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Soil carbon is decreasing under “undisturbed” Amazonian forest

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ABSTRACT

Warming climate can cause release of carbon stocks in soils, but direct observations in tropical soils have been lacking. A unique data set from a study near Manaus, Brazil allows comparison of samples taken before and after a ~28-year period in 176 plots in undisturbed forest (i.e., intact forest with no visible sign of modern human action and > 100 m from a forest edge, with 98% of the plots being > 300 m from an edge). The data indicate a significant loss of carbon in the top 20 cm of soil (2.98 MgC ha⁻¹ over 28 years, an average of 0.11 Mg ha⁻¹ year⁻¹, or 0.3828% year⁻¹ of the carbon stock). Carbon emissions would be substantial if the pattern for the top 20 cm at this location holds throughout Amazonia, and the implications are huge if the same pattern holds for the deeper soil layers. Release of soil carbon can contribute to a positive feedback, where emissions cause greater warming that further augments the emissions.

Keywords: Soil carbon; Amazon forest; Global warming; GHG emissions; Climate change

INTRODUCTION

Carbon stocks in the soil under Amazonia's vast forests are a source of concern because of the potential of future global warming to cause their release as carbon dioxide. The potential magnitude of carbon emissions from tropical soils is sufficient to dominate short-term carbon cycle feedbacks (Townsend et al., 1992). Amazonia is a key part of this concern because its vast area and large carbon inventories (per-hectare carbon stocks) mean that even slight changes in the region's carbon balance would have consequences for global climate. For example, changes in soil carbon have been simulated by Jones et al. (2005) using the RothC soil model together with climate and vegetation information from the HadCM3LC climate and biosphere model. The RothC model has a two-pool representation of soil carbon that is believed to be more reliable than the one-pool soil component in the HadCM3LC model itself, which was also run for comparison in the study and showed higher soil emissions than RothC. Manaus, Brazil (the site of the present study) was one of the four locations in the world for which simulated results were generated. For Manaus over the 2000-2100 period, the effect of temperature increase alone in the RothC model was a loss of 16 MgC ha⁻¹ (tons of carbon per hectare) from the soil to 1 m depth (Jones et al., 2005). If this applies to the 5×10^6 km² in Brazil's Legal Amazonia region, it implies emission 8.0 PgC (billion tons of carbon) over the course of the century, or an average of 80 TgC year⁻¹ (million tons of carbon per year). Approximately two-thirds of the Amazon basin is in Brazil, and the total emissions would therefore be larger if the remainder of the basin were considered. In addition to this effect of temperature alone, Jones et al. (2005) calculated a much larger soil-carbon loss as a result of loss of the forest's carbon inputs to the soil under a dieback scenario indicated by the HadCM3LC model that these authors used for their vegetation scenario. The more recent HadGEM2-ES model does not show this dieback, mainly due to its inclusion of beneficial effects of higher CO₂ (Good et al., 2013). Although the rapid dieback shown by the older model is believed to be exaggerated, the forest's resistance to climate change shown by the newer model is believed to be overly optimistic. The newer model omits negative effects of higher CO₂, including an increase in lianas that is already observed at the Biological Dynamics of Forest Fragments Project (BDFFP) study area near Manaus that was also the site of the current study (Fearnside, 2013; Laurance et al., 2014a,b). Whether or not dieback takes place, the effects of temperature increase alone would be expected to occur, thus causing a substantial emission from Amazonian forest soil. The 80 TgC year⁻¹ emission calculated by Jones et al. (2005) from temperature alone can be compared to Brazil's 95 TgC annual emission from fossil fuels in 2010 (Brazil, MCTI, 2016).

The question of soil carbon emissions from climate change has been the subject of an unusual sequence of controversies on both theoretical and observational grounds, with frequent refutations of different calculations. The issues involved are considered to have a "contentious nature" (Lehmann and Kleber, 2015). Uncertainty regarding soil-carbon emissions is one of the greatest sources of overall uncertainty in modeling future climate (Bradford et al., 2016). In the case of tropical soils, data are practically nonexistent on observed losses of carbon, and studies have inconsistent results. Basic parameters for modeling carbon emissions are also poorly quantified. For example, using radioisotopic methods, He et al. (2016) found that the mean ages of soil carbon in the top meter assumed

in the IPCC's CMIP5 earth-system models are, on average, more than six times too low. In terms of carbon sequestration that is predicted to result from increased inputs to the soil from plant growth stimulated by CO₂ fertilization, the difference by the end of the 21st century totals 170 PgC in the top meter of soil. For efforts to contain global warming, this means that the help that has been expected from carbon sequestration in the soil will be less than had been thought and human society must therefore do more to mitigate emissions. In addition, a shorter residence time of carbon in the soil means that net carbon losses from warming soil will be greater, since there will be less compensation from the long-term storage of carbon inputs from plants.

Not all effects of climate change lead to decreased soil carbon. Amazonia has been experiencing an increased frequency of severe droughts, causing tree mortality (Brando et al., 2008; Dai, 2013; Duffy et al., 2015; Lewis et al., 2011; Marengo and Espinoza, 2016; Williamson et al., 2000). At the same time, tree growth has been increasing, resulting in faster turnover of forest biomass (Baker et al., 2004; Malhi et al., 2004; Phillips et al., 2004), which also implies greater deposition of dead biomass (necromass). A common assumption is that additions to soil carbon will result from increased inputs of organic matter, such as necromass resulting from tree mortality, leaf litter, root exudates and turnover of fine roots. For example, Quesada et al. (2010) predicted an average increase in soil carbon stock of 0.33 MgC ha⁻¹ year⁻¹ in Amazonia by assuming that carbon in the top 30 cm of soil would increase in direct proportion to the increase in tree mortality found by Phillips et al. (2004).

