Point-by-point response to anonymous Referee#2 comments

Dear Referee#2,

We would like to thank you for your time and thorough evaluation of our manuscript "*The role of geochemistry in organic carbon stabilization in tropical rainforest soils*", (https://doi.org/10.5194/soil-2020-92). We are very pleased that you positively assessed our work and recognized its relevance. Your comments helped us to significantly improve our manuscript and we want to sincerely thank you for the constructive and valuable insights.

We have addressed all comments and suggestions to the best of our ability. Please find below a point-by-point response to all the concerns raised and how we addressed them. Reviewer original comments are highlighted in grey. New text to be added or modified in the manuscript has quotation marks and is blue-colored in the response.

We hope you find our response and changes to the manuscript satisfying and we are looking forward to hearing from you.

Yours sincerely,

The authors

REVIEWER#2 COMMENT 1: "However, the most important concern for me is the research design, why the slope plots are 6 while valley and plateau are 3 each?"

Our response: The reviewer points out an important detail of the sample design related to topography of the investigated landscape. We describe in section "2.2 Study design and soil sampling": The dominating landscape feature in all study regions were slopes, whereas plateau and valley positions were much smaller compartments. We also wanted to assess the hypothetical effect of different hillslope positions (different in slope and curvature) on erosion and SOC stocks under tropical rainforests (Dialynas et al., 2016). Hence, it is not possible to describe the soil conditions and its erosional modification among slopes with just one sampled position. We therefore sampled at both topslope and midslope positions to account for their spatial extent and different geometry along the catenae. During pretests, ANOVA showed no significant differences in SOC stock means across top- and midslopes in each study region. As such, we decided to group the two slope positions together in further ANOVAs to reduce redundancy in the topographic position grouping.

Used Literature:

Dialynas, Y. G., Bastola S., Bras, R. L., Marin-Spiotta, E., Silver, W. L., Arnone, E., and Noto, L. V.: Impact of hydrologically driven hillslope erosion and landslide occurrence on soil organic carbon dynamics in tropical watersheds, Water Resour. Res., 52, 8895-8919, 10.1002/2016WR018925, 2016.

REVIEWER#2 COMMENT 2: "How could you justify the absence of soil erosion at the sampling plots as mentioned in your results section while sediment soils were collected in the valley plots? Kindly elaborate on this in your discussion."

Our response: Thanks for this comment. We reported in section "3.1 Climate and topography": We could not find significant differences in the means of SOC stocks and geochemical soil properties between plateau and slope positions. In the case of erosion, we would have expected some differences in soil properties and SOC stocks between these positions. The only differences were caused by valley positions because of fluvial activities unrelated to hillslope processes along the investigated catenae.

This was confirmed by another study analyzing $^{239+240}Pu$ activity and inventories as a means for direct measurement of erosional soil removal. Here we found that the $^{239+240}Pu$ inventories, sampled along the same catenae as used in our study did not show topographic patterns, which indicates little or no soil erosion (Wilken et al., 2020). We therefore excluded valley positions from further analysis in the manuscript and kindly refer to the supplementary results and short discussion therein.

Used literature:

Wilken, F., Fiener, P., Ketterer, M., Meusburger, K., Muhindo, D. I., van Oost, K., and Doetterl, S.: Assessing soil erosion of forest and cropland sites in wet tropical Africa using $^{239+240}Pu$ fallout radionuclides, SOIL DISCUSSIONS, in review, https://doi.org/10.5194/soil-2020-95, 2020.

REVIEWER#2 COMMENT 3: "Though in forest, there is no or little surface soil erosion but landslides occur most of the time in Tropical forest."

Our response: This is an important comment. During fieldwork, we could indeed observe landslides after heavy rainfalls on very exposed and steep slopes along roadcuts. However, those areas were free from vegetation and usually strongly altered by human activity. We were aware of this during our scouting trips and paid attention to install the study plots in areas that are as little as possible affected by landslides to exclude the effect of the latter thus focusing on the hypothesized effect of surface soil erosion which takes place at the broader hillslope-scale. While we cannot exclude our areas to be affected by naturally occurring landslides, we can exclude those events for the time needed to establish the current vegetation coverage since vegetation patterns were fairly regular across landforms and replicates. Additionally, landforms and sampled soils did not show signs of larger erosional events in the recent past. All soils were deeply weathered and showed (outside of valleys and fluvial systems) no layering or other signs that would indicate a disturbance event in the past. We added this information to section "2.2 Study design and soil sampling":

