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DIGGING DEEPER: THE VALUE OF DEEP SOIL CARBON FOR POTENTIAL REDD+ PROJECTS IN TROPICAL FOREST COMMUNITIES IN AMAZONIA

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With 5 figures, 2 tables and 1 photo
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Summary: The deforestation of tropical forests plays a key role in terms of carbon dioxide emissions and thus accelerates climate change. With the initiative Reducing Emissions from Deforestation and Forest Degradation (REDD+), the UN spearheaded an approach to valorize ecosystems for their sequestered organic carbon (OC) to protect them for the sake of mitigating global climate change. In Brazil, where large areas of intact forests abound, especially within the territories of indigenous people, REDD+ schemes are highly sought after but are often hard to establish due to the given uncertainties in carbon stock evaluation at greater soil depths, intercultural communication problems and power asymmetries. With permission from the Kayapo/Mekragnoti tribe, our interdisciplinary research team dug a 10.0 m soil profile under a pristine forest situated on their indigenous territory in Pará, Brazil. Our results show that by following the Land Use, Land Use Change and Forestry (LULUCF) guidelines of the United Nations Framework Convention on Climate Change (UNFCCC), focusing on the first 0.3 m of soil only captures 21 % of the total soil OC present. Furthermore, only 51 % of soil OC was stored in the first metre, while 84 % of OC was captured if the sampling depth expanded to 3.0 m. This study notes that for adequate calculation and validation of stored soil OC, at least one real measurement (i.e., the Tier 3 approach) is needed to represent OC stocks in the subsoil.

Zusammenfassung: Die Abholzung des tropischen Regenwaldes spielt eine große Rolle beim Ausstoß von Kohlendioxid und treibt somit den Klimawandel an. Mit dem Programm Reducing Emissions from Deforestation and Forest Degradation (REDD+) wurde durch die UN eine Möglichkeit geschaffen, natürliche Ökosysteme u.a. gemäß Ihrer ober- sowie unterirdischen Kohlenstoffspeicherleistung in Wert zu setzen. In Brasilien ist dies besonders interessant für Indigene, die große Gebiete intakten Regenwaldes mit entsprechend hohem Sequestrierungspotential besitzen. Umstritten bleibt die Frage, bis in welche Bodentiefe der finanzielle Wert einer solchen Fläche bemessen werden sollte. Auf Einladung des Volkes der Kayapo/ Stamm Mekragnoti hatten wir die Möglichkeit ein 10 m tiefes Bodenprofil in einem ursprünglichen Regenwald in Pará/ Brasilien zu beproben. Die Ergebnisse zeigen, dass nur 21 % des Bodenkohlenstoff erfasst werden, wenn die Bemessungsgrundlage den Mindestvorgaben der IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (LULUCF) folgen. Bereits 51 % des Bodenkohlenstoffs sind im ersten Meter gespeichert, wohingegen 84 % des Bodenkohlenstoffs bis in 3.0 m Tiefe berücksichtigt werden. Diese Studie zeigt, wie wichtig es ist, den Kohlenstoff im Boden auf der Grundlage von Feldmessungen („Tier 3-Ansatz") zu berechnen, und es einen großen Unterschied macht, bis in welche Tiefe der Bodenkohlenstoff berücksichtigt wird.

Keywords: deep soil carbon, subsoil, Amazon rain forest, REDD+, soil organic matter, carbon markets, Brazil

1 Introduction

The deforestation of tropical forests is one of the main drivers of increased atmospheric carbon dioxide emissions and therefore a key topic in the analysis of causes and mitigation of climate change (Arima et al. 2014; Fearnside 2017). In recent decades (1996–2010), more than 1 Mio km^2 of tropical forests has been destroyed by deforestation, much of it in the Amazon. The Brazilian Amazon is one of the largest tropical forest ecosystems in the world, holding one-third of the world's remaining tropical forests (FAO 2012), clearly making the preservation of these forests an undertaking of global importance. There are many strategies under discussion and testing to reach this goal. One of these strategies takes advantage of world driven economic constraints and links preservation to market value. With the initiative 'Reducing Emissions from Deforestation and Forest Degradation' (REDD+), the United Nations has spearheaded an initiative that should allocate forest ecosystems a value equivalent to the CO_2 emissions spared by avoiding deforestation or to the additional CO_2 that has been sequestered if reforestation is the case. Consequently, the REDD+ initiatives and projects