A unique opportunity to directly observe changes in forest carbon stocks is provided by the BDFFP, a long-term research project run by the National Institute for Research in Amazonia (INPA) and the Smithsonian Institution in an area approximately 80 km north of the city of Manaus, Amazonas state, Brazil. The site is undisturbed in that it has no known or detectable perturbations from clearing, logging or other modern human activity, although all of the Amazon forest was inhabited by indigenous peoples in past centuries. A soil survey of the BDFFP site conducted between 1984 and 1986 (Fearnside and Leal Filho, 2001) collected samples in marked plots. We collected new samples in 2012-2013 in 176 of the previously sampled plots in the forest interior (> 100 m from a forest edge, with all but seven plots > 300 m from an edge). The objective of the study is to infer stock changes over the ~28-year period between the surveys and to consider the significance of the results for global change.

MATERIALS AND METHODS

The plots used in the present study are spread over a 60-km² area (5 × 12 km) that is the site of a long-term study of the effects of forest fragmentation (Laurance et al., 2018). In addition to isolated reserves, there are also large areas of continuous forest in the fragmentation study. The present soil study only used plots in the continuous forest, not the forest fragments that are also under study at the BDFFP site. The site is centered at 2°20' S, 60°00' W with altitude of 50 – 100 m. Annual precipitation varies from 1900 to 3500 mm, and mean above-ground live biomass is 356 Mg ha⁻¹ (Laurance et al., 1999). The soils are xanthic ferralsols in the FAO/UNESCO system, Oxisols in the U.S. soil taxonomy and yellow latosols in the Brazilian system (Fearnside and Leal Filho, 2001).

Samples for soil carbon in the 0-20 cm depth range were composites of five samples (the four corners of each 20 × 20 m plot plus one at the center). Sampling methodology for the composite samples used for determination of carbon concentration was identical in the two surveys. Samples were taken using a tubular push corer 2.2 cm in diameter. The composite samples did not include litter but did include the topsoil (A horizon). In both surveys samples were then air dried in a solar drier. In the first survey they were further dried for 24 hours in an electric oven at 105°C. Visible plant fragments and charcoal were removed manually and the samples were ground with a pestle and sieved to 2 mm mesh. Voucher specimens from the 1984-1986 survey had been kept in sealed glass jars on shelves in a laboratory where extreme heat and humidity were limited. Small portions of the soil both from the voucher specimens and from the samples collected in the 2012-2013 survey were ground to powder in a mechanical grinder and analyzed at the same time for total carbon by the combustion method using the same apparatus (a Vaio Max C/N elemental analyzer from Elementar Instruments, Hannau, Germany). The Laboratory of Soils and Plants at INPA, where the analyses were done, has an “A” rating from the Brazilian Enterprise for Agricultural and Ranching Research (EMBRAPA). For additional details on methods, see Barros and Fearnside (2016).

Soil bulk density was collected from a single volumetric sample at the center of each plot. The volumetric sampler used in the 2012-2013 survey was a cylinder with a diameter of 3.75 cm, which was driven into the ground to 20 cm depth (Supplementary Material, Figure S-2). In both surveys the volumetric samples did not include litter but did include the topsoil (A horizon). The volumetric samples were dried to constant weight in an electric oven at 105°C. Usable data for soil bulk density are only available for the 2012-2013 sampling, so bulk density in the 1984-1986 period is assumed to be the same. In the 1984-1986 survey the mean soil bulk density for the 176 plots used in the present study was only $0.63 \pm 0.19 \text{ g cm}^{-3}$, a value far below the $0.94 \pm 0.25 \text{ g cm}^{-3}$ value from the 2012-2013 survey (Supplementary Material, Table S1), implying an unrealistic 49% increase in soil bulk density. Because the volumetric sampler used in the 1984-1986 inventory was not available until 1985, the volumetric samples in many of the plots were taken separately from the samples used for carbon and other soil characters. The 1984-1986 survey used a 20-cm depth sampler (Supplementary Material, Figure S-3). Because several people took these volumetric samples the possibility exists that some lack of communication resulted in deviations from the sampling protocol. In contrast, the samples in the 2012-2013 survey were all collected by the same person (HSB).

We made paired comparisons of the carbon content of the 2012-2013 survey with the voucher specimens from 1984-1986 in the same plots. Paired t-tests were performed in Microsoft Excel software to assess changes in carbon concentrations and stocks.

RESULTS

Soil carbon stocks under continuous forest declined (Table 1). Substantial variability in initial carbon stocks among plots ($CV = 0.24$) would prevent detection of any change were it not for the paired comparisons that a longitudinal study of permanent plots allows.

Table 1: carbon stocks and changes in soil carbon stocks in continuous forest.

