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Carbon, nitrogen and sulfur (CNS) status and dynamics in Amazon basin upland soils, Brazil

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Key Points:

- Quantification of Amazon basin upland soil CNS concentrations and C_{org}/N ratios
- CNS median concentrations are similar to European soils; ranges are more narrow
- In up to 50 years after deforestation, average C_t, C_{org} and N losses of up to 20 % in post-forest soils
- Intra-annual dynamics of soil pH-values and electrical conductivities under generally acidic to strongly acidic conditions and very low λ
- Central Amazonas soils show stronger differences between forest and post-forest land than southern Amazonas soils – indicator of significant impact and edge effects in the south?

Key words: tropical soils; terra firme; oxisol; ferralsol; soil biogeochemistry; climate change; nutrient ratios, hydrological gradient

Abstract. Given the dimensions of the Amazon basin (7.5 million km^2), its internal dynamics, increasing anthropogenic strain on this large biome, and its global role as one of two continental biospheric tipping elements, it appears crucial to have data-based knowledge on carbon and nitrogen concentrations and pools as well as on possible intra-annual dynamics. We quantified carbon (C_t, C_{org}), nitrogen (N) and sulfur (S) concentrations in litter (ORG) and mineral soil material (TOP 0–20 cm, BOT 30–50 cm) of upland (terra firme) oxisols across Amazonas state and present a first pool calculation. Data are based on triplicate seasonal sampling at 29 sites (forest and post-forest) within the binational project EcoRespira-Amazon (ERA). Repeated sampling increased data accuracy and allows for interpreting intra-annual (seasonal) and climate-change related dynamics. Extreme conditions between the dry season in 2016 and the subsequent wet season (ENSO-related) show differences more clearly. Median CNS in the Amazon basin TOP soils (C_t 1.9, C_{org} 1.6, N 0.15, S 0.03 wt-% under forest canopy) as well as C_{org}/N ratios show concentrations similar to European soils (FOREGS, GEMAS). TOP C_t concentrations ranged from 1.02 to 3.29 wt-% (median_Forest 2.17 wt-%; median_Post-Forest 1.75 wt-%), N from 0.088 to 0.233 wt-% (median_Forest 0.17 wt-%; median_Post-Forest 0.09 wt-%) and S from 0.012 to 0.051 wt.-% (median_Forest 0.03 wt.-%; median_Post-Forest 0.02 wt-

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42 %). C_{org}/N ratios ranged from 6 to 14 (median 10). A first pool calculation (hectare-based) illustrates forest versus

43 post-forest changes. The elements are unevenly distributed in the basin with generally higher CNS values in the

44 central part (Amazonas graben) as compared to the southern part of the basin. Deforestation and drought condi-

45 tions lead to C and N losses – within 50 years after deforestation, C and N losses average 10 to 15 %. Regional

46 climate change with increased drought will likely speed up carbon and nitrogen losses.

47 **1   Introduction**

48 The Amazon basin is seen as one of the terrestrial tipping elements (Lenton et al., 2008) with global impacts to

49 be expected when triggered (Reid et al., 2015). Several works suggest that the Amazon rainforest biome may tip

50 by the end of this century, and give rise to a subsequent, more dry forest environment (Shukla et al., 2008). Re-

51 cent changes in the basin (Davidson et al., 2012; Fearnside, 2018; Hubbell et al., 2008; Longobardi et al., 2016;

52 McGrath et al., 2001; Rosa et al., 2016; Shukla et al., 2008), including increasing extreme events such as drought

53 (e.g., dry season 2016) with strong impacts on the hydrological cycle far beyond the basin (Aragão, 2012; Da-

54 vidson et al., 2012; Jiménez-Muñoz et al., 2016; Lewis et al., 2011; Marengo, 2006) corroborate that hypothesis.

55 It is in this light that evidence-based knowledge and reliable data are needed to better assess possible resilience

56 and consequences of current land use in the basin. Nagy et al. (2016) compiled related state-of-the-art of

57 knowledge in biosphere-atmosphere-human land use interactions within the Amazon basin, updating and ex-

58 panding previous work (e.g., McClain et al., 2001). Cerri et al. (2006a) pointed out the knowns and unknowns of

59 land conversion in Latin America with particular emphasis on soil carbon sequestration, with Cerri et al. (2006b)

60 breaking this attempt down to the Amazonian tropical rainforest biome. One conclusion is that reliable data are

61 still scarce. Nitrogen data are particularly missing. Given the relevance of the carbon and nitrogen cycles in

62 global change, and the diverse estimates of related soil pools (e.g. Baldock, 2007; McNeill and Unkovich, 2007)

63 it appears particularly valuable to obtain better data. Various questions remain unanswered to better understand

64 carbon, nitrogen and sulfur (CNS) cycling in humid tropical forest regions, and particularly about consequences

65 of human impact in such systems. Key questions for this work can thus be formulated:

66 What are CNS concentrations in Amazon basin soils – and how do these compare to other world soils? Are there

67 differences in CNS status between forest and post-forest land? Is the CNS status similar throughout the year or

68 do we see intra-annual dynamics? How do mineral soil CNS concentrations relate to the organic litter layer? Is

69 the hydrological difference between the more humid central part of the basin and its southern "shoulder" rele-

70 vant? Which consequences may future increasing drought conditions have for CNS behaviour in Amazon basin

71 soils?

72 Answers to these questions are used for a first upscaling attempt that also looks into the near future. Within the

73 binational project EcoRespira-Amazon (ERA: https://blogs.hrz.tu-freiberg.de/ecorespira/), we studied the geo-

74 chemistry of upland (terra firme) oxisols in Amazonas state, Brazil. It shows the CNS status and its intra-annual

75 dynamics. The latter is based on our observations under extreme dry season and under wet season conditions

76 during El Niño-Southern Oscillation (ENSO) and post-ENSO dominance (Jiménez-Muñoz et al., 2016).

77 Soil diversity in the tropics is high (Sanchez, 2019: 71f). Humid tropical soils such as those dominating the Am-

78 azon basin are often reported to be nutrient-depleted (Richter and Babbar, 1991), even referred to as 'infertile

79 soils' (Irion, 1978). This generalization may be partly true for base cations that are easily leached under the dom-

80 inant high to very high soil acidity and plenty of water (Juo and Franzluebbers, 2003). Hydrolysis of primary

2

81 minerals there is about 100 times higher as compared to temperate climate soils (Glaser et al., 2004). The oxisols

82 (ferralsols) in our study fall into this category (Juo and Franzluebbers, 2003). Other components including CNS

83 may not follow such simplified vision. Sanchez (1977) already published average organic carbon values of 2.01

84 wt.-%. Bohn et al. (2001: 156f) interpret that as a result of strong interactions between soil organic matter

85 (SOM) with Fe and Al hydroxy-oxides and allophane, which could stabilize SOM against microbial decay. At

86 the same time, they acknowledge "*the high rate of year-round biomass production in the humid tropics*", which

87 counteracts the relative nutrient paucity in these soils. Previous works usually deliver spatially-clustered data;

88 sometimes focussing on very large-scale soil variations (Quesada et al., 2010). A closer look at intra-basin phys-

89 ico-chemical variability appears necessary and helpful in order to better understand CNS dynamics and soil

90 fertility in this potentially vulnerable system. Pre-Columbian tropical agricultural practices, such as "Indigenous

91 Black Earth" (terra preta do índio) demonstrate that significant carbon and nitrogen enrichment is possible under

92 these climatic conditions and that long-term steady state can be reached through appropriate land-use techniques

93 (Glaser and Birk, 2012). These historical anthroposols may exemplify sustainable agriculture, to be frequently

94 encountered near old settlements (Roosevelt, 2013; Sanchez, 2019: 285f; own observations).

95 Litter (ORG) and mineral soil (TOP and BOT) was collected to assess their element concentrations at the study

96 sites. Repeated sampling of the same sites under different seasonal conditions served both quality control and to

97 investigate seasonal dynamics, based on our observation of radically changing litter layer thickness between dry

98 and wet season. Following a presentation of pH-values, electrical conductivity and soil colour, the CNS results

99 in ORG, TOP and BOT material are discussed in detail. An attempt is made to upscale results to upland Amazon

100 soil for the entire basin.

101 **2   Materials and methods**

102 **2.1   Site characteristics**

103 We sampled at 29 sites from 13 upland (terra firme) locations within Amazonas state, Brazil, covering an area of

104 roughly 930 by 800 km (740,000 km²). Each location (Figure 1) represents 2–3 sites with different land cover; at

105 least one forested (F), the other pastureland, plantation or agroforestry (post-forest sites, PF). The native forest

106 locations showed some (mostly minor) human impact; their conjunct areas were considerably larger in the cen-

107 tral part as compared to the south. To represent much of Amazon basin upland soils and their land cover, a corre-

108 sponding number of sites was studied in the central part of the basin and across southern Amazonas state (Figure

109 1). Soils are generally fully oxidized on the macro scale (Sanchez, 1977). They were classified as oxisols (or

110 ferralsols or latosols depending on classification type; Batjes, 2016; Ross, 2006; Sanchez, 2019). Hydrolysis

111 under oxidizing acidic conditions is the dominant weathering agent (Juo and Franzluebbers, 2003).