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generate carbon credits for the reduced greenhouse gas (GHG) emissions that would otherwise be released by deforestation and degradation of native forest. Nevertheless, questions prevail regarding who ultimately benefits from these carbon credits and how their values are correctly and realistically assessed. The question of who benefits or who has ownership of the carbon credits derived from REDD+ projects is directly linked to the question of who legitimately owns the territory and the forest resources. In Brazil, indigenous peoples hold the exclusive usufruct of the natural resources of 1.1 Mio km^2 of the Amazon region (Garzón 2009 and RAISG 2015), which should include the right to directly develop and negotiate REDD+ projects. However, the reality is that this situation is often not the case, as only isolated projects have been put into practice in the past (Caplow et al. 2011). Additionally, the compensatory payments are often channelled into the hands of so-called "carbon cowboys", consultants and firms that specialize in this kind of double dealing (Zwick and Borges 2012). This process yields one of the main arguments of the Brazilian government against any kind of direct payment of environmental services (PES).

Apart from the political complexities, a further aggravating factor is the complexity of assessing the value of a native forest. The IPCC (2006) *Guidelines for National Greenhouse Gas Inventories* provides a three-tiered approach to estimate, report, and monitor GHG emissions (Birdsey et al. 2013). The "three tiers" include different levels of evaluating the stored carbon in the ecosystem. These tiers include (i) IPCC default values for carbon stocks in different ecoregions and country-specific activity data, (ii) country-specific data about forests and carbon stocks within detailed strata, and (iii) country-specific activity data inventories with repeated direct measurements of changes in carbon stocks or models parameterized with country-specific data and country-specific activity data.

The scenario is further complicated by the two pools to consider in the calculation of the sequestered carbon: the aboveground and belowground pools. While the assessment of the aboveground, or standing, biomass is possible by increasingly accurate remote sensing techniques, the belowground biomass, along with the (dead) soil organic carbon (OC), still imposes a substantial challenge to quick, precise, and cost-effective monitoring and pricing. The IPCC (2003) *Good Practice Guidance for Land Use, Land Use Change and Forestry* (GPG-LULUCF) recommends integrating soil OC storage down to a minimum soil depth of 0.3 m. This depth is surprisingly shallow, particularly in deeply weathered tropical soils, such as Ferralsols, the most common soil type in the Brazilian Amazon, where soil depth can often exceed depths greater than tens of metres (Quesada et al. 2011). Based on the FAO soil classification system, Batjes (1996) stated that the global soil OC budget increases by 60 % if the soil OC storage calculation increased to a depth of two metres instead of only the first metre, let alone the first 30 cm. Accordingly, Jobbágy and Jackson (2000) found that half of the OC was stored in the second and third metres in tropical evergreen forests and that the remaining half was stored in the first metre. To evaluate the "fair" soil depth down to which soil OC should be determined to map OC stocks completely, we dug a 10 m soil pit under Amazonian pristine forest in the Menkragnoti Reserve, Pará, Brazil. Our objectives were (i) to determine the amount of carbon stored under a tropical forest in order to evaluate the lost value imposed by the IPCC suggestion to integrate only the first 0.3 m of soil and (ii) to evaluate the IPCC Tier 3 approach as a possible tool leading to fair the valorization of carbon credits, thus potentially facilitating a higher number of working REDD+ projects.

2 Material and methods

2.1 Research area

The study area is situated in southeast Pára, in the Brazilian Amazon (Fig. 1), with an annual rainfall of 2278 mm, a drier season from May to September and an average temperature of 24.7°C. The native vegetation is a semi-evergreen tropical forest (Volkoff et al. 2012) with tree canopy layers reaching up to 30 m. The prevailing soil type in this area is Ferralsol (Quesada et al 2011), characterized by a high content of kaolinitic clay and Al and Fe oxides resulting from deep weathering. Along Highway 163, there are many small settlements and mid-sized towns of pioneers who have occupied the region since the mid-1970s; their inhabitants engage in cattle ranching, the service sector, and agriculture. Agricultural practices gradually change from the south to the north, with comparably large farms growing mainly soy, corn and cotton in Mato Grosso (in the south) and small-scale, cattle farming in Pará (in the north). Of the total 1.1 Mio km^2, or 22.3 %, of the Brazilian Amazon region (5 Mio km^2) that are declared as indigenous