	Soil carbon stock (MgC ha ⁻¹)		
	Beginning	End	Change
Mean	29.29 ^a	26.31 ^b	-2.98
Standard deviation	5.59	6.21	5.01
n	176	176	176
Paired t-test			p < 0.001
	Soil carbon concentration (%C)		
	Beginning	End	Change
Mean	1.63 ^a	1.49 ^b	-0.14
Standard deviation	0.43	0.52	0.28
n	176	176	176
Paired t-test			p < 0.001
	Soil bulk density (g cm ⁻³)		
	Beginning	End	Change
Mean		0.94	
Standard deviation		0.25	
n		176	

a, b – different letters in the same row indicate significant difference with 99% probability in the paired t-test.

The results can be visualized from a graph of the carbon stock in each sampled plot before and after the ~28 year time interval (Figure 1). If there were no change in carbon stock, all of the points would be aligned along the diagonal bisecting the graph (or be randomly distributed around it). Instead, most of our points fall below this line, indicating carbon loss. The values for all plots are given in the Supplementary Material (Table S1). The mean carbon loss of 2.98 MgC ha⁻¹ over 28 years is equivalent to 0.11 MgC ha⁻¹ year⁻¹. This is a 0.3828% annual release relative to the 27.80 MgC ha⁻¹ midpoint between the beginning and ending mean carbon stock (from Table 1). This represents the best estimate of the percentage release each year relative to the carbon stock at the beginning of the year. Note that this release is a net amount, representing the difference between inputs and outputs, rather than the fractional loss constant (*k*) that determines the turnover time of carbon stocks at equilibrium.

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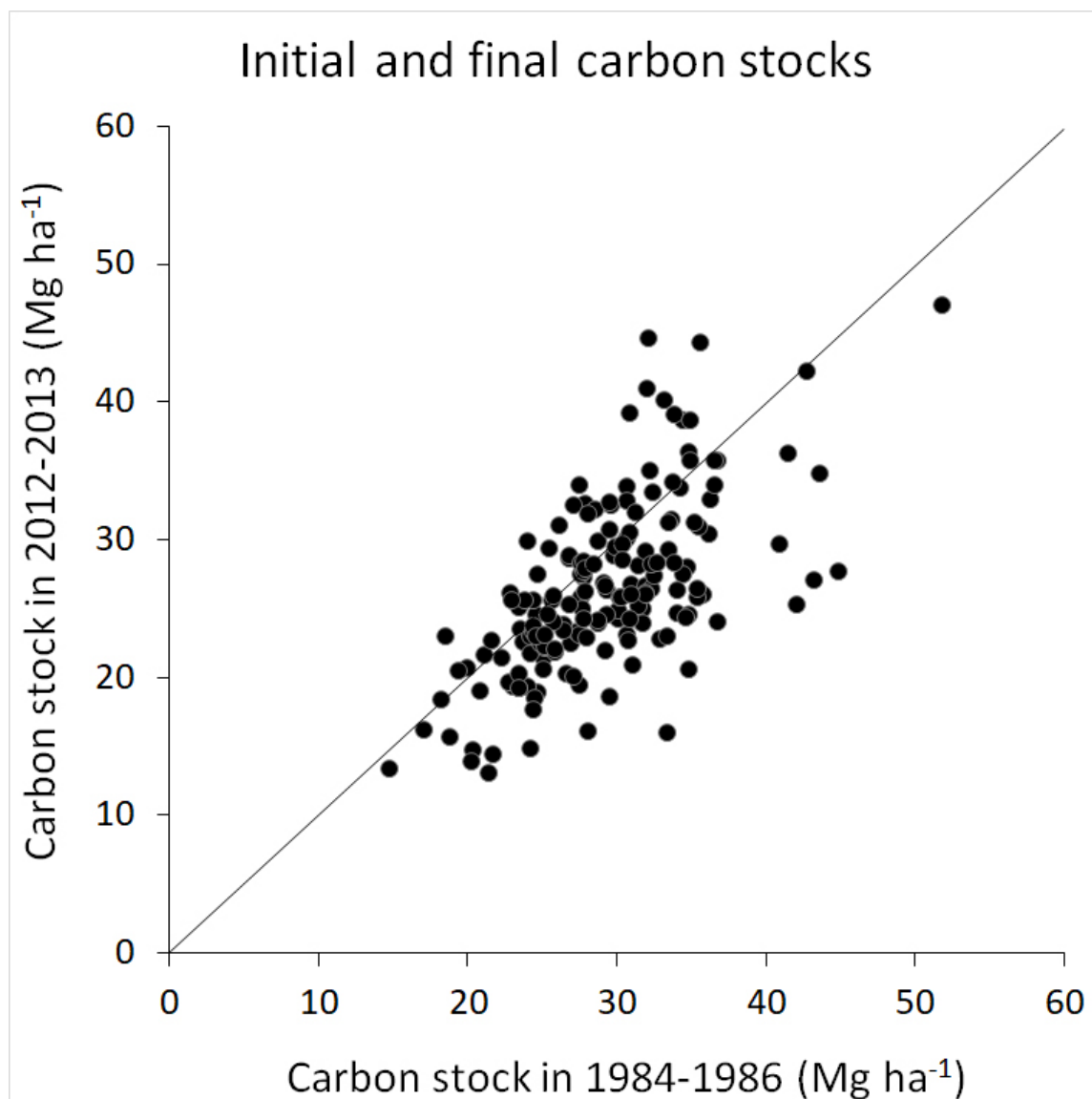


Figure 1. Carbon stocks to 20 cm depth in the 176 pairs of soil samples before and after an interval of ~28 years. If there had been no change, all points would fall on the diagonal or be randomly distributed about it. Most plots (133, or 76%) lie below this line, indicating a decrease in carbon stock.