112 Average location altitudes range from 25 m a.s.l. (06 Manacapuru) to 190 m a.s.l. (07 Apuí and 12 Nova

113 Califórnia) with a median altitude of 90 m a.s.l. (mean: 105 m a.s.l.). The central part of the Amazon basin (So-

114 limões-Amazon Graben) is characterized by lower average altitudes (median 75 m a.s.l., mean 80 m a.s.l.) and

115 younger lithological material; mostly Cretaceous, Tertiary and Quaternary sediments (CPRM 2005). Deforesta-

116 tion is still moderate, albeit rather substantial near the selected locations. Six of the 13 locations are located here

117 (Figure 1: 01–06), all part of the Eastern Amazon Basin plateau (Ross, 2006). The other seven locations (07–13)

118 represent the southern "shoulder" of the basin, the 'Marginal depression of southern Amazônica' (Ross, 2006)

119   with a median elevation of 150 m a.s.l. (mean 130 m a.s.l.). Geologically, this is part of the older Amazonian

120   Craton with partly surfacing Paleoproterozoic, Silurian and Devonian rocks and some Tertiary and Quaternary

121   sediments (CPRM 2005). Deforestation here is partly radical (> 90 %).

122   Average annual temperature in the study area is 27 °C with maxima in September and October (28 °C) and min-

123   ima from January to March (26.3 °C). The mean annual number of days with maximum monthly and annual

124   temperatures exceeding 30 °C is 300 with the highest average in August and October (29 days) and the lowest in

125   February (20 days). Sunshine hours average 1828.5 annually with monthly values exceeding 200 hours in July,

126   August and September. Average atmospheric pressure in Manaus is 1003.7 millibar (PMSL 1010.7 mbar) with

127   minima in November (1002.6 mbar; PMSL 1009.2 mbar), rising gradually until July (1005.4 mbar; PMSL

128   1012.5 mbar). Average annual precipitation amounts to 2301.2 mm with the driest month being August (64.3

129   mm). April is the wettest month with 319.0 mm. The mean annual number of days with precipitation above or

130   equal to 1 mm is 155, with the highest average in January and March (19 days) and the lowest in September (6

131   days). The mean annual number of days with precipitation above or equal to 10 mm is 73 days, with the highest

132   average in April (10 days) and the lowest in August (2 days). With 15 mm threshold, the mean annual number of

133   days is 54 with the highest in April (8 days) and the lowest in August (1 day). Relatively high air humidity oc-

134   curs all year round (avg. 82.8 %) with minima in September (72.2 %) and maxima in March (86.9 %). Annual

135   mean prevailing wind direction is Southeast, followed by north-easterly air streams. Average annual potential

136   evapotranspiration is 192 mm with maxima in October (234.4 mm) and minima in February (167.1 mm).

137   These average data (climate normal of 1981–2010) see some shift, when comparing them with data from the past

138   (CLINO 1961-1990; electronic supplement Table A01). Conditions during the sampling time (2016 and 2017)

139   were about 38 % dryer in the central part and 66 % more dry in the southern part, compared with the climate

140   normal 1981–2010. The southern region is generally dryer then the central one. All information is based on sta-

141   tion data from the INMET network (electronic supplement Table A01).

142   **2.2   Soil sampling**

143   Ninety percent of the ERA sites (minimum one hectare each; n = 26) were sampled in triplicate (February and

144   March 2016, weak wet; July and August 2016, extremely dry; February and March 2017, normal wet) to obtain a

145   robust database. Locations 04 and 10 were sampled a fourth time in February 2018 to compensate previous ac-

146   cess problems. All sampling spots were geo-referenced (handheld GPS/GLONASS receivers Garmin GPS 64s)

147   with an accuracy of ± 3 m even under dense forest canopy. Litter material (ORG) was collected across the entire

148   site with latex glove-protected hands into thoroughly cleaned cotton bags and closed tight until further pro-

149   cessing. Mineral soil was sampled manually by soil auger (Sondaterra, Piracicaba, São Paulo State, Brazil) in

150   two different depths (TOP: 0–20 cm, n = 79; BOT: 30–50 cm, n = 80) into Rilsan® polymer sampling bags after

151   carefully removing surface litter, visible root material and small stones. Three spots were sampled at each site.

152   Resulting samples (3 x TOP, 3 x BOT) were united to composite TOP and BOT samples per site. The auger was

153   thoroughly cleaned between all individual samples. This procedure was repeated in all three campaigns. Use of

154   disposable latex lab-gloves further reduced contamination risks during sampling. Soil humidity was measured in

155   the field (TDR sensor, Delta-T Devices, United Kingdom).

156   **2.3   Sample processing, soil solution pH, electrical conductivity and soil colour**

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157   Litter and mineral soil material were air-dried in the lab, crushed in an agate mortar and pistil, and (nylon) sieved

158   to particles < 2 mm. Larger material (stones, root material) was discarded. The fine material was ground and

159   milled to analytical size (< 63 μm) in a planetary ball mill (Pulverisette 7, Fritsch, Idar-Oberstein, Germany) and

160   a rotating disc mill (RS 200, Retsch, Haan, Germany); both with agate grinding jars and balls. Sample powder

161   was tested for effective grain size by sieving through nylon test sieves. All equipment was thoroughly cleaned

162   after each sample.

163   Soil solution electrical conductivity (λ in μS cm^{-1}) and pH-values (pH$_{H2O}$ and pH$_{CaCl2}$) were determined in the soil

164   fraction < 2 mm. For each sample, 2-times 15.0 g of soil were weighed into two beakers (double determination)

165   to be filled with 75 mL of deionized water and stirred for 1 hr. Conductivities were determined with calibrated

166   'cond 3110' electrodes (Meinsberg, Germany). In the same solution and a 0.01 mol CaCl$_2$ solution, pH was

167   measured. Following 1 hr of sedimentation time, pH-values were determined in the supernatant solution with

168   calibrated EGA 161 electrodes (Meinsberg, Germany), adapted to low-conductivity solutions.

169   Soil colours were determined from air-dried samples (< 2 mm) under constant light conditions using the Munsell

170   soil colour charts (1992) with reference to hue, value and chroma (electronic supplement Table A02).

171   **2.4   Elemental analysis (CNS)**

172   Twenty (20.0) milligrams of analytical grade ORG, TOP and BOT aliquots of each pulverized sample (n = 244)

173   were weighed into small tinfoil containers using an analytical balance (Sartorius Micro Pro 11, Göttingen, Ger-

174   many). 60 mg of tungsten^{VI}oxide catalyst was added and the tinfoil tightly sealed. This sealed container was

175   placed into the Elemental analyser (El Cube, Elementar Analysensysteme, Hanau, Germany) for subsequent

176   determination of total carbon (C$_t$), total nitrogen (N) and total sulfur (S) concentrations. To determine total or-

177   ganic carbon (C$_{org}$), another aliquot was treated with a drop of 10 % HCl solution. After gas release (CO$_2$ ↑), the

178   sample was treated as before. Resulting C-concentration equals the amount of C$_{org}$; prerequisite for calculating

179   C$_{org}$/N ratios. Calibration and daily factor determination were done using 4-aminobenzenesulfonic acid. Certified

180   reference material (ORIS, BHA-1) and our in-house reference material for tropical soil (BraSol) were added as

181   unknown samples and treated accordingly. Quantification limits were C: 0.040, N: 0.003, S: 0.003 wt-%). Sam-

182   ple duplicates reproduced identical values for carbon (RSD ≤1 %); standard deviations remained under 5% RSD

183   for nitrogen and sulfur. Reference material concentrations were always reproduced within their recommended

184   ranges. See Matschullat et al. (2018) for more details.

185   **2.5   Statistical evaluation**

186   Non-parametric techniques were used to calculate basic descriptive statistics (Hall and Sheather, 1988; Sheather

187   and McKean, 1987). Graphics were drawn with the program R (3.4.3) using the package *tidyverse*, including

188   *ggplot 2*.

189   **3   Results and discussion**

190   **3.1   pH-values and electrical conductivity**

191 TOP soil pH-values were acidic to strongly acidic with median lows of 4.2 in the dry season (pH_{H2O}; Table 1).

192 Average BOT pH_{H2O} values of 4.3–4.6 in forest-covered soil; 4.6–4.9 in post-forest soil point at reduced weather-

193 ing rates in lower soil horizons. Forest soils were more acidic throughout in both TOP and BOT levels ($\Delta \geq 0.3$

194 pH_{H2O} units) as compared to post-forest soils. This is likely due to much stronger rhizosphere metabolism in for-

195 ests and considerably lower biomass in post-forest soils (Jones et al., 2003). Considerable cation exchange ca-

196 pacity throughout can be derived from the delta pH between its determination in water and in $CaCl_2$ (Mekaru and

197 Uehara, 1972; Sanchez, 2019: 203; Table 1). Individual liming of agricultural soil cannot be excluded, resulting

198 in higher pH-values at those sites (Figures 2, 3). Independent of land cover, intra-annual dynamics are high with

199 a pH_{H2O} delta of up to 0.7 units or 63 μmol H^+ L^{-1} between (extreme) dry season and wet season (TOP); weaker in

200 BOT material (Δ 0.3 pH_{H2O} units; Table 1; Figure 2). Highly reduced hydrolysis during the dry season liberates

201 less buffering cations (Ca, Mg) from the upper soil layers; soil solution pH drops. This effect is even noticeable

202 in pH_{CaCl2} determinations, yet more subtle. Intra-annual soil pH swings should influence nutrient availability and

203 microbial community dynamics. Relevant differences emerge between the central and southern parts of Amazo-

204 nas state with considerably higher pH-values in TOP soil material after deforestation in the south (Figure 2).