"Attention was paid to install the study plots in areas that are as little as possible affected by landslides. The occurrence of natural landslides cannot be excluded with certainty. However, the vegetation patterns were fairly regular across landforms and replicates thus events can be excluded for the time needed to establish the current vegetation coverages. Additionally, landforms and sampled soils did not show signs of larger erosional events in the recent past. All soils were deeply weathered and showed no layering or other signs that would indicate a disturbance event in the past outside of valleys and fluvial systems. "

REVIEWER#2 COMMENT 4: "I understand that one of the main focuses was Geochemistry of the three sites, while you also recorded soil fertility parameters especially chemical. but anywhere biological parameter such enzymes related to carbon cycle such as b-glucosidase which decompose carbon source is important for the decomposition were recorded? or mentioned in relation to the study."

Our response: The authors thank the reviewer for this very important comment. Soil microbial related properties are crucial to understand SOC dynamics in a given setting. As such, microbial biomass carbon and extracellular enzyme activity were measured and explored in more detail by our colleagues during a 120-day incubation experiment on the same soil samples used in our study, the results of which are being prepared for a separate manuscript (Kidinda et al., 2021). As the reviewer already stated, the focus of our manuscript was the impact of geochemistry on SOC dynamics in contrasting geochemical regions under tropical conditions. Therefore, we kindly refer to the connected work of Kidinda et al. (2021) published in the same special issue for details on the microbial activity along the investigated soil sequences.

Used literature:

Kidinda, L. K., Olagoke, F. K., Vogel, C., Kalbitz, K., and Doetterl, S.: Patterns of microbial processes shaped by parent material and soil depth in tropical rainforest soils, SOIL DISCUSSIONS, in review, https://doi.org/10.5194/soil-2020-80, 2020.

REVIEWER#2 COMMENT 5: "1) could you elaborate why the slope of you compared sites of different slopes eg., Kibale site (3-55%) while Kahuzi-Biega and Nyungwe have similar slopes (1-60%)."

Our response: Thanks for this comment. We tried our best to keep the slopes comparable across the study regions, but this was not always possible. However, there are no significant differences in the means of the slopes across study regions ($p = 0.97$) and no significant correlations between slope and SOC stock ($p = 0.63$). Therefore, we are confident that the differences in the slope range between study regions were not affecting our target variables.

REVIEWER#2 COMMENT 6: "2) Soil development is dependent to several factors including environment, which are different from the three. What was your reference of standardization to justify the study comparison between the sites."

Our response: Thanks for this important question. Our choice for the study sites was based on prior knowledge of similarities between vegetation structure, climate and topography. Overall, the soil forming factors are comparable among our study sites except for parent material, which differed in geochemistry and texture (Figure R1). As different parent materials impact geochemical soil properties and therefore the potential to stabilize SOC, we hypothesized that parent material geochemistry would shape patterns of SOC stocks and soil C fractions the most.