The spread of results can be visualized from a histogram of the frequencies of the changes in carbon stock falling into different ranges (Figure 2). A similar histogram for changes in carbon concentration is included in the Supplementary Material (Figure S1). The preponderance of carbon losses is clear in both histograms. The histograms show normal distributions with both the means ($-2.98 \text{ MgC ha}^{-1}$, -0.14 \%C) and the medians ($-2.93 \text{ MgC ha}^{-1}$, -0.17 \%C) in negative territory. The finding of carbon loss is clearly not influenced by outliers (the dataset has none). Of the 176 plots, 133 (76%) lost carbon stock and 43 (24%) gained carbon. In the case of random variation with no change in mean carbon stock, 50% of the plots would be expected to lose carbon. For a sample of 176 plots,

the probability of a result this far above the expected 50% is only 3.364×10^{-12} . Put another way, if one were to flip a coin 176 times, the chance of having heads as the result for 133 or more of the tosses would be just one in 297 billion (Wolfram|Alpha, 2011).

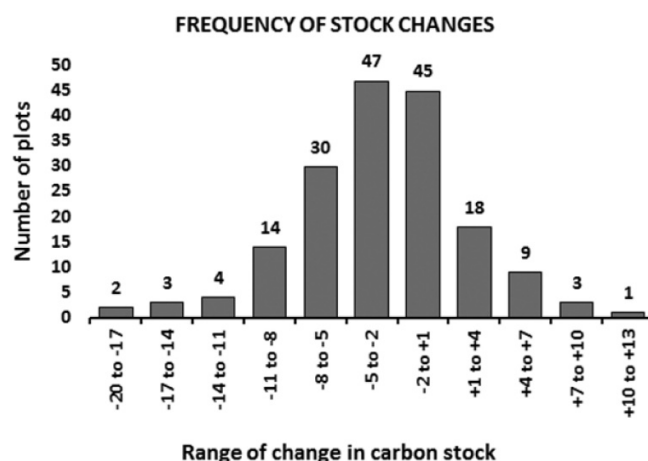


Figure 2. Histogram of the frequency of carbon stock changes over the ~28-year interval. Both the mean ($-2.98 \text{ MgC ha}^{-1}$, $\text{SD} = 5.01$, $n = 176$) and the median ($-2.93 \text{ MgC ha}^{-1}$) are negative, indicating carbon loss.

DISCUSSION

Comparisons with expected trends

Our finding of carbon loss runs counter to the logical expectation of an increase in soil carbon as a result of the increases in Amazon forest biomass. Increased forest biomass has been reported in studies monitoring permanent plots in Amazonia (Baker et al., 2004; Higuchi et al., 1997; Phillips et al., 1998). With an increase in biomass, a greater amount of carbon would fall to the ground after the trees die, followed by decomposition of necromass and an increase in soil carbon stocks in these ecosystems. In the BDFFP study area, biomass increased in plots $> 300 \text{ m}$ from a forest edge from 1981 to 2003, together with increases of both growth and mortality of trees (i.e., increased turnover) and many changes in species composition (S.G. Laurance et al., 2009; W.F. Laurance et al., 2004). Tree growth rates have accelerated over this period, with substantial variation between years. Note that up to 1997 there was no detectible increase in forest biomass observed in measurements in forest interior plots (Laurance et al., 1997; see Fearnside, 2000).

Enhanced soil-carbon emission after enrichment by inputs from decomposition of necromass can be expected to be temporary. Over the long term, the carbon transfer from the biomass to the soil compartment via necromass will be emitted to the atmosphere when the carbon stock tends to a lower equilibrium, as is suggested by the results of our study. In the case of forest edge plots at our study site ($< 100 \text{ m}$ from an edge), where increased necromass had been present for ~30 years, soil carbon had increased in the top 20 cm (Barros and Fearnside, 2016).

Since tree growth increased in plots > 300 m from a forest edge in our study area over the 1981-2003 period, with growth rates increasing by an average of 4% over the period (W.F. Laurance et al., 2004; S.G. Laurance et al., 2009), our finding of a carbon loss in the top 20 cm of soil in these plots suggests that soil carbon stocks would not be greatly enhanced if forest growth were to be further stimulated by higher atmospheric CO₂. Additional evidence that soil carbon stock in the top 20 cm is not increasing as a function of the increase in the primary productivity of the forest is provided by soil profiles taken at a site on the ZF-2 road ~50 km north of Manaus, or approximately 30 km from the site of the present study (and on the same soil type). Profiles taken in the 1980s (Chauvel, 1982; Cerri and Volkoff, 1987), when compared with set of 36 profiles taken at the same site ~20 years later (Telles et al., 2003), show that, although the carbon stock in the surface soil did not change in this comparison, the soil from 50 to 200 cm depth had substantially less carbon in the more recent profiles, indicating an overall carbon loss (see Telles et al., 2003, p. 11).

Uncertainty in our study

The quantitative results (i.e., the change in carbon, either in MgC or as a percentage) assume that there was no change in the carbon content of the stored samples over the ~28-year period. One can presume that if any changes occurred during the storage period, the changes would be in the direction of losing soil carbon. This would result in a bias that would underestimate any carbon losses and so could not explain why the qualitative result (i.e., whether soil carbon is being lost, gained or remaining unchanged) was one of loss rather than of either a gain or no change.