205 This change signal is visible in BOT soil, too, yet not as pronounced.

206 Soil solution electrical conductivity (λ in μS cm^{-1}) serves as proxy for solute transport in water-filled pore space

207 (WFPS). λ was significantly higher in the dry season as compared to the wet season, and forest soil showed

208 consistently higher ✦than post-forest soil (Figure 3), corroborating the pH-value results. BOT material presents

209 even lower soil solution electrical conductivities (27–34 μS cm^{-1} in forest soil; 17–26 μS cm^{-1} in post-forest soil;

210 ranges represent intra-annual variation). The median maximum difference between dry and wet season was 50

211 μS cm^{-1} (Table 1; Figure 2).

212 Decreasing soil pH with increasing electrical conductivities in the dry season are clearly noticeable. Yet, their

213 effect on soil fertility and element dynamics may be too small to be of practical relevance at any given site. λ is

214 considerably more dynamic in forest soil as compared to post-forest soil (Table 1, Figure 3 and electronic sup-

215 plement Table A02). This difference may result from soil physical changes such as decreasing porosity and in-

216 creasing density after deforestation.

217 Materials dominantly displayed light yellowish brown (10YR 6/4) colour characteristics (electronic supplement

218 Table A02), indicative of Fe oxihydroxides (hematite, goethite). Typical humic A-horizons (Ah) were generally

219 very thin. The deeper mineral soil layer (BOT) always showed slightly lighter and more reddish colours (very

220 pale brown, 10YR 7/4; indicating prevalence of goethite) with significantly different chemical composition from

221 TOP soil material (Tables 1–4).

222 **3.2   ORG material carbon, nitrogen and sulfur (CNS)**

223 Soil litter (ORG) accumulation in the Amazon basin changes radically between dry and wet seasons (Δ of up to

224 40 cm). We did not perform quantitative measurements, yet data from Sanches et al., (2008) and Valentini et al.,

225 (2008) corroborate this observation with intra-annual variation factors of 3 to 4. Due to an unusually strong EN-

226 SO event from 2015 to 2017 (Jiménez-Muñoz et al., 2016), seasonal differences were particularly pronounced

227 between our sampling campaigns Ph_02 and Ph_03. Litter accumulation varied of a few centimeters (Ju-

228   ly/August) to several decimeters thickness (February/ March). Litter material always was much thicker under

229   forest canopy as compared to any post-forest land cover.

230   The litter layer showed median concentrations between 34 and 49 wt.-% (C_t), 27 to 46 wt.-% (C_{org}), 0.6 to 2.3 wt.-

231   % (N), 0.09 to 0.23 wt.-% (S) and C_{org}/N ratios between 18 and 65 (electronic supplement Table A02). A more

232   differentiated view is needed to see regional and temporal differences. Significant difference emerged for CNS

233   with higher values in the central and rainier part (Table 2). Independent of geographical and morphological posi-

234   tion, forest litter shows lower C and N values than post-forest material. In the central part, post-forest land cover

235   presents higher C and N concentrations than forest soil litter, while lower ones were determined in post-forest

236   litter in the south. Intra-annual relative differences of ±5 % from the median value occur, with a clear tendency

237   to higher values in the rainy season; again independent of land use (electronic supplement Table A02). Forest

238   litter clearly shows faster decomposition with much lower C_{org}/N ratios as compared to post-forest soils. This is

239   particularly strong in the southern (dryer) part and additionally supported by the comparison between wet and

240   dry season (Table 2). This seasonal shift is accompanied by CNS losses that are particularly high for N (about -

241   20 %). In general, losses are higher in post-forest material (Table 4).

3.3   Mineral soil carbon, nitrogen and sulfur

243   Carbon (total and organic), nitrogen and sulfur were fully quantifiable in all samples. A non-differentiated com-

244   parison (central vs. southern part, forest vs. post-forest sites) of the new ERA data with global (UCC, WSA,

245   WISE30sec) and European (FOREGS, GEMAS) average data (Table 3 for references) show that upper crustal

246   data (UCC) are inappropriate for comparison, that world soil average (WSA) sulfur data lie far above both Euro-

247   pean soil data (FOREGS, GEMAS) and the Amazon basin soils, while the new ferralsol data (FR_t) from the

248   WISE30sec approach (Batjes, 2016) show similar values for C_{org} and N (Table 3). European soil CNS averages

249   (FOREGS, GEMAS) are in very good agreement with the new Amazonas data.

250   Intra-annual changes emerge between both land-cover types with generally stronger losses in post-forest soils,

251   when comparing the two extreme seasons Ph_02 and Ph_03 (Table 4). Inverse conditions emerge for litter mate-

252   rial (ORG) as compared to the mineral soil. ORG showed lower concentrations throughout in the extreme dry

253   season (Ph_02) as compared to the wet season (Ph_03), while TOP and BOT material mostly showed no change

254   or slightly decreasing (ø -5 to -20 %) concentrations from the extreme dry to the wet season (Table 4). Only TOP

255   soil in the central part of the basin showed increasing concentrations between the seasons (ø +5 to +15 %).

256   Related results for sulfur are non-conclusive. The C/S ratio is normal (about 200 in TOP; Blume et al., 2016:

257   56 ff.). While seasonal changes clearly occur (Table 3), they show partly contradictory behavior in the three

258   different materials. The dominant oxisols in upland (terra firme) environments of the Amazon basin yield above-

259   average amounts of clay minerals (median 42%; electronic supplement Table A02) and yet show very good

260   drainage characteristics under forest land-cover (Table 1 with λ as proxy for drainage). Under oxidizing condi-

261   tions, available dissolved sulfur (as sulfate) would likely bond to abundant Fe in the system, forming ferrous

262   sulfate and not wash out.

263   **TOP mineral soil (0–20 cm).** Although Sanchez (1977) reported 2.01 wt-% of organic carbon in Brazilian

264   oxisols, corroborated by work from Sanchez (2019: 264), the misleading notion that tropical soils are generally

265   nutrient poor and show low CNS values is still widespread. Organic carbon dominated the C species (median 81

266 % for all data; Table 2). TOP material C is likely younger (years) than C in lower soil parts (decades to centuries
267 in BOT and beyond; Cuevas, 2001; Schmidt et al., 2011; Trumbore and Carmargo, 2009). The south of the basin
268 presented lower total C_{org} and N values than its central part, and forest soils generally show higher values than
269 post-forest soils, independent of geographical position (Figures 4 and 5). This is less pronounced to invisible in
270 the south, likely reflecting an adaptation to earlier deforestation. Major deforestation started only after the con-
271 struction of the Transamazônica Highway (since 1972) with significant migration and settlement throughout the
272 basin (Fearnside, 2005). Therefore, more pronounced alterations in the C soil balance should have occurred only
273 within the last ±50 years. Related differences are very visible in the central part with losses of C_t (-13%), C_{org} (-
274 15%) and N_t (-12%), whereas the southern parts do not show any significant difference between TOP soil CNS
275 concentrations under forest canopy or post-forest land use (Table 4). We assume that this is due to the fact that
276 the south faces much more human impact and remaining forest stretches are influenced by edge effects (Barros
277 and Fearnside, 2016). This hypothesis is corroborated by our data from Apuí (Loc. 07, 08) and Lábrea (Loc. 10)
278 for more natural conditions versus those from Humaitá (Loc 09) and Boca do Acre (Loc 13) with more disturbed
279 conditions. Observed seasonal dynamics are much stronger at the more natural-condition sites (electronic sup-
280 plement Table A02).

281 While CNS decreased from wet to dry season in organic litter material (= biodegradation and export), TOP min-
282 eral soil shows differentiated behaviour. C_t and C_{org} increased in forest soil, and C_{org} decreased in post-forest soil,
283 pointing at slower biogeochemical turnover in post-forest soil with reduced microbial activity and less pore
284 space. Sinking pH-values likely inhibits microbial activity, too, enhancing possibly drought inhibition (Barbhui-
285 ya et al., 2004). Nitrogen decreased under both soil cover types, albeit stronger in post-forest soil. This observa-
286 tion has been made in both the central parts of the basin and in its south. In the south, differences between for-
287 ested (large increase) and post-forest soils (moderate increase to decrease) corroborate the hypothesis of changes
288 in biogeochemical metabolism between forested and post-forest soils (Table 4). It is very likely that plants, par-
289 ticularly trees take up the elements and soil serves as temporary storage.

290 **BOT mineral soil (30–50 cm).** Not surprisingly, C_{org} and N data show considerably lower concentrations in the
291 BOT layer as compared to TOP material (Figures 4 and 5). Jobbágy and Jackson (2000) calculated the relative
292 SOC amounts by depth. Their compilation resulted in roughly a factor of 2 between the layers equivalent to our
293 TOP and BOT samples; similar to this work. CNS are lower in BOT than TOP and increase from wet to dry
294 season under forest canopy, with much smaller increase values for post-forest soils (Table 4). It is noteworthy
295 that these seasonal dynamics obviously influence the entire rhizosphere and are not restricted to the uppermost
296 material with the highest root mass. The smaller increase in post-forest soil can be explained by considerably
297 longer turnover rates due to relatively reduced soil biological metabolism (Rangel-Vasconcelos et al., 2015).
298 This is corroborated by slightly lower C_{org}/N ratios in the BOT_m materials (electronic supplement Table A02).