Fig. 1: Location of the research area

reserves (RAISG 2015), 0.28 Mio km² are situated in Pará (ISA 2014). These areas hold small human populations and are characterized by a comparably low intervention frequency and intensity of the forest ecosystems, the latter of which is a prerequisite to analyse the soil OC storage under a pristine forest down to the deeper subsoil. The soil pit (08° 19'31.2 S / 054° 40'12.2 W) was installed in the Menkragnoti Reserve, which has an area of 4.914 255 ha and a population of approximately 1200 people (ISA 2017). The reserve is located approximately 60 km east of a village called Castelo de Sonhos and is only accessible by a gravel road. Access to indigenous territories in Brazil is generally restricted and requires an invitation by the members of the tribe themselves, which was graciously granted to us and was reciprocated by a complete data-sharing agreement.

2.2 Soil sampling and analysis

The 10 m soil pit was dug by hand with the help of a professional well builder (photo 1). The pit's diameter was 1.2 m. Mixed soil samples were taken at 0.2 m increments, with 4 replicates along a vertical strand (every 90° around the circle profile). The samples were initially air-dried until they could be dried in a laboratory oven at 50°C until a consistent weight was achieved. All samples were sieved <2 mm for further analysis. For calculating bulk density, three undisturbed core samples (100 cm^3) were taken at increments of 1.0 m. Soils were classified according to IUSS Working Group (FAO 2015).

pH values were determined in distilled water in cases of bulk soil samples (2.5:1) and measured potentiometrically with a Metrohm 632 pH metre otherwise. Exchangeable, plant available cations (Ca, K, Mg), exchangeable Al and exchangeable Fe were analysed using Mehlich-3 extraction (Mehlich 1984). An inductively coupled plasma optical emission spectrometer (Varian 725-ES; Agilent Technologies, Santa Clara, USA) was used for elemental analyses. We distinguished soil texture through pipette analysis using tetrasodium diphosphate as the dispersant (Blume et al. 2011).

Soil OC concentrations were determined by an elemental analyser (vario ISOTOPE cube, Elementar GmbH, Hanau, Germany) after the samples were ground with a ball mill (Retsch MM200, Haan, Germany). Bulk density was calculated gravimetrically after drying the samples taken by a soil corer of defined volume (100 cm^3) for 48 h at 105°C.

3 Results

3.1 Soil organic carbon concentration and general soil parameters

The soil profile revealed two soil layers (Fig. 2). The first layer showed classical properties of a Haplic

Photo 1: The well builder entering the soil profile

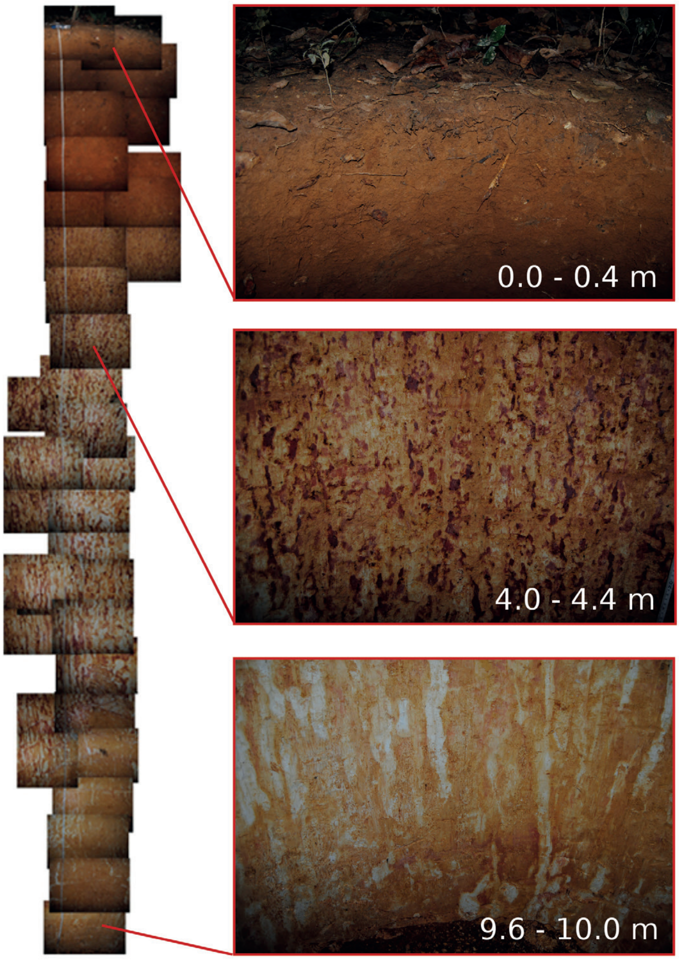

Fig. 2: Soil profile of the 10 m pit

Tab. 1: General soil parameters with standard deviations in parentheses. All values except the texture and pH values are the average value for the one-metre increments. The red line shows the change between the two soil layers.