Bulk density was assumed not to change over the study period. Loss of soil organic matter implies an increase in soil bulk density (e.g., Zhou et al., 2006), which, when the density measurements at the end of the period are applied to the initial samples, would make the calculated initial masses of soil at the beginning of the period greater and thereby overestimate the calculated losses of soil carbon. As explained in the methods section, a set of bulk density measurements for the same plots in the 1984-1986 survey (Supplementary Material, Table S1) was not used because of doubts about the sampling methodology. This is the most likely explanation for the 1984-1986 values being much lower, implying an unrealistically drastic increase in mean soil bulk density over the period. Unlike the 1984-1986 soil bulk density values, the values in the present study are consistent with those found in other studies in the same region (Barros and Fearnside, 2015). We note that any difference in soil density between the beginning and the end of the ~28-year period would not affect the values for carbon concentration (percent by weight), since the carbon concentration values determined for the beginning of the period were determined from stored voucher specimens at the same time as the determinations for samples from the end of the period – not from the results of analyses done at the time of the initial survey.

Air drying of soil samples causes some carbon loss as compared to the wet soil under the forest (Barlett and James, 1980). However, these losses would be equal for the samples from both surveys, and so would not affect our estimates of carbon loss over the period. The additional drying of samples for 24 hours at 105°C in the case of the 1984-1986

survey could have released some carbon. However, because losses in this additional drying would underestimate the initial carbon stock, the result would be a bias in the opposite direction from our finding of a carbon loss.

A possible bias in the direction of increasing the calculated carbon loss arises from the difference in drying procedures. The lack of a final oven drying in the second survey means the soil in the second survey would contain a (very) small amount of water. This water would be counted as part of the weight of the soil being analyzed, such that the amount of carbon detected would underestimate the concentration (percentage) present. However, comparison of air-dried samples with the same samples after an additional oven drying indicates only 2-3% water content in the air-dried samples (C.A. Quesada, personal communication, 2017), which would not change our conclusions. In general, possible biases make our quantitative finding conservative as an estimate of the amount of carbon being emitted from soils under Amazonian forest.

Implications for global emissions

The Paris Agreement of 2015 commits the signing countries to keep mean global temperature from passing a limit “well below” 2°C above the pre-industrial mean, and to “pursue efforts to limit temperature increase to 1.5°C above pre-industrial levels” (UNFCCC, 2015). Unlike the Kyoto Protocol, which focused on “directly human-induced” emissions (UNFCCC, 1997), respecting the limits agreed in the Paris Agreement will require that all emissions in the world be mitigated irrespective of whether they are intentionally emitted by humans. These emissions include those from warming of soil as a result of climate change. Reliable estimates of the amounts being emitted are therefore essential for determining the total emission reduction that the countries of the world must achieve.

We emphasize that the results of our measurement at one location cannot be reliably extrapolated to Amazonia as a whole because soil-carbon change will depend on the varied soil properties and climatic conditions at each location. We also lack an explanation of the reasons for the observed decline in soil carbon at our study site in a way that would allow process-based calculations or a spatially disaggregated extrapolation of declines at other sites. Neither clay content nor initial carbon concentration showed any relation to the changes in carbon concentration in our dataset (Data in Supplementary Material, Table S1). However, this being the first measurement of soil-carbon change under undisturbed Amazonian forest, a back-of-the envelope calculation is warranted as an indication of the scale of the emission our results imply, so long as the high uncertainty involved is recognized. This uncertainty applies to global discussions of the potential impact of future climate change and their implications for the amount of mitigation needed to contain these changes. As is a general principle in modeling (Watt, 1966), excluding uncertain information from global estimates does not make those estimates more reliable – instead it simply makes them less realistic.

The top 1 m under undisturbed vegetation in Brazil’s Legal Amazonia region, which represents roughly two-thirds of ‘panAmazonia’ or ‘greater Amazonia’ (See Fearnside, 1997), has been estimated to contain an average of 94 MgC ha⁻¹, of which 42 MgC ha⁻¹ is in

the top 20 cm (Moraes et al., 1995). The stock in Brazil's Legal Amazonia region is estimated at 21 PgC to 20 cm depth and 47 PgC to 1 m depth (Moraes et al., 1995). Soil-carbon inventories (per-hectare stocks) in the portion of pan-Amazonia outside of Brazil are generally greater than those in the Brazilian portion of the region (Gardi et al., 2015, p. 137).

The mean carbon loss of 0.3828% year⁻¹ in the top 20 cm of soil near Manaus, if applied to the 21 PgC in this layer in Brazil's Legal Amazon region (Moraes et al., 1995), implies an emission of 80 TgC year⁻¹ from this layer. If this percentage of emission applies to the 47 PgC in the top meter of soil (Moraes et al., 1995), it implies emission of 180 TgC year⁻¹ from Legal Amazonia. The estimates of soil carbon stocks by Morais et al. (1995) refer to soil under native vegetation based on 1162 soil pits from the RadamBrasil surveys (Brazil, Projeto RadamBrasil, 1973-1983). These values represent original carbon stocks, and the current stocks under natural vegetation would be lower due to loss of part of this vegetation to deforestation. About 20% of Brazil's Amazon forest has now been cleared (Brazil, INPE, 2019), plus a larger percentage of the roughly 25% of Legal Amazonia where the original vegetation was *cerrado* savanna. Most of the deforested area is converted to cattle pasture, where soil carbon decreases under normal management (Fearnside and Barbosa, 1998). Nevertheless, the magnitude of carbon release from areas under natural vegetation is clearly very substantial, and the areas that have been cleared are also net sources of carbon emission from biomass both from land-use change and from impacts of climate change.