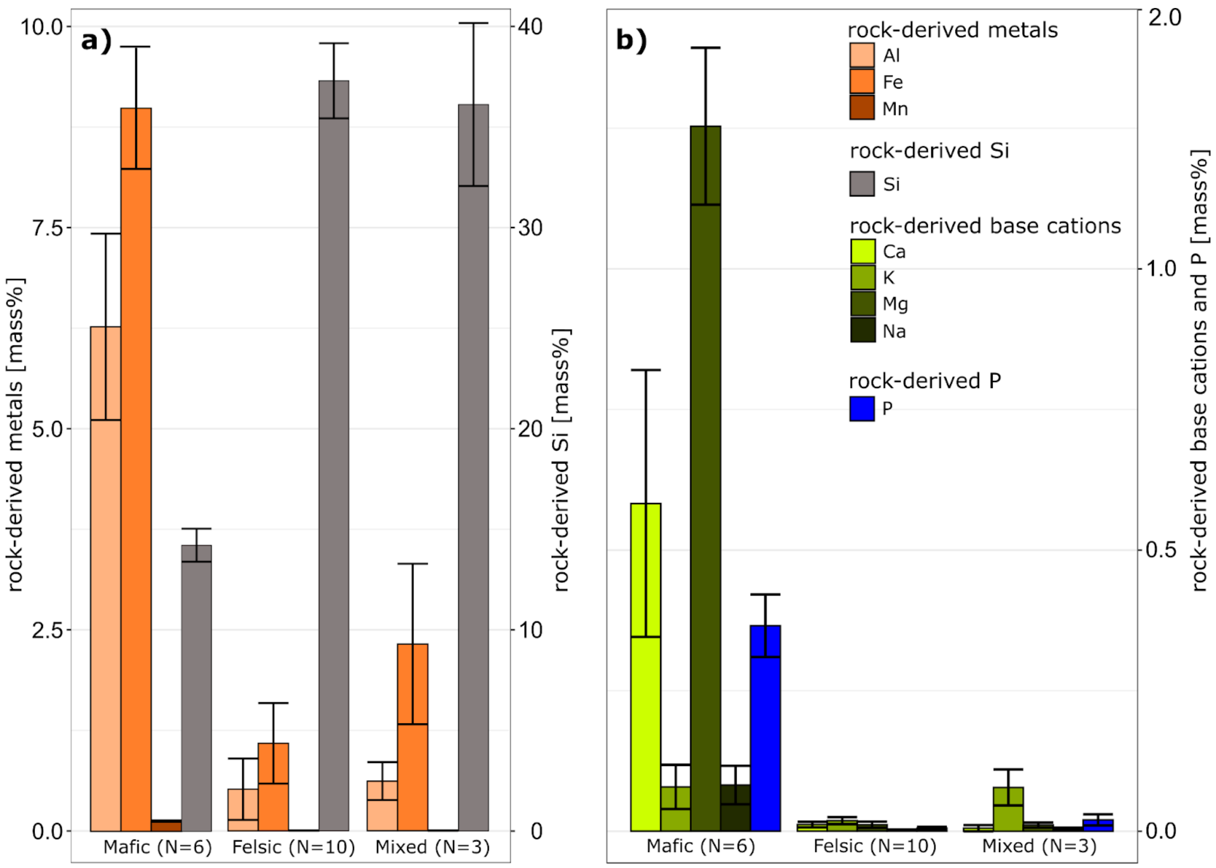

Figure R1: Chemical composition of unweathered rock samples representing the parent material for soil formation in three studied geochemical regions (mean +/- standard error). Panel 3a shows the distribution and concentration of rock-derived aluminum (Al), iron (Fe) and manganese (Mn) and total silica content (Si). Panel 3b shows the distribution and concentration of rock-derived calcium (Ca), potassium (K), magnesium (Mg), sodium (Na) and phosphorus (P). Note the difference in scale on y-axis between panel 3a and 3b (Doetterl et al., 2021a; 2021b).

Used Literature:

Doetterl, S., Asifiwe, R.K., Baert, G., Bamba, F., Bauters, M., Bukombe, B., Cadisch, G, Cizungu, L., Cooper, M., Hoyt, A., Kabaske, C., Kalbitz, K., Kidinda, K.L., Maier, A., Mainka, M., Mayrock, J., Muhindo, D., Mujinya, B., Mukotanyi, S.M., Nabahungu, L., Reichenbach, M., Rewald, B., Six, J., Stegmann, A., Summerauer, L., Unseld, R., van Oost, K., Verheyen, K., Vogel, C., Wilken, F., Fiener, P. Organic matter cycling along geochemical, geomorphic and disturbance gradients in forests and cropland of the African Tropics - Project TropSOC DATABASE_v1.0, Earth System Science Data DISCUSSIONS (pre-print), https://doi.org/10.5194/essd-2021-73, 2021a.

Doetterl, S.; Bukombe, B.; Cooper, M.; Kidinda, L.; Muhindo, D.; Reichenbach, M.; Stegmann, A.; Summerauer, L.; 36 Wilken, F.; Fiener, P. TropSOC Database. Version 1.0. GFZ Data Services. https://doi.org/10.5880/fidgeo.2021.009, 37, 2021b.

REVIEWER#2 COMMENT 7: "3) in material and methods you are referring to Fick and Hijmans, 2017. is his work conducted in all your study regions?"

Our response: This is indeed an important question. The outcome of Fick and Hijams (2017) is the WorldClim 2 dataset, which provides spatially interpolated monthly climate data for global land areas at a spatial resolution of approximately 1 km² using data from between 9,000 to 60,000 weather stations with a temporal range of 1970-2000. Datasets used for representing covariates and climate elements in the tropics are from the Center for Tropical Agriculture (CIAT) in Columbia. The WorldClim 2 dataset is suitable for comparing the different regions but not for comparing the climatic variability along the investigated catenae within the regions due to the coarse resolution of this global dataset. We installed three weather stations (ATMOS 41, Meter, Germany) in each geochemical region close to the investigated catenae. This enabled us to collect micrometeorological data at a temporal resolution of 5 minutes on precipitation, air temperature, relative humidity and air pressure (Doetter et al., 2021a; 2021b). However, these local climate stations only recorded for 2.5 years by now which is why we resort to the larger scale but coarser WorldClim 2 dataset.