Depth [m]	OC [%]	pH value	Al mmolc kg^{-1}	Fe mmolc kg^{-1}	K mmolc kg^{-1}	Ca mmolc kg^{-1}	Mg mmolc kg^{-1}	Clay [%]	Sil [%]	Sand [%]
1.0	1.30 (±0.38)	4.40	179.35 (±5.11)	3.38 (±1.68)	0.47 (±0.23)	0.56 (±10.18)	0.30 (±0.18)	70.47	16.95	12.59
2.0	0.51 (±0.17)	4.79	159.60 (±5.17)	0.62 (±0.12)	0.17 (±0.04)	0.39 (±10.17)	0.16 (±0.05)	59.90	25.08	15.02
3.0	0.18 (±0.08)	5.21	117.80 (±22.14)	0.45 (±0.04)	0.13 (±0.02)	0.75 (±10.43)	0.18 (±0.03)	46.67	41.01	12.32
4.0	0.08 (±0.03)	5.36	76.92 (±8.86)	0.37 (±0.05)	0.13 (±0.04)	0.58 (±10.30)	0.13 (±0.02)	43.18	50.28	6.54
5.0	0.05 (±0.01)	5.11	65.91 (±3.16)	0.38 (±0.05)	0.16 (±0.01)	1.49 (±11.50)	0.25 (±0.15)	36.15	55.04	8.81
6.0	0.04 (±0.01)	5.21	56.01 (±4.42)	0.37 (±0.03)	0.10 (±0.03)	0.54 (±10.44)	0.16 (±0.06)	27.54	67.07	5.39
7.0	0.04 (±0.02)	5.12	47.83 (±4.95)	0.36 (±0.05)	0.08 (±0.03)	0.52 (±10.29)	0.13 (±0.01)	24.64	69.40	5.96
8.0	0.03 (±0.01)	5.00	33.25 (±11.76)	0.27 (±0.07)	0.13 (±0.07)	0.50 (±10.36)	0.12 (±0.05)	17.08	76.37	6.55
9.0	0.02 (±0.01)	5.15	51.77 (±3.24)	0.29 (±0.05)	0.12 (±0.04)	0.23 (±10.16)	0.14 (±0.03)	18.15	76.13	5.72
10.0	0.02 (±0.01)	5.16	55.93 (±2.73)	0.37 (±0.03)	0.13 (±0.03)	0.45 (±10.20)	0.12 (±0.01)	19.54	76.69	3.77

Ferralsol, with bulk densities from 0.9–1.2 g cm-3, pH ranging between 4.1–5.2, and high clay contents of 60-70 % (Tab. 1). Exchangeable Al was the dominant cation with an average of 150.2 mmolc kg^{-1} ± 29.3, while exchangeable K, Ca and Mg had significantly smaller amounts (Tab. 1). The second layer was influenced by seasonal groundwater oscillations and differed in its soil properties. The bulk density was higher, the pH value levelled out at 5.3, and the clay content decreased to less than 20 % between 9.0–10.0 m.

The average value of exchangeable Al was only one-third (50.5 mmolc kg^{-1} ± 13.9) of the amount measured in the upper layer. The amounts of other exchangeable cations also decreased.

As expected, the soil OC concentration decreased constantly with depth (Fig. 3). The highest concentrations were found in the first 0.2 m at 18.6 g kg^{-1} ± 2.3, whereas at a depth of 9.8 to 10.0 m, the OC concentration decreased to a minimum of 0.2 g kg^{-1} ± 0.0. At depths greater than 3.0 m, the OC concentration fell below 1 g kg^{-1}, which coincided with the shift from the first to the second layer in the soil profile (Fig. 2).