A limitation of available studies is the restriction of information to changes in the surface soil, such as the 20-cm depth of samples in the current study. What happens to carbon stocks in deeper layers can have substantial consequences for feedback between soil-carbon emissions and global warming. The deeper layers will eventually warm in response to global temperature increases. The only existing study of "whole soil" carbon flux in response to warming is that of Pries et al. (2017), who warmed soil experimentally to 1-m depth in a boreal forest. The study's authors believe that the substantial releases they found for soil between 30 and 100 cm depth apply to all soils in the world. If our measurements for percentage releases in the 0-20 layer at Manaus apply to these deeper depths in Amazonia, and especially if they apply to soil below 1-m depth, the implied magnitude of releases is of considerable concern for determining the amount of mitigation needed both to keep global temperatures within the limits agreed in the 2015 Paris Accords (UNFCCC, 2015) and to assure the avoidance of a runaway greenhouse.

CONCLUSIONS

Soil-carbon stocks decreased in continuous forests in central Amazonia. Our results showing a decrease in soil carbon are worrying as an indication of the potential for climate change to release large amounts of carbon from Amazonian forest soils. This concern is not diminished by the likelihood that the carbon stocks in these soils may undergo temporary increases from greater tree mortality and necromass inputs to the forest floor over the course of a transition driven by climate change.

Our finding of carbon loss from undisturbed forest-interior plots adds to concern over possible contribution to positive feedbacks between carbon release from different global ecosystems and the global warming these releases cause. The same would apply to the Amazon forest under a hotter and dryer climate regime with more frequent extreme drought events.

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REFERENCES

- Baker T.R., O.L. Phillips, Y. Malhi, , S.A. Almeida, L. Arroyo, A. Fiore, T. Erwin, N. Higuchi, J.T. Killeen, S.G. Laurance, W.F. Laurance, S.L. Lewis., A. Monteagudo, D.A. Neil, P.N. Vargas, N.C.A. Pitman, J.N.M. Silva, and R.V. Martínez. 2004. Increasing biomass in Amazonian forest plots. *Philos. Trans. Roy. Soc. London Series B* 359:353-365. doi:10.1098/rstb.2003.1422
- Barros, H.S., and P.M. Fearnside, 2015. Pedo-transfer functions for estimating soil bulk density in central Amazonia. *Rev. Bras. Ciên. Solo* 39:397-407. doi:10.1590/01000683rbc20140358
- Barros, H.S., and P.M. Fearnside. 2016. Soil carbon stock changes due to edge effects in central Amazon forest fragments. *For. Ecol. Manage.* 379:30-36. doi:10.1016/j.foreco.2016.08.002.
- Bartlett, R., and B. James. 1980. Studying dried, stored soil samples — Some pitfalls. *Soil Sci. Soc. Amer. Jour.* 44:721-724. doi:10.2136/sssaj1980.03615995004400040011x

- Bradford, M.A., W.R. Wieder, G.B. Bonan, N. Fierer, P.A. Raymond, and T.W. Crowther. 2016. Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change* 6:751-758. doi:10.1038/NCLIMATE3071
- Brando, P.M., D.C. Nepstad, E.A. Davidson, S.E. Trumbore, D. Ray, and P. Camargo. 2008. Drought effects on litterfall, wood production and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. *Philos. Trans. Roy. Soc. London Series B* 363:1839-1848. doi:10.1098/rstb.2007.0031
- Brazil, INPE (Instituto Nacional de Pesquisas Espaciais). 2019. Projeto de Monitoramento do Desmatamento na Amazônia Legal (PRODES). INPE, São José dos Campos, SP, Brazil. <http://www.dpi.inpe.br/prodesdigital/prodes.php>.
- Brazil, MCTI (Ministério da Ciência, Tecnologia Inovação), 2016. *Terceira Comunicação Nacional do Brasil à Convenção Quadro das Nações Unidas sobre Mudança do Clima*. MCTI, Brasília, DF, Brazil.
- Brazil, Projeto RadamBrasil. 1973–1983. Levantamento de recursos naturais. Ministério das Minas e Energia, Departamento Nacional de Produção Mineral, Rio de Janeiro, RJ, Brazil, 36 vols.
- Cerri, C.C., and B. Volkoff, 1987. Carbon content in a yellow Latosol of central Amazon rain forest. *Acta Oecolog.* 8:29-42. http://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_5/b_fdi_18-19/23655.pdf
- Chauvel, A. 1982. Os Latossolos Amarelos Álicos argilosos dentro dos ecossistemas das bacias experimentais do INPA e da região vizinha, *Acta Amaz.* 12:47-60. doi:10.1590/S0044-59672008000400005
- Dai, A. 2013. Increasing drought under global warming in observations and models. *Nature Climate Change* 3:52–58. doi:10.1038/nclimate1633
- Duffy, P.B., P. Brando, G.P. Asner, and C.B. Field. 2015. Projections of future meteorological drought and wet periods in the Amazon. *Proc. Nat. Acad. Sci. USA.* 112:13172-13177. doi:10.1073/pnas.1421010112
- Fearnside, P.M. 1997. The main resources of Amazonia. In: *Latin American Studies Association (LASA), XX International Congress, Guadalajara, Mexico, 7-19 April 1997*. LASA, University of Pittsburg, Pittsburg, PA, U.S.A. <http://168.96.200.17/ar/libros/lasa97/fearnside.pdf>
- Fearnside, P.M. 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change* 46:115-158. doi:10.1023/A:1005569915357

