Alves et al. 1997	
Cacaulandia, Rondônia	9	8.9 (7.8-10)	3 yrs agriculture	5	Alves et al. 1997	
Cacaulandia, Rondônia	11	6.2 (5.6-6.7)	Approximately 2 yrs agriculture	5	Alves et al. 1997	
Cacaulandia, Rondônia	18	8.9 (7.9-9.8)	History unknown	5	Alves et al. 1997	
Lago Januacá, AM-010 and BR-174 Highways, Amazonas	4-30	5.0	6-10 yrs pasture	5	Steininger 2000	
Santa Cruz, Bolivia	4-25	5.4	Long-term pasture (> 5 yrs)	5	Steininger 2000	
Santa Cruz, Bolivia	4-12	9.0	5 plots short-term agriculture (1-yr agriculture); 3 plots medium fallow (≥ 4 cycles of 1-yr cultivation + 5-8 yrs fallow); 1 plot long-term pasture.	5	Steininger 2000	
Lago Januacá, AM-010 and BR-174 Highways, Amazonas	4-12	7.7	6 plots short-term agriculture, 1 plot short fallow agriculture (4 cycles of 1 yr agriculture alternating with 3 yrs fallow); 1 plot	5	Steininger 2000	

			long-term agriculture (6 yrs rice); 3 plots long-term pasture.			
Jamarí, Rondonia	4	9.1	2 yrs agriculture + 4 yrs fallow + 2 yrs agriculture	0	Hughes et al. 2000	
Jamarí, Rondonia	4	8.6	2 yrs agriculture + 4 yrs fallow + 2 yrs agriculture	0	Hughes et al. 2000	
Jamarí, Rondonia	4	12.3	2 yrs agriculture + 4 yrs fallow + 2 yrs agriculture	0	Hughes et al. 2000	
Jamarí, Rondonia	4	15.9	Cleared and abandoned without agricultural use	0	Hughes et al. 2000	
Jamarí, Rondonia	4	8.9	2 yrs agriculture	0	Hughes et al. 2000	

a.) For forest types with aboveground C > 93 MgC ha^{-1}. For those with ≤ MgC ha^{-1} growth rate = 3.7 MgC ha^{-1} yr^{-1}. Carbon growth rate (4.24 Mg ha^{-1} yr^{-1}) converted to biomass at 0.485 MgC/Mg biomass (da Silva 2007).

b.) The aboveground live biomass per hectare growth rate used in Brazil, MCT (2004) is cited, but the carbon-balance calculation (Brazil, MCT 2010, p. 242) assumes that secondary forests have a biomass 35% that of the primary vegetation (Brazil, MCT 2010, p. 239). Although insufficient information is reported to quantify this precisely, an approximation can be made from the per-hectare carbon stock values given by forest type. Considering the unweighted average for these per-hectare stocks by RADAMBRASIL volume (Brazil, MCT 2010, p. 236) and the proportions of each forest type in the region (from Fearnside 1994, p. 105), the average total carbon stock of primary forest is 160 MgC ha^{-1} (above + below ground + litter),or 100.5 MgC aboveground live biomass in trees considering the 37.2% factor for below-ground, lianas and litter used in the report (Brazil, MCT 2010, p. 235). This implies a dry weight of 207.1 Mg ha^{-1} of biomass for primary forest (considering the 0.485 MgC/Mg biomass conversion used in the report), making the 35% value for aboveground live biomass 72.5 Mg ha^{-1}. Transitions over the 1994-2002 period (Brazil, MCT 2010, p. 242) indicate that of 911,484 ha of secondary forest present in 1994, only 54,845 ha remained 8 years later; at the average clearing rate of 107,080 ha yr^{-1}, the average age at clearing is 8.5 yr, assuming a linear decrease (it would be greater if the decrease were exponential, implying a higher growth rate). The growth rate of aboveground live biomass in secondary forest is therefore 72.5/8.5 = 8.5 Mg ha^{-1} yr^{-1}.

c.) Space-borne LiDAR; based on Alves et al. 1997 (for forests with < 53 MgC ha^{-1} of aboveground live biomass).

Table S5: Estimates of secondary forest area in Brazilian Amazonia

Year	Secondary forest area (10^3 km^2)	Cumulative deforestation (10^3 km^2)[a]	Percentage in secondary forest (%)[b]	Reference
1986	100.9	336.2	30	Houghton et al. 2000
1990	123.8	415.2	30	Fearnside 2000
1992	158.0	440.2	36	Lucas et al. 2000
1990-1994	82.3	442.6	19	Brazil, MCT 2004, p. 147
1994	9.1	470.0	2	Brazil, MCT 2010, p. 242
2000	140.0	583.3	24	Carreiras et al. 2006
2002	10.3	623.1	2	Brazil, MCT 2010, p. 242
2002	161.0	623.1	26	Neeff et al. 2006
2006	131.9	709.6	19	Almeida et al. 2010

[a]Brazil, INPE 2015.

[b]Percentages are calculated from the secondary forest area, with the exception of Houghton et al. (2000) where the reverse is calculated.

Table S6: Secondary forest land-use transitions and implied carbon fluxes in the Amazonia Biome in Brazil's Second National Inventory (a)										
Land use	Use code	Area (ha) converted to secondary forest 1994-2002	Net CO_2 emission 1994-2002 (Gg CO_2)	Net carbon emission 1994-2002 (Gg C)	Original forest C density (above + belowground) MgC ha^{-1}(b)	Original forest C stock (above + belowground) (Gg C)	Secondary forest C stock (above + belowground) (Gg C)	Secondary forest C density (above + belowground) MgC ha^{-1}(b)	Secondary forest gain (above + belowground) 1994-2002 (Gg C)	
Unmanaged forest	FNM	119,957.00	56,600.46	15,436.49	197.97	23,748.44	8,311.96	69.29	8,311.96	
Managed forest	FM	12,967.00	6,251.30	1,704.90	197.97	2,567.14	898.50	69.29	898.50	
Secondary forest	Fsec	54,845.00	-9,406.33	-2,565.36	197.97	10,857.92	3,800.27	69.29	3,800.27	
Reforestation	Ref	56.00	6.22	1.70	197.97	11.09	3.88	69.29	3.88	
Planted pasture	Ap	772,591.00	-35,761.00	-9,753.00	197.97	152,953.43	53,533.70	69.29	53,533.70	
Agricultural area	Ac	73,057.00	-4,372.16	-1,192.41	197.97	14,463.43	5,062.20	69.29	5,062.20	
Other uses	O	10.00	-0.77	-0.21	197.97	1.98	0.69	69.29	0.69	
Not observed	NO	308.00								
Total		1,033,791.00	13,317.72	3,632.11		204,603.43	71,611.20		71,611.20	
					Carbon gain per year in secondary forests (8 years) =				8,951.40	

(a) Data source: Brazil, MCT (2010, p. 242).

(b) See Wandelli and Fearnside (2015, p. 147).

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