299 Given a time-lag maximum of several decades after deforestation only, distinctly lower values (ca.
300 -20 %) for C and N in post-forest soil is quite a strong signal (Table 2). No significant change emerged for sulfur
301 between forested and deforested soil, contradictory to results from McClung et al. (1959; cited in Sanchez,
302 2019), which may not apply due to their Cerrado-based approach. Our median values of all forested versus all
303 post-forest sites deliver clear results, whereas individual sites may not always show conclusive results between
304 dry and wet season samples (electronic supplement Table A02).

305   This comparison of averages (all forest, all post-forest sites) hides that the central and southern parts of the re-

306   gion behave differently, with the southern sites showing lower values for all four components, independent of

307   land cover (Table 4, Figures 4 and 5). Yet, there is the distinct difference between forest and post-forest soil. In

308   the central (wetter) part of the basin, decreases of -22 % C_t and -13 % C_{org}, -13 % N occurred. No significant

309   change is visible in BOT material from the southern parts of the basin.

310   **3.4   Upscaling**

311   Based on ORG, TOP and BOT concentration data, material densities and estimated areas, we attempt upscaling

312   our CNS results for one hectare of terra firme in the Amazon basin (Table 5; Figure 6).

313   Assuming a conservative annual average litter (ORG) thickness of 5 cm under forest canopy and of 1 cm at post-

314   forest sites, and an average litter density of 0.03 g cm^3 (Chojnacky et al., 2009), one hectare would generate a

315   mass of 15,000 kg under forest canopy and 3000 kg on post-forest soil. Based on average CNS concentrations,

316   pools would yield 6150/1260 kg of total carbon, 5550/1170 kg of C_{org}, 240/42 kg of N, and 26/5 kg of S in for-

317   est/post-forest environments, respectively (Table 5; Figure 6). Obviously, already visible losses are in the order

318   of magnitude of 60 % between forest and post-forest soil.

319   With an average TOP thickness of 20 cm (to stay in line with the sampling depth) and an average density of 1.3

320   g cm^3 (Neves et al., 2003) each hectare of upland soil delivers about 2600 metric tons with pools of about 60 tons

321   of C_t (46 tons C_{org}) in forest and 46 (40) tons in post-forest environments, 4.6/3.6 tons of N and 0.8/0.6 tons of S

322   (Figure 6). The soils are generally highly acidic (Table 1). Higher seepage water availability in the wet season

323   obviously discharges mobilizable cations, leading to lower conductivities, while these cations sorb onto soil

324   particles in the dry season.

325   Using a similar mass-balance approach as for the TOP, a 20 cm-thick lamina of BOT material with likely slight-

326   ly higher density (1.4 g cm^3), producing a total mass of 2800 tons per hectare, would yield pools of about 31 tons

327   of C_t (25 tons of C_{org}), 2.2 tons of N and 0.6 tons of S in forested soil. Under post-forest conditions, values are 25 t

328   C_t, 22 t C_{org}, 2.2 t N, and 0.6 t S (Figure 6). This is expectedly lower than in TOP soil, yet shows the relevance of

329   deeper C dynamics (Jobbagy and Jackson, 2000; Schmidt et al., 2011).

330   Most root mass resides in the top 50 cm of the local soil profiles (Canadell et al., 1996; Schenk and Jackson,

331   2002; Sternberg et al., 1998; our own observations). Therefore, the combined TOP and BOT samples (with BOT

332   calculated here to 30 cm thickness) should represent the bulk rhizosphere. Figure 6 shows the pool sizes for one

333   hectare in comparison between forested and post-forested soil. The CNS pools are relatively high with about 110

334   t of C_t, 90 t of C_{org}, 8 t of N, and 2 t of S per hectare forest soil. Pools in post-forest soil are roughly 20 % lower.

335   Given that such loss occurred within a maximum time of 50 years since deforestation (at some sites, deforesta-

336   tion happened just a short time ago), similar effect must be expected in other parts of the Amazon basin that are

337   under deforestation risk in the near future.

338   **4   Conclusions**

339   The initially formulated key questions can be answered as follows:

340 • What are CNS concentrations in Amazon basin soils – and how do these relate to other world soils?

341 Surprisingly, average CNS concentration (in wt-% TOP$_{total}$: C$_t$ 2.2, C$_{org}$ 1.8, N 0.17, S 0.03) are similar to those

342 of Europe with Mediterranean to sub-polar climatic conditions (mostly temperate; in wt-% TOP FOREGS: C$_t$

343 2.2, C$_{org}$ 1.7, N 0.17, S 0.02). The range of Amazon basin CNS values appears to be considerably more

344 narrow; logical given more homogenous climatological and lithological conditions.

345 • Are there differences in nutrient status and carbon between forested and post-forest land? Differentiation is

346 needed between the central and southern parts of the basin, and between the upper (TOP) and lower (BOT)

347 soil layers within the rhizosphere. C$_t$ and C$_{org}$ are relatively enriched in central Amazonas forest soil (TOP and

348 BOT), while depleted in litter material (ORG) in comparison with post-forest soil (Table 2). In the southern

349 parts of the basin, no conclusive or significant difference emerges for CNS in mineral soil, while post-forest

350 soils are slightly enriched in the ORG layer. Such difference between the more wet and relatively less

351 disturbed sites in the central part and the south suggest that edge effects already dominate the southern

352 locations. The other, most likely influential driver is the underlying lithology with younger sedimentary

353 material in the central part but much older and metamorphic and magmatic materials in the southern part.

354 • Is the CNS status similar throughout the year or do we see intra-annual dynamics? Such dynamics are visible,

355 albeit subtle. Between wet (Phase 03) and dry season (Phase 02) as the two extremes in our study, ORG

356 material shows losses throughout; on average more so at post-forest sites. Gains emerged generally in

357 mineral soil with mostly stronger signals in forest than post-forest soil (Table 4). Again, significant

358 differences emerged between the central and southern parts of the basin with stronger gains in the south in

359 forest TOP soil. A strong gain in total S appeared in BOT of the central part as an anomaly (+58%). Such

360 intra-annual dynamics, very likely soil water-dependent, suggest significant influence of future hydrological

361 changes in the basin, as suggested by various authors (Lenton et al., 2008).

362 • How do mineral soil CNS concentrations relate to the organic litter layer? On average, ORG material shows

363 higher concentrations of C$_t$ and C$_{org}$, of N and of S than mineral soil (Table 2). A distinction emerged between

364 the central and southern parts. The highest ratios occur for C$_t$ and C$_{org}$. In the central part, these ratios are

365 lower for forest sites than for post-forest ones, while there is no significant difference in the southern part.

366 This finding may corroborate the previous hypothesis that edge effects already dominate soil chemistry in

367 this sub region.

368 • Is the hydrological difference between the more humid central part of the basin and its southern "shoulder"

369 relevant? The central parts appear to be better buffered against change as compared to the southern part,

370 which already is significantly more dry. Since deforestation in the south is partly extreme (exceeding 90 %),

371 such evidence suggests that increasing drought conditions will exacerbate the situation, leading to even more

372 drought in the dry season.

373 • Which consequences may future increasing drought conditions have for CNS behaviour in Amazon basin

374 soils? Given our observation of considerably lower average pH$_{H2O}$ values and higher electrical conductivity in

375 the dry season as compared to wet seasons, it can be inferred that the dry-season accumulation of (organic)

376 acids with related liberation of easily dissolvable cations will increase chemical erosion and subsequent

377 nutrient loss. This observation is more pronounced in forest soil as compared to post-forest soil, likely an

378 effect of reduced porosity and water conductivity in post-forest soils. Given the initial nutrient scarcity of

379 inner humid-tropical soils, increased loss is certainly unwanted.

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396   **References**

397   Aragão, L.E.O.C. The rainforest's water pump. Nature 489: 217-218; doi 10.1038/nature11485, 2012.

398   Baldock, J.A. Composition and cycling of organic carbon in soil. In: Marschner, D., Rengel, Z. (Eds.) Nutrient

399   cycling in terrestrial ecosystems. Soil Biol 10: 1-35; Springer Verlag, 2007.

400   Barbhuiya, A.R., Arunachalam, A., Pandey, H.N., Arunachalam, K., Khan, M.L., Nath, P.C. Dynamics of soil

401   microbial biomass C, N and P in disturbed and undisturbed stands of a tropical wet-evergreen forest. Eur J

402   Soil Biol 40: 113–121; doi 10.1016/j.ejsobi.2005.02.003, 2004.

403   Barros, H.S., Fearnside, P.M. Soil carbon stock changes due to edge effects in central Amazon forest fragments.

404   Forest Ecol Manage 379: 30-36; doi 10.1016/j.foreco.2016.08.002, 2016.

405   Batjes, N.H. Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global

406   soil carbon stocks. Geoderma 269: 61-68; doi 10.1016/j.geoderma.2016.01.034, 2016.

407   Blume, H.P., Brümmer, G.W., Fleige, H., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K.,

408   Wilke, B.M. Scheffer/Schachtschabel Soil Science. Springer Verlag, 630 p. doi 10.1007/978-3-642-30942-7,

409   2016.

410   Bohn, H.L., McNeal, B.L., O'Connor, G.A. Soil chemistry. 3ᵉ ed. John Wiley; 320 p., page 156, 2001.

411   Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D. Maximum rooting depth

412   of vegetation types at the global scale. Oecol 108: 583-595; doi 10.1007/BF00329030, 1996.