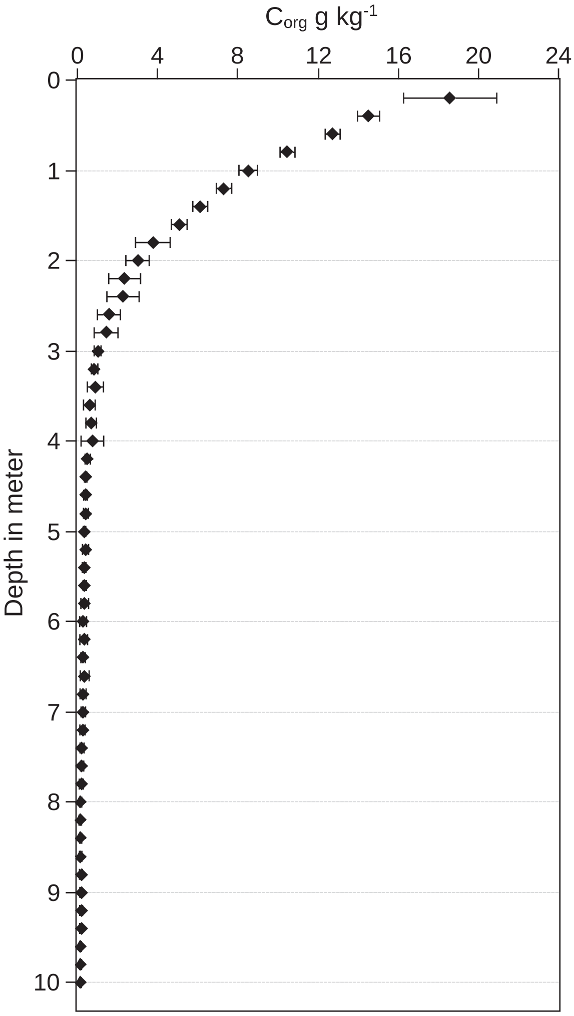

Fig. 3: Average (n = 4) soil OC concentration (g OC kg-1). Error bars show standard deviation.

3.2 Soil OC storage and vertical distribution

In total, 216.1 Mg C ha^{-1} ± 22.6 was stored in the first 10.0 m of soil. Roughly half of soil OC was stored in the first metre of the soil pit (111.0 Mg C ha^{-1} ± 11.8). Soil OC stocks decreased exponentially with depth (Fig. 4). However, 2.9 Mg C ha^{-1} ± 0.7 was still stored in the 9.0 to 10.0 m increment. If soil OC storage had been calculated using the IPCC guideline (0.3 m), only 46.5 Mg C ha^{-1} ± 11.8 would be taken into account (Fig. 4 – orange bar).

If the OC storage to a depth of 10.0 m is considered 100 %, only 22 % of the C-storage potential falls within the first 30 cm. The first metre represents 52 % of total storage, while 84 % of soil OC is accounted for when soil sampling was increased to a depth of 3.0 m (Fig. 5). If the soil OC storage is scaled up to the territory of the Menkragnoti Reserve (49143 km^2), the difference in the stored soil OC measured between the sampling depth of 0.3 m and 10.0 m comprises over 870 Mio Mg OC (Tab. 2).

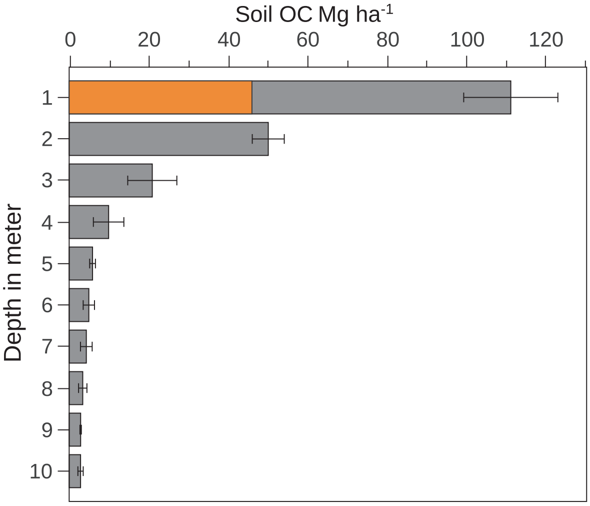

Fig. 4: Soil OC stocks and the vertical distribution per metre. The orange bar demonstrates the soil OC storage for the first 0.3 m. Error bars show standard deviation.