Used literature:

Doetterl, S., Asifiwe, R.K., Baert, G., Bamba, F., Bauters, M., Bukombe, B., Cadisch, G, Cizungu, L., Cooper, M., Hoyt, A., Kabaske, C., Kalbitz, K., Kidinda, K.L., Maier, A., Mainka, M., Mayrock, J., Muhindo, D., Mujinya, B., Mukotanyi, S.M., Nabahungu, L., Reichenbach, M., Rewald, B., Six, J., Stegmann, A., Summerauer, L., Unseld, R., van Oost, K., Verheyen, K., Vogel, C., Wilken, F., Fiener, P. Organic matter cycling along geochemical, geomorphic and disturbance gradients in forests and cropland of the African Tropics - Project TropSOC DATABASE_v1.0, Earth System Science Data DISCUSSIONS (pre-print), https://doi.org/10.5194/essd-2021-73, 2021a.

Doetterl, S.; Bukombe, B.; Cooper, M.; Kidinda, L.; Muhindo, D.; Reichenbach, M.; Stegmann, A.; Summerauer, L.; 36 Wilken, F.; Fiener, P. TropSOC Database. Version 1.0. GFZ Data Services. https://doi.org/10.5880/fidgeo.2021.009, 37, 2021b.

Fick, S. E., and Hijmans, R. J.: WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas, Int. J. Climatol., 37, 4302–4315, https://doi.org/10.1002/joc.5086, 2017.

REVIEWER#2 COMMENT 8: "4) How could you compared results from three different slope length beside variability sites elevation. e.g., Nyungwe and Kibale sites are more variable than Kahuzi biega."

Our response: The authors like to thank the referee for this question, which helped us to recognize a mistake in our slope length calculation. We corrected the paragraph as follows:

"Slope length in Kahuzi-Biéga was 70±56 m (max. 170 m), in Nyungwe 101±103 m (max. 339 m) and in Kibale 149±125 m (max. 374 m)."

The slope length shows indeed high variances across the study regions with different maximum slope lengths. But there are no significant correlations between SOC stocks and slope length. Regarding the minor or absent soil erosion in our study sites, we considered slope length as an irrelevant factor in explaining SOC stocks at the plot scale under pristine tropical rainforest. Even though shallow subsoil SOC stocks (30-40 cm) show significant correlations with altitude ($p < 0.01$), they become non significant when controlled for geochemical soil properties (DCB extr. oxides, exchangeable bases, total P). This orographic effect as a function of MAP and MAT is interpreted as a second-order control which affects SOC stocks indirectly via geochemical soil properties. As such, our study site comparison regarding SOC stocks should not be biased by the variability in elevation and slope length. However, we admit that the more complex topography in our study regions ask for the catchment size where the plots are located instead of just using the slope length as a proxy for soil erosion. Due to the weak DEM this could not be calculated in the required precision.

REVIEWER#2 COMMENT 9: "5) How can you explain the absence of soil erosion in plots, while the sampling was conducted during rainy season (March to June)?"

Our response: The reviewer points out a very important remark, since the tropical rainforest climatic type shows the highest rainfall erosivity (Panagos et al., 2017). At the same time, global erosion studies from tropical forest sites show rather low mean erosion rates of 0.2 Mg ha-1 yr-1 compared to other climate zones (Xiong et al., 2019). This can be attributed to a variety of interactions between precipitation, standing vegetation and organic soil layers. For example, closed canopy covers, understoreys, litter and organic soil layers reduces the kinetic energy of raindrops significantly thus decreasing splash erosion and therefore preventing i.a. soil crusting which in turn affects the soil infiltration capacity (Labriére et al., 2015; Singer and Shainberg, 2004). The litter layer and ground vegetation helps to prevent soil erosion by funneled stemflow (Dunkerley, 2020). But also plant roots enhance soil erosion resistance (Li et al., 2017). Our study sites showed all above mentioned features of multiple layers of vegetation, organic soil layers and roots, which prevents soil erosion as a result of heavy rainfall events during the rainy season.