413   Cerri, C.C., Bernoux, M., Cerri, C.E.P., Lal, R. Challenges and opportunities of soil carbon sequestration in

414   Latin America. In: Lal, R., Cerri, C.C., Bernoux, M., Etchevers, J., Cerri, E. (Eds.) Carbon sequestration in

415   soils of Latin America. Food Products Press, New York, pages 41-47; doi 10-1300/5755_02, 2006a.

416   Cerri, C.E.P., Cerri, C.C., Bernoux, M., Volkoff, B., Rondón, M.A. Potential of soil carbon sequestration in the

417   Amazonian tropical rainforests. In: Lal, R., Cerri, C.C., Bernoux, M., Etchevers, J., Cerri, E. (Eds.) Carbon se-

SOIL
Discussions

Open Access

EGU

418   questration in soils of Latin America. Food Products Press, New York, pages 245-266; doi 10-1300/5755_12,
419   2006b.
420   Chojnacky, D., Amacher, M., Gavazzi, M. Separating duff and litter for improved mass and carbon estimates.
421   South J Appl Forest 33, 1: 29-34, 2009.
422   CPRM. Mapa geológico do Estado do Amazonas (Geological map of Amazonas state). www.cprm.gov.br. Last
423   access 02-2019, 2005.
424   Cuevas, E. Soil versus biological controls on nutrient cycling in terra firme forests. In: McClain, M.E., Victoria,
425   R.L., Richey, J.E. (Eds.) The biogeochemistry of the Amazon basin. Oxford Univ Press; 53-67; ISBN0-19-
426   511431-0, 2001.
427   Davidson, E.A., de Araújo, A.C., Artaxo, P., Balch, J.K., Foster Brown, I., Bustamante, M.M.C., Coe, M.T.,
428   DeFries, R.S., Keller, M., Longo, M., Munger, J.W., Schroeder, W., Soares-Filho, B.S., Souza, C.M., Wofsy,
429   S.C. The Amazon basin in transition. Nature 481, 7381: 321-328; doi 10.1038/nature10717, 2012.
430   Fearnside, P.M. Deforestation in Brazilian Amazonia: History, rates and consequences. Conserv Biol 19, 3: 680-
431   688; doi 10.1111/j.1523-1739.2005.00697.x, 2005.
432   Fearnside, P.M. Brazil's Amazonian forest carbon: the key to southern Amazonia's significance for global cli-
433   mate. Reg Environ Change 18: 47-61; doi 10.1007/s10113-1007-2, 2018.
434   Glaser, B., Birk, J. State of the scientific knowledge on properties and genesis of anthropogenic dark earths in
435   central Amazonia (terra preta do índio). Geochem Cosmochim Acta 82: 39-51; doi 10.1016/j.gca.2010.11.029,
436   2012.
437   Glaser, B., Guggenberger, G.Z., Zech, W. Identifying the Pre-Columbian anthropogenic input on present soil
438   properties of Amazonian dark earths (Terra Preta). In: Glaser, B., Woods, W. (Eds.) Amazonian dark earths:
439   Explorations in space and time. Springer, Heidelberg: 145 – 158, 2004.
440   Hall, P., Sheather, S.J. On the distribution of a studentized quantile. J Royal Statist Soc Ser B50: 380-391, 1988
441   Hubbell, S.P., He, F., Condit, R., Borda-de-Água, L., Kellner, J., ter Steege, H. How many tree species are there
442   in the Amazon and how many of them will go extinct? PNAS 105, 1: 11498-11504; doi
443   10.1073/pnas.0801915105, 2008.
444   Irion, G. Soil infertility in the Amazonian Rain Forest. Naturwiss 65, 10: 515-519, 1978.
445   Jiménez-Muñoz, J.C., Mattar, C., Barichivich, J., Santamaria-Artigas, A., Takahashi, K., Malhi, Y., Sobrino,
446   J.A., van der Schrier, G. Record-breaking warming and extreme drought in the Amazon rainforest during the
447   course of El Niño 2015–2016. Nature Sci Rep 6: 33130, doi 10.1038/srep33130, 2016.
448   Jobbágy, E.G., Jackson, R.B. The vertical distribution of soil organic carbon and its relation to climate and vege-
449   tation. Ecol Appl 10, 2: 423–436; doi 10.1890/1051-0761(2000)010, 2000.
450   Jones, D.T., Susilo, F.X., Bignell, D.E., Hardiwinoto, S., Gillison, A.N., Eggleton, P. Termite assemblage col-
451   lapse along a land-use intensification gradient in lowland central Sumatra, Indonesia. J Appl Soil Ecol 40: 380-
452   391; doi 10.1046/j.1365-2664.2003.00794.x, 2003.
453   Juo, A.S.R., Franzluebbers, K. Tropical soils. Properties and management for sustainable agriculture. Oxford
454   University Press, 281 p., 2003.
455   Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J. Tipping elements
456   in the Earth's climate system. PNAS 105, 6: 1786–1793; doi 10.1073/pnas.0705414105, 2008.
457   Lewis, S.L., Brando, P.M., Phillips, O.L., van der Heijden, G.M.F., Nepstad, D. The 2010 Amazon drought.
458   Science 331: 554; doi 10.1126/science.1200807, 2011.

459   Longobardi, P., Montenegro, A., Beltrami, H., Eby, M. Deforestation-induced climate change: Effects of spatial
460   scale. PLOS One 11, 4: e0153357; doi 10.1371/journal.pone.0153357, 2016.
461   Marengo, J.A. On the hydrological cycle of the Amazon Basin: A historical review and current state-of-the-art.
462   Rev Bras Meteorol 21, 3: 1-19; 2006.
463   Matschullat, J., Reimann, C., Birke, M., dos Santos Carvalho, D., GEMAS Project Team. GEMAS: CNS con-
464   centrations and C/N ratios in European agricultural soil. Sci Total Environ 627: 975-984, 2018.
465   McClain, M.E., Victoria, R.L., Richey, J.E. (Eds.) The biogeochemistry of the Amazon basin. Oxford Univ
466   Press; 365 p., 2001.
467   McClung, A.C., de Freitas, L.M.M., Lott, W.L. Analysis of several Brazilian soils in relation to plant responses
468   to sulfur. Soil Sci Soc Am Proc 23: 221-224; doi 10.2136/sssaj1959.03615995002300030020x, 1959.
469   McGrath, D., Smith, C.K., Gholz, H.L., de Assis Oliveira, F. Effects of land-use change on soil nutrient dynam-
470   ics in Amazonia. Ecosys 4: 625-645; doi 10.1007/s10021-001-0033-0, 2001.
471   McNeill, A., Unkovich, M. The nitrogen cycle in terrestrial ecosystems. In: Marschner, D., Rengel, Z. (Eds.)
472   Nutrient cycling in terrestrial ecosystems. Soil Biol 10: 37-64; Springer Verlag, 2007.
473   Mekaru, T., Uehara, G. Anion adsorption in ferruginous tropical soils. Soil Sci Soc Am Proc 36: 296-300, 1972.
474   Munsell A.H. Munsell soil colour charts. Macbeth Publishers, New York, 1992.
475   Nagy, L., Forsberg, B., Artaxo, P. Interactions between biosphere, atmosphere and human land use in the Ama-
476   zon basin. Ecol Studies 227: 477 p.; Springer Science Publications, 2016.
477   Neves, C.S.V.J., Feller, C., Guimarães, M.F., Medina, C.C., Tavares Filho, J., Fortier, M. Soil bulk density and
478   porosity of homogeneous morphological units identified by the cropping profile method in clayey oxisols in
479   Brazil. Soil Tillage Res 71, 2: 109-119; doi 10.1016/S0167-1987(03)00023-0, 2003.
480   Quesada, C.A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T.R., Czimczik, C., Fyllas, N.M., Martinelli, L., Nar-
481   doto, G.B., Schmerler, J., Santos, A.J.B., Hodnett, M.G., Herrera, R., Luizão, F.J., Arneth, A., Lloyd, G.,
482   Dezzeo, N., Hilke, I., Kuhlmann, I., Raessler, M., Brand, W.A., Geilmann, H., Moraes Filho, J.O., Carvalho,
483   F.P., Araujo Filho, R.N., Chaves, J.E., Cruz Junior, O.F., Pimentel, T.P., Paiva, R. Variations in chemical and
484   physical properties of Amazon forest soils in relation to their genesis. Biogeosci 7: 1515-1541; doi 10.5194/bg-
485   7-1515-2010, 2010.
486   Rangel-Vasconcelos, L.G.T., Zarin, D.J., de Assis Oliveira, F., Silva Vasconcelos, S., Reis de Carvalho, C.J., de
487   Lourdes Silva Santos, M.M. Effect of water availability on soil microbial biomass in secondary forest in east-
488   ern Amazonia. Rev Bras Ciencia Solo 39: 377-384; doi 10.1590/01000683rbcs20140135, 2015.
489   Reid, P.C., Hari, R.E., Beaugrand, G., Livingstone, D.M., Marty, C., Straile, D., Barichivich, J., Goberville, E.,
490   Adrian, R., Aono, Y., Brown, R., Foster, J., Groisman, P., Hélaouët, P., Hsiung Hsu, H., Kirby, R., Knight, J.,
491   Kraberg, A., Li, J., Lo, T.T., Myneni, R.B., North, R.P., Pounds, J.A., Sparks, T., Stübi, R., Tian, Y., Wiltshire,
492   K.H., Xiao, D., Zhu, Z. Global impacts of the 1980s regime shift. Global Change Biol 22, 2: 682-703; doi
493   10.1111/gcb.13106, 2015.
494   Reimann, C., Caritat, P de. Chemical elements in the environment. Factsheets for the geochemist and environ-
495   mental scientist. Springer, New York; 398 p., 1998.
496   Reimann, C., Birke, M., Demetriades, A., Filzmoser, P., O'Connor, P. Chemistry of Europe's Agricultural Soils,
497   Part A. Methodology and Interpretation of the GEMAS Data Set. Geol Jb B 102: 523 p.; ISBN 978-3-510-
498   96846-6, 2014.
499   Richter, D.D., Babbar, L.I. Soil diversity in the tropics. Adv Ecol Res 21: 315-389, 1991.