- Fearnside, P.M. 2013. Vines, CO₂ and Amazon forest dieback. *Nature* [online comment] <http://www.nature.com/nature/journal/vaop/ncurrent/full/nature11882.html>
- Fearnside, P.M., and R.I. Barbosa. 1998. Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *For. Ecol. Manage.* 108:147-166. doi:10.1016/S0378-1127(98)00222-9
- Fearnside, P.M., and N. Leal Filho. 2001. Soil and development in Amazonia: Lessons from the Biological Dynamics of Forest Fragments Project. In: R.O. Bierregaard, C. Gascon, T.E. Lovejoy, and R. Mesquita, editors, *Lessons from Amazonia: The Ecology and Conservation of a Fragmented Forest*. Yale University Press, New Haven, CT, U.S.A. pp. 291-312.
- Gardi, C., M. Angelini, S. Barcelo, J. Comerma, C. Cruz Gaistardo, A. Encina Rojas, A. Jones, P. Krasilnikov, M.L. Mendonca Santos Brefin, L. Montanarella, O. Muniz Ugarte, P. Schad, M.I. Vara Rodriguez, R. Vargas, and M. Ravina da Silva, editors. 2015. *Soil Atlas of Latin America and the Caribbean*, European Commission – Publications Office of the European Union, L-2995, Luxembourg, 176 pp. doi:10.2788/37334
- Good, P, C. Jones, J. Lowe, R. Betts, and N. Gedney. 2013. Comparing tropical forest projections from two generations of Hadley Centre Earth System models, HadGEM2-ES and HadCM3LC. *Jour. Climate* 26:495–511. doi:10.1175/JCLI-D-11-00366.1
- He, Y., S.E. Trumbore, M.S. Torn, J.W. Harden, L.J.S. Vaughn, S.D. Allison, and J.T. Randerson. 2016. Radiocarbon constraints imply reduced carbon uptake by soils during the 21st century. *Science* 353:1419-1424. doi:10.1126/science.aad4273
- Higuchi, N., J. dos Santos, R.J. Ribeiro, J.V. de Freitas, G. Vieira, A. Cöic, and L.J. Minette. 1997. Crescimento e incremento de uma floresta amazônica de terra-firme manejada experimentalmente. In: Higuchi, N., Ferraz, J.B.S., Antony, L., Luizão, F., Luizão, R., Biot, Y., Hunter, I., Proctor, J., Ross, S., editors, *Bionte: Biomassa e Nutrientes Florestais, Relatório Final*. Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, AM, Brazil. pp. 87-132.
- Jones, C., C. McConnell, K. Coleman, P. Cox, P. Falloon, D. Jenkinson, and D. Powlson. 2005. Global climate change and soil carbon stocks; predictions from two contrasting models for turnover of organic carbon in soil. *Global Change Biol.* 11:154-166. doi:10.1111/j.1365-2486.2004.00885.x
- Laurance, S.G., W.F. Laurance, H. Nascimento, A. Andrade, P.M. Fearnside, E. Rebello, and R. Condit. 2009. Long-term variation in Amazon forest dynamics. *Jour. Vegetat. Science* 20:323-333. doi:10.1111/j.1654-1103.2009.01044.x
- Laurance, W.F., A.S. Andrade, A. Magrath, J.L.C. Camargo, J.J. Valsko, M. Campbell, P.M. Fearnside, W. Edwards, T.E. Lovejoy, and S.G. Laurance. 2014a. Long-term

changes in liana abundance and forest dynamics in undisturbed Amazonian forests.
Ecology 95:1604-1611. doi:10.1890/13-1571.1