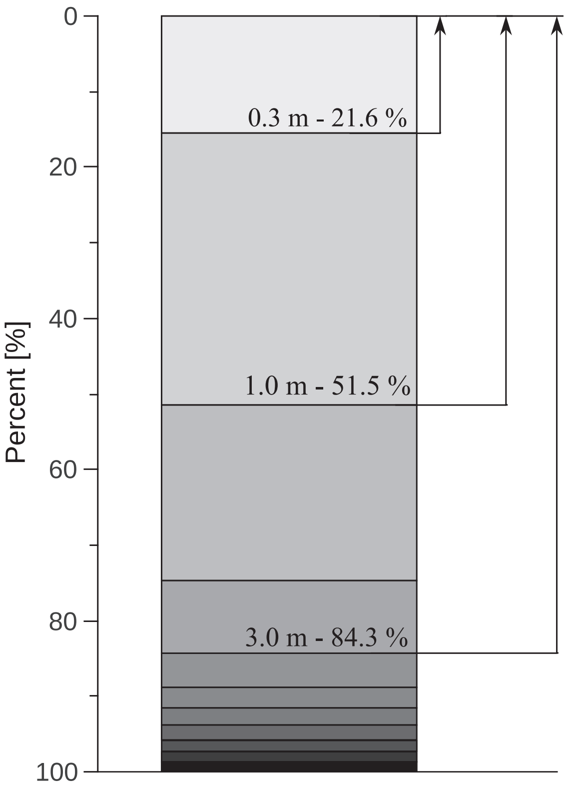

Fig. 5: Percent proportion of the vertical distribution of the soil OC storage.

4 Discussion

The vertical distribution of soil OC to a depth of 10.0 m showed that the majority of OC (> 87 %) is stored at depths greater than 0.3 m. Therefore, soil OC stocks are highly underestimated if only the first 0.3 m is considered, which is the minimum requirement of the GPG-LULUCF. Even if soil OC to a depth of 1.0 m is integrated into calculations, only 55 % of soil OC is reflected. Nevertheless, 0.3 m is still a conventional sampling depth in many studies (e.g., Braz et al. 2013, Twongyirwe et al. 2013, Eclesia et al. 2012). Few studies have sampled soils deeper than 3.0 m; one of them is the study by Harper and Tibbett (2013), who analysed deeply weathered regolith down to depths of 12 to 38 m in Australia. These authors reported similar results to our analyses; 218 Mg OC ha^{-1} ± 2.7 was stored in the sampled 12.0 m profile, which is surprisingly similar to our results of 216 Mg OC ha^{-1} ± 22.6 in the 10.0 m profile (despite the low comparability of the ecosystems). Trumbore et al. (1995) sampled deep carbon to a depth of 8.0 m in eastern Pará. These authors compared the soil OC storage of forest sites to degraded sites and managed pastures and reported soil OC stocks from 257 - 300 Mg OC ha^{-1}, values slightly higher than those measured in our study, which might be due to the influence of seasonal groundwater that periodically rose to a soil depth of approximately 2.0 m in the latter case. Reductive dissolution of ferric Fe in oxide form to dissolved ferrous Fe leads to a significant release of OC into the soil solution (Hagedorn et al. 2000).

In a study by Strey et al. (2016), similar δ13C values were measured in soils under pastures that had been transformed from tropical rainforest, showing that 20 % of soil OC was exchanged from forest-derived to pasture-derived OC in soil depths of 0.6 - 1.0 m. This exchange occurred in less than a decade. A study by Trumbore et al. (1995) found that soil samples deeper than 1.0 m showed only minimal differences (< 0.6‰) in their 13C signal after ~23 years of pasture use, but if the CO_2 emissions from soil were analysed for δ13C isotopes, the isotopic change could be tracked down to a depth of 8.0 m. This result provides evidence that land-use changes influence soil OC in deep soil layers, but it does so with a certain delay. This fact was also underlined by findings from Nepstad et al (1994), who analysed the rooting depth at the same sampling spot as Trumbore et al. (1995). These authors found roots in managed pasture to a depth of 8.0 m. However, in forest soil, roots were found to a depth of 18.0 m. Nevertheless, the debate over which depth soil OC monitoring and thus valorization should occur is still open. Indeed, the soil depth from which OC is sampled and the carbon pool is determined is extremely important, particularly when this affects the basis for prizing CO_2 certificates, e.g., in REDD+ schemes (Tab. 2).