500   Roosevelt, A.C. The Amazon and the Anthropocene: 13,000 years of human influence in a tropical rainforest.
501   Anthropocene 4: 69-87; doi 10.1016/j.ancene.2014.05.001, 2013.
502   Rosa, I.M.D., Smith, M.J., Wearn, O.R., Purves, D., Ewers, R.M. The environmental legacy of modern tropical
503   deforestation. Current Biol Rep 26: 2161-2166; doi 10.1016/j.cub.2016.06.013, 2016.
504   Ross, J.L.S. Ecogeografia do Brasil. Subsídios para planejamento ambiental. Oficina de textos, São Paulo; 208
505   p.; ISBN 85-86238-60-0 (in Portuguese), 2006.
506   Rudnick, R.L., Gao, S. Composition of the continental crust. In: Holland, H.D., Turekian, K.K. (Eds.) Treatise
507   on geochemistry 2nd ed., chapter 4.1: 51 p. ISBN: 978-0-08-098300-4; doi 10.1016/B978-0-08-095975-
508   7.00301-6, 2014.
509   Salminen, R. (Ed) FOREGS. Geochemical atlas of Europe. Part 1: Background information, methodology and
510   maps. Geol Surv Finland, Espoo; 525 p; ISBN 951-690-921-3, 2005.
511   Sanches, L., Valentini, C.M.A., Borges Pinto Jr, O., Souza Nogueira, J., Vourlitis, G.L., Sacardi Biudes, M., da
512   Silva, C.J., Bambi, P., de Almeida Lobo, F. Seasonal and interannual litter dynamics of a tropical semidecidu-
513   ous forest of the southern Amazon Basin, Brazil. J Geophys Res 113: G04007; doi 10.1029/2007JG000593,
514   2008.
515   Sanchez, P.A. Properties and management of soil in the tropics. Wiley Interscience, New York; cited in Bohn et
516   al. (2001), 1977.
517   Sanchez, P.A. Properties and management of soil in the tropics. 2nd ed, 666 p. Cambridge Univ Press, New York;
518   ISBN 978-1-107-17605-8, 2019.
519   Schenk, H.J., Jackson, R.B. The global biogeography of roots. Ecol Monogr 72, 3: 311-328; doi 10.1890/0012-
520   9615(2002)072, 2002.
521   Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kögel-
522   Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E. Persis-
523   tence of soil organic matter as an ecosystem property. Nature 478: 49-56, 2011.
524   Sheater, S.J., McKean, J.W. A comparison of testing and confidence intervals for the median. Stat Probabil Lett
525   6: 31-36; doi 10.1016/0167-7152(87)90055-1, 1987.
526   Shukla, J., Nobre, C., Sellers, P. Amazon deforestation and climate change. Science 247: 1322-1325, 2008.
527   Sternberg, L. da S.L., Green, L., Moreira, M.Z., Nepstad, D., Martinelli, L.A., Victória, R. Root distribution in
528   an Amazonian seasonal forest as derived from δ^{13}C profiles. Plant Soil 205: 45-50, 1998.
529   Trumbore, S., Barbosa de Camargo, P. Soil carbon dynamics. In: Amazonia and global change. Geophys Mono-
530   graph Ser 186: 451-462; doi 10.1029/2008GM000741, 2009.
531   Valentini, C.M.A., Sanches, L., de Paula, S.R., Vourlitis, G.L., de Souza Nogueira, J., Pinto Jr, O.B., de Almeida
532   Lobo, F. Soil respiration and aboveground litter dynamics of a tropical transitional forest in northwest Mato
533   Grosso, Brazil. J Geophys Res 113: G00B10; doi 10.1029/2007JG000619, 2008.
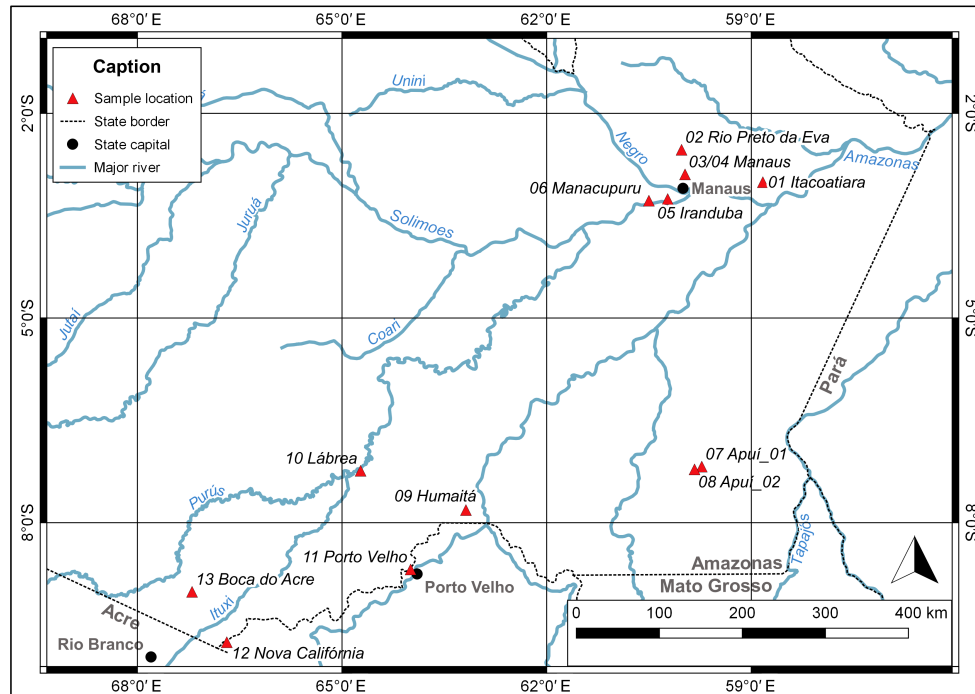
534
535 **Figure 1. Location map Amazon basin (based on QGIS: 2.18.14 Las Palmas)**
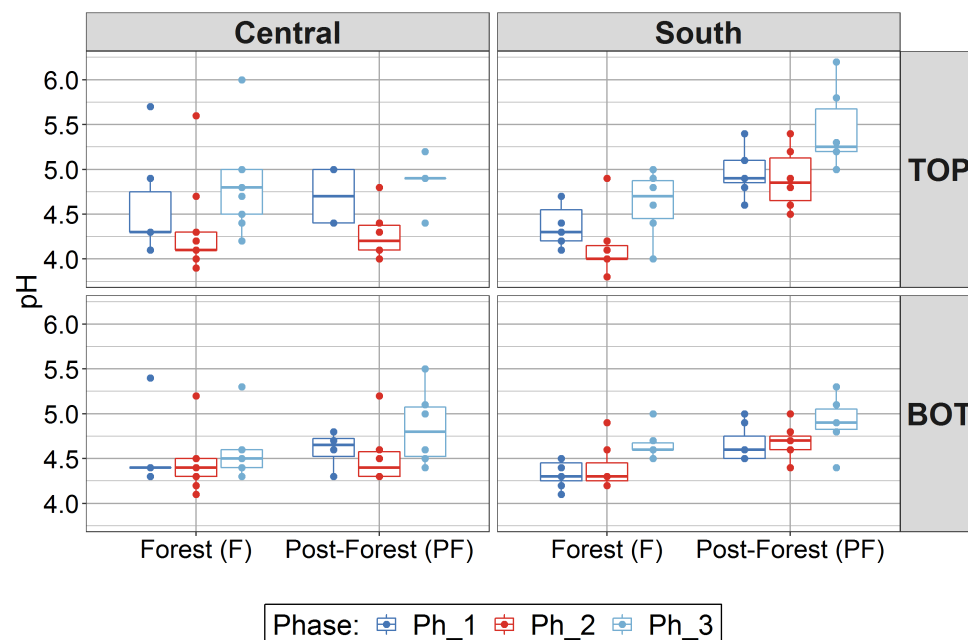
536
537 **Figure 2. Boxplots show seasonal pH_{H2O} dynamics in Amazonas upland soils, differentiated by region (central and**
538 **south) as well as soil depth (TOP, BOT). See text for details**

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Figure 3. Soil solution electrical conductivity (✦) versus pH-value (pH$_{H2O}$) in TOP and BOT samples from all ERA
sites, differentiated by the central and southern locations and by forest (F) and post-forest (PF) land use