- Laurance, W.F., A.S. Andrade, A. Magrach, J.L.C. Camargo, M. Campbell, P.M. Fearnside, W. Edwards, J.J. Valsko, T.E. Lovejoy, and S.G. Laurance. 2014b. Apparent environmental synergism drives the dynamics of Amazonian forest fragments. Ecology 95:3018-3026. doi:10.1890/14-0330.1
- Laurance, W.F., J.L.C. Camargo, P.M. Fearnside, T.E. Lovejoy, G.B. Williamson, R.C.G. Mesquita, C.F.J. Meyer, P.E.D. Bobrowiec, and S.G.W. Laurance. 2018. An Amazonian rainforest and its fragments as a laboratory of global change. Biol. Reviews 93(1):223–247. doi:10.1111/brv.12343
- Laurance, W.F., P.M. Fearnside, S.G. Laurance, P. Delamonica, T.E. Lovejoy, J.M. Rankin-de Merona, J.Q. Chambers, and C. Gascon. 1999. Relationship between soils on Amazon forest biomass: A landscape-scale study. For. Ecol. Manage. 118:127-138. doi:10.1016/S0378-1127(98)00494-0
- Laurance, W.F., S.G. Laurance, L.V. Ferreira, J. Rankin-de Merona, C. Gascon, and T.E. Lovejoy. 1997. Biomass collapse in Amazonian forest fragments. Science 278:1117-1118. doi:10.1126/science.278.5340.1117
- Laurance, W.F., A.A. Oliveira, S.G. Laurance, R. Condit, H. Nascimento, A. Sanchez-Thorin, T.E. Lovejoy, A. Andrade, S. d'Angelo, and C. Dick. 2004. Pervasive alteration of tree communities in undisturbed Amazonian forests. Nature 428:171-175. doi:10.1038/nature02383
- Lehmann, J., and M. Kleber. 2015. The contentious nature of soil organic matter. Nature 528:60-68. doi:10.1038/nature16069
- Lewis S.L., P.M. Brando, O.L. Phillips, G.M.F. Van der Heijden, and D. Nepstad. 2011. The 2010 Amazon drought. Science 331:554. doi:10.1126/science.1200807
- Malhi, Y., T.R. Baker, O.L. Phillips et al. 2004. The above-ground coarse wood productivity of 104 Neotropical forest plots. Global Change Biol. 10:563–591. doi:10.1111/j.1529-8817.2003.00778.x
- Marengo, J.A., and J.C. Espinoza. 2016. Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. Internat. Jour. Climatology 36:1033–1050. doi:10.1002/joc.4420
- Moraes, J.L., C.C. Cerri, J.M. Melillo, D. Kicklighter, C. Neil, D.L. Skole, and P.A. Steudler. 1995. Soil carbon stocks of the Brazilian Amazon Basin. Soil Sci. Soc. Amer. Jour. 59:244-247. doi:10.2136/sssaj1995.03615995005900010038x

- Phillips, O.L., T.R. Baker, L. Arroyo et al. 2004. Patterns and process in Amazon tree turnover, 1976-2001. *Philos. Trans. Roy. Soc. London Series B* 359:437-462. doi:10.1098/rstb.2003.1438
- Phillips, O.L., Y. Malhi, N. Higuchi, W.F. Laurance, V.P. Nuñez, M.R. Vásquez, S.G. Laurance, L.V. Ferreira, M. Stern, S. Brown, and J. Grace. 1998. Changes in the carbon balance of tropical forests: evidence from long-term plots. *Science* 282:439-442. doi:10.1126/science.282.5388.439
- Pries, C.E.H., C. Castanha, R.C. Porras, and M.S. Torn. 2017. The whole-soil carbon flux in response to warming. *Science* 355:1420-1423. doi:10.1126/Science.aal1319
- Quesada, C.A., J. Lloyd, O.L. Phillips, F. Luizão, M. Schwarz, and J.M. Araújo Filho. 2010. A baseline for soil carbon monitoring in Amazonia. In: Gilkes, R., Nattaporn, P., editors, 19th World Congress of Soil Science, Soil Solutions for a Changing World. 2010, Brisbane, Australia. International Union of Soil Sciences, University of Western Australia, Crawley, Australia. pp. 437-440. <http://iuss.org/19th%20WCSS/Symposium/pdf/0117.pdf>
- Telles, E.C.C., P.B. Camargo, L.A. Martinelli, S.E. Trumbore, E.S. Costa, J. Santos, N. Higuchi, and R.C. Oliveira Jr. 2003. Influence of soil texture on carbon dynamics and storage potential in tropical forest soils of Amazonia. *Glob. Biogeochem. Cycles* 17, 1040-1052. doi:10.1029/2002GB001953
- Townsend, A.R., P.M. Vitousek, and E.A. Holland. 1992. Tropical soils could dominate the short-term carbon cycle feedbacks to increase global temperatures. *Climatic Change* 22:293-303. doi:10.1007/BF00142430
- UNFCCC (United Nations Framework Convention on Climate Change). 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Document FCCC/CP/1997/7/Add1, UNFCCC, Bonn, Germany. <https://unfccc.int/resource/docs/convkp/kpeng.pdf>
- UNFCCC (United Nations Framework Convention on Climate Change). 2015. Adoption of the Paris Agreement. FCCC/CP/2015/L.9/Rev.1. UNFCCC, Bonn, Germany. 32 pp. <https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>
- Watt, K.E.F. 1966. The nature of systems analysis. In: K.E. F. Watt, editor, *Systems Analysis in Ecology*. Academic Press, New York. pp 1-14.
- Williamson, G.B., W.F. Laurance, A.A. Oliveira, P. Delamonica, C. Gascon, T.E. Lovejoy, and L. Pohl. 2000. Amazonian Tree Mortality during the 1997 El Nino Drought. *Conserv. Biol.* 14:1538-1542. doi:10.1046/j.1523-1739.2000.99298.x
- Wolfram|Alpha. 2011. Coin toss probabilities. Wolfram Alpha LLC, Champaign, IL, U.S.A.

619 <http://www.wolframalpha.com/widgets/view.jsp?id=d821210668c6cc5a02db1069cc>
620 52464f
621
622 Zhou, G., S. Liu, Z. Li, D. Zhang, X. Tang, C. Zhou, J. Yan, and J. Mol. 2006. Old-growth
623 forests can accumulate carbon in soils. Science 314:1417.
624 doi:10.1126/science.1130168
625