Next, when considering the question regarding which depth soil OC stocks should be measured to, if the first and second tiers of the IPCC Guidelines for National Greenhouse Gas Inventories are adequate to calculate approximate soil OC stocks or if it is crucial to realize the tier three approach and execute at least individual direct measurements must be discussed.

Two renowned Brazilian research institutes published their estimated OC stocks for the Menkragnoti territory based on the first and second tier approaches. The Amazon Environmental Research Institute (IPAM) estimated 81 Mg OC ha^{-1} and a total amount of 398 Mio Mg OC for the complete area. This estimate was based on the study of by Saatchi et al. (2007). The Instituto Socioambiental (ISA) calculated 141.0 Mg OC ha^{-1} and 694 Mio Mg OC for the Menkragnoti territory, which is approximately 50 % more OC than in the study by Saatchi et al. (2007). Both studies included aboveground and below-

Tab. 2: Calculated soil OC stocks for the Menkragnoti territory based on different soil depths

	0.0 – 0.3 m	**0.0 – 1.0 m**	**0.0 – 3.0 m**	**0.0 – 10.0 m**
Mg OC ha^{-1}	46.47	110.95	181.86	216.05
Mg OC modelled for the area [ha] of the Menkrãgnoti*	228.5 Mio.	545.3 Mio.	893.7 Mio.	1.1 Bill.
Amount of OC stocks compared to the total 10 m [%]	21.6	51.5	84.3	100
Equivalent price for Mg CO_2 modelled for the stored soil OC°	1.28 Bill. €	3.05 Bill. €	5.01 Bill. €	5.95 Bill. €

* 4914254 ha

° price per Mg CO_2 emission 19th Nov. 2016 - http://www.investing.com/commodities/carbon-emissions-historical-data

ground living biomass but did not integrate soil OC stocks (ISA and Forest Trends 2010). If we compare the calculated OC stocks of the living biomass to the data we measured for soil OC, the use of a 2.0 m soil profile exceeds the OC stocks (161.0 Mg OC ha^{-1}) of the plant biomass. When soil OC to a depth of 10.0 m is integrated (216.1 Mg OC ha^{-1} ± 22.6), the soil OC stocks are over 70.0 Mg OC ha^{-1} higher than the biomass OC stocks estimated by ISA and more than twice as high as the corresponding values from IPAM (2009). These facts demonstrate how necessary it is to integrate soil OC into the valorization of ecosystems. Although, for the first evaluation, soil data may be estimated by the first or second tier approach, depending on the available database; in the long term, and for the future monitoring of soil OC stocks, an individual sampling approach in the project area is indispensable and cannot be replaced by satellite data or modelled soil maps. Nevertheless, when considering the increased value of the ecosystem through the integration of soil data, the additional cost and work might be worthwhile to, at minimum, integrate soil OC to a depth of 1.0 m or, even better, to a depth of 3.0 m since this depth encompasses the majority of soil OC and is evidently influenced by land-use change.

Quantifying the amount of carbon sequestered in the soil of an intact tropical forest provides a way to place value on the forest in order to protect it and is a strong argument to refrain from deforesting it (Robertson 2006). At an international level, the fact that the calculation of carbon stocks is being limited to a depth of 1.0 metre implies disadvantages for tropical forest communities all over the world since they will have to compete with well-managed agriculture as a land-use option without being able to add the value of deep carbon, water and biodiversity being produced by the tropical forest (Boy et al. 2016).

5 Conclusion

To adequately valorize the amount of OC stored in a native ecosystem, we highly recommend considering the subsoil, as our results show that in the case of an Amazonian tropical forest, the amount of OC stored in the soil can be twice the amount of the OC stored in the living biomass if assessed correctly. Therefore, carbon assessment should not be based on the tier 1 and/or the tier 2 approach alone; it should also include field measurements (tier 3) to prevent severe undervaluation of the ecosystem. With respect to the practical feasibility of this approach, we would further recommend integrating soil samples to, at minimum, a depth of 3.0 m, as we found 84 % of soil OC stored within this depth. Furthermore, we showed that sampling is possible with simple tools (although it is labour intensive). Apart from the technical questions of accurate measurements and calculations of OC stocks, the political framework and conditions of possible applications of scientific knowledge need to be considered individually in each case and should give critical regard to power structure, including distinctive knowledge bodies and their representing political institutions.

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