540
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542
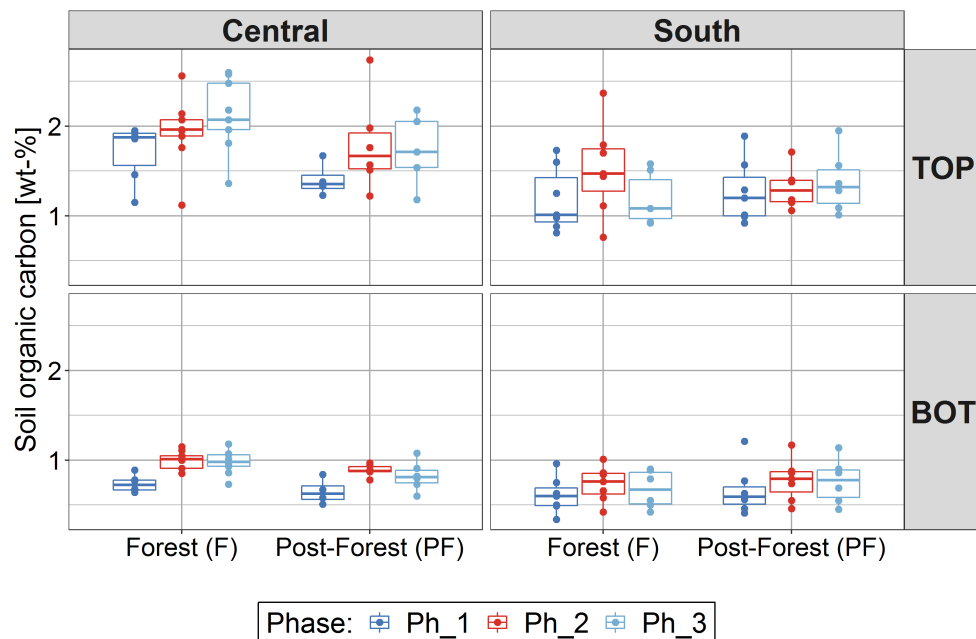
Figure 4. Soil organic carbon boxplots show seasonal dynamics relative to Amazonas region (central and south) as
well as soil depth (TOP, BOT). See text for details

543
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16
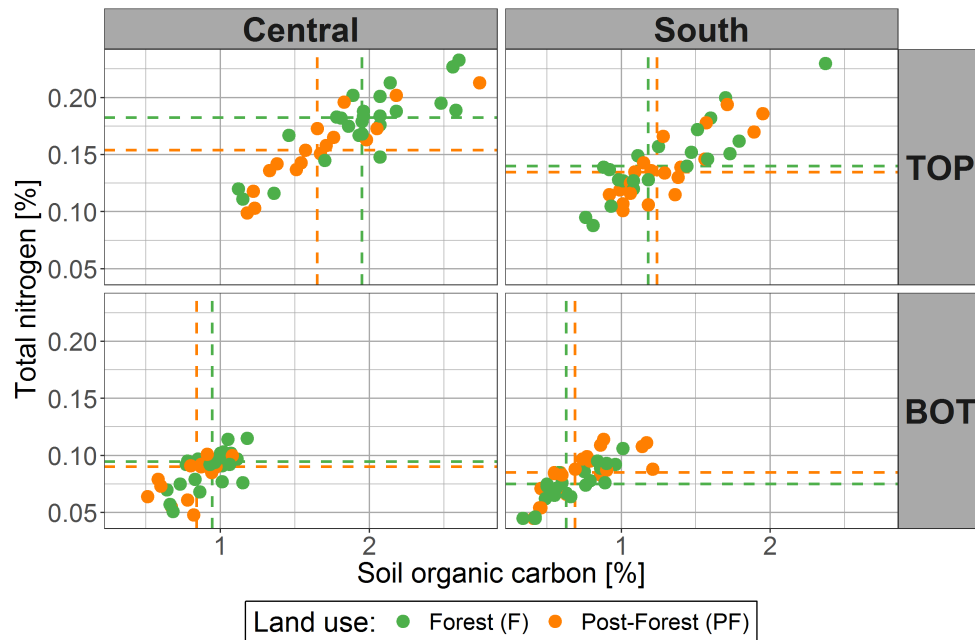
Figure 5. Total soil organic carbon and nitrogen (wt-%) in TOP and BOT samples from all ERA sites, differentiated by the central and southern locations and by forest (F) and post-forest (PF) land use
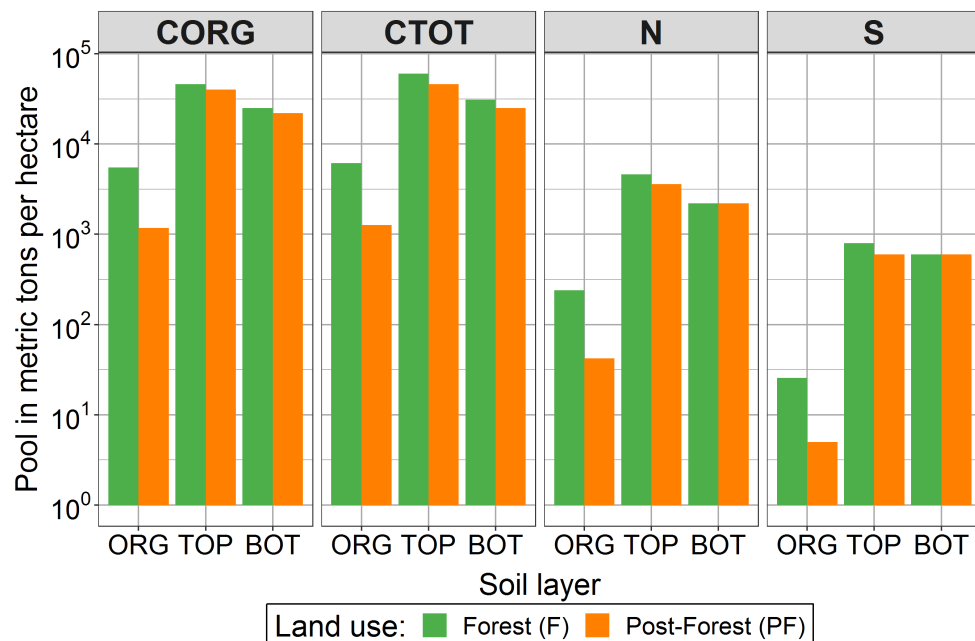
Figure 6. Average total and organic carbon (C_t, C_{org}), nitrogen (N) and sulfur (S) pool sizes per hectare of Amazon Basin soil layers under forest and post-forest land cover

552 **Table 1. Median* soil pH (pH$_{H2O}$ and pH$_{CaCl2}$) and electrical conductivities (λ in μS cm^{-1}) in three subsequent field cam-**
553 **paigns, representing moderately wet (Ph_01), very dry (Ph_02) and very wet (Ph_03) seasons. Data are differentiated**
554 **by land cover (Forest and Post-Forest)**

	pH$_{H2O}$			pH$_{CaCl2}$			λ (μS cm^{-1})		
Season	**Ph_01**	**Ph_02**	**Ph_03**	**Ph_01**	**Ph_02**	**Ph_03**	**Ph_01**	**Ph_02**	**Ph_03**
TOP$_{total}$	4.6	4.2	4.9	3.9	3.8	3.9	43	69	32
TOP$_{Forest}$	4.3	4.1	4.8	3.8	3.7	3.8	49	81	32
TOP$_{Post-Forest}$	4.9	4.6	5.2	4.0	4.0	4.0	32	46	23
BOT$_{total}$	4.5	4.5	4.6	3.9	3.9	4.0	24	30	22
BOT$_{Forest}$	4.4	4.3	4.6	3.8	3.9	4.0	28	33	23
BOT$_{Post-Forest}$	4.6	4.6	4.9	3.9	3.9	4.0	23	25	17

555 *Median: average of all median values from all data sub collectives

556 **Table 2. Median CNS data (wt-%) for all samples (n = 85), differentiated by geographical position and land cover**

| Group	Type	C$_t$	C$_{org}$	N	S	C$_{org}$/N
all data	ORG	42	38	1.4	0.17	27
	TOP	1.9	1.6	0.16	0.03	10
	BOT	1.0	0.8	0.08	0.02	9
all central	ORG	43	39	1.6	0.19	27
	TOP	2.4	2.0	0.18	0.03	11
	BOT	1.1	0.9	0.09	0.03	10
all south	ORG	41	37	1.4	0.16	30
	TOP	1.5	1.2	0.14	0.02	9
	BOT	0.8	0.7	0.08	0.02	9
all forest	ORG	41	37	1.6	0.17	26
	TOP	2.3	1.8	0.17	0.03	10
	BOT	1.1	0.9	0.08	0.02	10
forest central	ORG	41	29	1.6	0.17	27
	TOP	2.4	2.0	0.18	0.03	10
	BOT	1.1	0.9	0.09	0.03	10
forest south	ORG	41	38	1.8	0.17	25
	TOP	1.5	1.2	0.14	0.02	9
	BOT	0.8	0.7	0.08	0.01	9
all post-forest	ORG	42	39	1.4	0.16	32
	TOP	1.8	1.5	0.14	0.02	11
	BOT	0.9	0.8	0.08	0.02	9
post-forest C	ORG	45	42	1.8	0.21	26
	TOP	2.1	1.7	0.16	0.03	11
	BOT	1.0	0.8	0.08	0.02	10
post-forest S	ORG	41	37	1.2	0.14	32
	TOP	1.5	1.2	0.13	0.02	9
	BOT	0.9	0.7	0.08	0.02	8

557 Data rounded for clarity. Detailed values (all meaningful digits) in electronic supplement

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559 **Table 3. Median values for carbon (C, and C_org), total nitrogen (N) and total sulfur (S) in upper continental crust**
560 **(UCC), World Soil Averages (WSA), global ferralsols (WISE30sec), in European TOP and BOT mineral soil**
561 **(FOREGS and GEMAS) and in Amazon basin upland (terra firme) ferralsols (TOP, BOT) with forest (F) and post-**
562 **forest (PF) land cover**

(wt-%)	C_t	C_{org}	N	S
UCC	0.32	n.d.	0.008	0.06
WSA	n.d.	n.d.	n.d.	0.08
WISE30sec TOP	n.d.	1.7	0.15	n.d.
WISE30sec BOT	n.d.	1.0	0.10	n.d.
FOREGS TOP	2.2[#]	1.7	0.17[#]	0.02
FOREGS BOT	n.d.	0.4	n.d.	0.01
F-TOP	2.2	1.8	0.17	0.03
F-BOT	1.0	0.9	0.08	0.02
PF-TOP	1.8	1.4	0.14	0.02
PF-BOT	0.9	0.8	0.08	0.02

563 All values rounded for clarity. "n.d.": not determined. "F": forest, "PF": post-forest. UCC data: Rudnick and Gao
564 (2014). WSA and total carbon in UCC: Reimann and de Caritat (1998); WISE30sec data for global ferralsols, TOP
565 = 0–20 cm, BOT = 20–40 cm: Batjes (2016) and https://www.isric.org/explore/wise-databases; FOREGS data:
566 Salminen (2005), #C and N data: Matschullat et al. (2018), based on the GEMAS project (Reimann et al., 2014)

567 **Table 4. Wet season – dry season dynamics in CNS data (relative percentage change), differentiated by geographical**
568 **position (C = central, S = south) and land cover (forest and post-forest)**

		Median values all sites in wt.-%*			Wet to dry season	
	component	Ph_01*	Ph_02	Ph_03	forest	post-forest
ORG-C	C_t	41.6	41.7	46.6	- 9%	- 13%
	N	1.35	1.49	1.80	- 21%	- 17%
	S	0.201	0.172	0.194	- 8%	- 14%
ORG-S	C_t	40.6	40.8	43.3	- 10%	- 5%
	N	1.38	1.07	1.57	- 18%	- 29%
	S	0.158	0.129	0.169	- 9%	- 27%
TOP-C	C_t	2.12	2.50	2.31	+ 10%	+ 3%
	C_{org}	1.47	1.95	2.05	+ 5%	- 6%
	N	0.159	0.165	0.184	- 2%	- 4%
	S	0.032	0.029	0.030	- 12%	+ 4%
TOP-S	C_t	1.52	1.81	1.45	+ 35%	+ 7%
	C_{org}	1.10	1.40	1.18	+ 36%	- 3%
	N	0.135	0.143	0.136	+ 15%	- 4%
	S	0.023	0.021	0.021	+ 5%	- 8%
BOT-C	C_t	0.86	1.11	1.05	+ 10%	± 0%
	C_{org}	0.68	0.94	0.95	+ 3%	+ 8%
	N	0.075	0.093	0.092	+ 5%	+ 8%
	S	0.019	0.036	0.028	+ 12%	+ 58%
BOT-S	C_t	0.83	0.99	0.87	+ 13%	+ 6%
	C_{org}	0.60	0.78	0.67	+ 13%	+ 1%
	N	0.073	0.085	0.081	+ 13%	+ 8%
	S	0.015	0.018	0.016	+ 24%	± 0%

569 *The individual campaigns returned with slightly different numbers of samples: Ph_01: ORG-C 9,
570 ORG-S 14; TOP-C 10, TOP-S 14; BOT-C 10, BOT-S 14; Ph_02: ORG-C 14, ORG-S 13; TOP-C 15, TOP-S
571 13; BOT-C 15, BOT-S 14; Ph_03: ORG-C 15, ORG-S 10; TOP-C 15, TOP-S 12; BOT-C 15, BOT-S 12
572 Phase 01 was excluded from the intra-annual calculation, since it was an untypical, ENSO-driven,
573 weak wet season

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574 **Table 5. Nutrient element stocks (in kilograms) in the three pools of litter (ORG), mineral topsoil (TOP: 0–20 cm) and**
575 **deeper mineral soil (BOT: 20–50 cm), differentiated by forest and post-forest land cover. Values present total stocks**
576 **per hectare, calculated from the median data in Tables 2–4**

	ORG		TOP		BOT	
	Forest	**Post-Forest**	**Forest**	**Post-Forest**	**Forest**	**Post-Forest**
C_t	6150	1260	60000	46000	31000	25000
C_{org}	5550	1170	46000	40000	25000	22000
N	240	42	4600	3600	2200	2200
S	25.5	5	800	600	600	600

577 <div align="center">All values rounded for clarity</div>
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580 **Electronic supplement**

581 **Table A01**. Average values for temperature and accumulated precipitation versus the climate normal
582 1961–1990 (CN_6190); based on eight INMET meteorological stations in Amazonas

Maximum temperature (°C)							
FEB	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	34.7	32.6	31.7			33.3	34.0	33.7
2017	34.0	31.1	30.5	32.0	31.0	31.5	33.9	31.7
CN_6190	**31.9**	**31.1**	**30.5**	**29.1**	**30.4**	**30.5**	**31.0**	**31.2**
MAR	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	33.1	32.2	31.5			32.7	33.7	31.6
2017	33.8	31.1	30.8	32.3	31.4	32.3	33.4	31.0
CN_6190	**31.9**	**30.7**	**30.1**	**30.9**	**30.6**	**31.0**	**30.8**	**31.3**
JUL	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	34.0	31.7	33.1	34.9	33.4	35.2	31.8	32.7
CN_6190	**31.1**	**30.1**	**31.1**	**31.9**	**31.3**	**32.0**	**29.2**	**31.1**
AUG	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016		33.6	33.8	35.3	34.4	35.7	33.4	34.3
CN_6190	**31.6**	**31.1**	**32.0**	**32.5**	**32.6**	**33.2**	**30.3**	**31.9**
Minimum temperature (°C)							
FEB	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	24.6	22.9	24.7	23.8	25.4	24.1	23.2	24.2
2017	23.3	22.9	23.6	23.2	24.5	23.7	20.3	23.7
CN-6190	**22.1**	**22.4**	**22.0**	**20.7**	**23.1**	**22.0**	**22.6**	**22.9**
MAR	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	23.4	22.5	24.3	24.0	25.4	24.2	22.9	24.2
2017	23.1	22.8	23.8	23.4	24.5	24.0	20.1	24.0
CN-6190	**22.2**	**22.5**	**22.3**	**21.0**	**23.2**	**22.3**	**22.6**	**22.9**
JUL	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	23.4	22.4	23.9	21.1	25.1	22.9	20.7	24.0
CN-6190	**21.5**	**21.5**	**21.8**	**19.0**	**22.7**	**21.2**	**21.6**	**21.9**
AUG	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	23.3	23.0	24.3	21.8	25.7	23.3	20.6	24.0
CN-6190	**21.5**	**21.6**	**21.9**	**19.3**	**23.0**	**21.5**	**21.7**	**22.3**
Corrected average temperature (°C)							
FEB	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	28.2	27.3	27.9	28.3	28.2	27.2	27.3	27.3
2017	27.1	27.4	26.7	26.6	26.8	26.3	26.1	26.9
CN-6190	**26.3**	**25.9**	**25.8**	**25.5**	**25.9**	**25.8**	**26.1**	**26.1**
MAR	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	27.3	27.2	27.5		27.9	27.1	27.1	27.1
2017	27.1	27.4	27.0	26.6	27.0	26.8	25.8	26.7
CN-6190	**26.3**	**25.5**	**25.9**	**26.0**	**26.0**	**26.1**	**26.0**	**26.2**
JUL	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	27.6	26.3	28.4	26.9	28.7	28.0	25.2	27.5
CN-6190	**25.4**	**24.8**	**26.2**	**25.0**	**26.5**	**26.1**	**24.7**	**25.8**
AUG	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	27.6	27.3	28.7	27.3	29.4	28.0	26.0	28.2
CN-6190	**25.7**	**25.4**	**26.7**	**25.5**	**27.3**	**26.7**	**25.2**	**26.3**
Accumulated monthly precipitation (mm)							
FEB	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	53.5	284	402.4	304.2	235.3	256	157.9	226.0
2017	162.7	267.1	377.5	328	257.4	390.9	441.2	317.9
CN-6190	**174.0**	**200.3**	**294.9**	**370.4**	**289.5**	**367.9**	**231.8**	**244.7**
MAR	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	109.8	175.4	628.9	295.2	281.9	391.2	311.8	408.3
2017	98.4	291.6	578.9	197	270	213.6	285.1	173.4
CN-6190	**274.2**	**265.9**	**348.0**	**371.8**	**335.4**	**293.5**	**241.7**	**301.3**
JUL	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	63	189.2	132.7	9.8	103.2	4.5	267.3	166.8
CN-6190	**198.5**	**175.7**	**129.5**	**45.7**	**85.4**	**74.7**	**247.6**	**124.5**
AUG	Barcelos	Fonte Boa	Itacoatiara	Lábrea	Manaus	Manicoré	S.G. Cach. (Uaupés)	Tefé
2016	75	88.8	79.3	5.7	49.8	54.4	142.7	59.5
CN-6190	**155.8**	**153.4**	**82.8**	**83.7**	**47.3**	**75.5**	**193.7**	**101.3**

583   **For Table A02, please see separate zip file**