Used Literature:

Dunkerley, D.: A review of the effect of throughfall and stemflow on soil properties and soil erosion, in: Precipitation Partitioning by Vegetation. A Global Synthesis, edited by: van Stan, J. T. I., Gutmann, E., and Friesen, J., Cham, Switzerland, Springer, 183-214, https://doi.org/10.1007/978-3-030-29702-2, 2020.

Labriére, N., Locatelli, B., Laumonier, Y., Freycon, V., and Bernoux, M.: Soil erosion in the humid tropics: A systematic quantitative review, Agric. Ecosyst. Environ. Agriculture, 203, 127-139, https://doi.org/10.1016/j.agee.2015.01.027, 2015.

Li, Q., Liu, G.-B., Zhang, Z., Tuo, D.-G., Bai, R.-R., and Qiao, F.-F.: Relative contribution of root physical enlacing and biochemistrical exudates to soil erosion resistance in the Loess soils, Catena, 153, 61-65, https://doi.org/10.1016/j.catena.2017.01.037, 2017.

Panagos, P., Borrelli, P., Meusburger, K., Yu, B., Klik, A., Lim, K. J., Yang, J. E., Ni, J., Miao, C., Chattopadhyay, N., Sadeghi, S. H., Hazbavi, Z., Zabihi, M., Larionov, G. A., Krasnov, S. F., Gorobets, A. V., Levi, Y., Erpul, G., Birkel, C., Hoyos, N., Naipal, V., Oliveira, P. T. S., Bonilla, C. A., Meddi, M., Nel, W.,Dashti, H. A., Boni, M., Diodato, N., van Oost, K., Nearing, M., and Ballabio, C.: Global rainfall erosivity assessment based on high-temporal resolution rainfall record, Scientific reports, 7, 1-12, 10.1038/s41598-017-04282-8, 2017.

Singer, M. J., and Shainberg, I.: Mineral soil surface crusts and wind and water erosion, Earth Surf. Process. Landdforms, 29, 1065-1075, 10.1002/esp.1102, 2004.

Xiong, M., Sun, R., and Chen, L.: A global comparison of soil erosion associated with land use and climate type, Geoderma, 343, 31-39, https://doi.org/10.1016/j.geoderma.2019.02.013, 2019.

REVIEWER#2 COMMENT 10: "6) on the paragraph 340 "Not significant correlation was found with the included climate variables (data not shown); For the reader to realize that they were not significant difference a figure or table is require. can you add that?"

Our response: The authors like to thank the referee for pointing this out and we agree to provide more details. Significant correlations between SOC stocks and climatic parameters (MAP, MAT and PET) are only found in the shallow subsoils (30-40 cm), whereas any correlations in topsoils (0-10 cm) and deep subsoils (60-70 cm) are absent. The correlation in the shallow subsoils disappears when controlled for soil properties (see Table R1). As such, SOC stocks are only indirectly affected by climate by its impact on geochemical soil properties and thus do not have independent explanation power. This is our rationale to focus on the direct effect of soil properties on SOC dynamics in our study sites. We will add Table R1 to the manuscript appendix.

However, we have to point out that the global WorldClim 2 dataset is only suitable to compare climatic differences across our study regions but cannot resolve the local variability between plots within the regions. As already mentioned in the response to Reviewer#2 comment 7, we installed weatherstation near the study plots to cover local climatic variability. But since we only have records of 2.5 years so far, we resort to the WorldClim 2 dataset.

Table R1: Partial correlation analysis between SOC_{bulk} and climate variables (Fick and Hijams, 2017) controlling for geochemical soil properties. Zero-order correlation displays the Pearson r when including no control variables. The controlled correlation shows the Pearson r when controlling for DCB extractable oxides of Al, Fe and Mn, exchangeable bases and total P. *p<0.05; **p<0.001.

soil depth [cm]	control variables	MAP	MAT	PET
0-10	zer-order	-0.17	0.00	-0.08
	DCB extr. oxides (Al, Fe, Mn), exchangeable bases, total P	-0.16	-0.26	-0.40
30-40	zer-order	0.67*	-0.90**	-0.93**
	DCB extr. oxides (Al, Fe, Mn), exchangeable bases, total P	-0.56	-0.03	-0.43
60-70	zer-order	-0.06	-0.24	-0.33
	DCB extr. oxides (Al, Fe, Mn), exchangeable bases, total P	0.00	-0.13	-0.14

Used Literature:

Fick, S. E., and Hijmans, R. J.: WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas, Int. J. Climatol., 37, 4302–4315, https://doi.org/10.1002/joc.5086, 2017.

REVIEWER#2 COMMENT 11: “7) on 360; You mentioned that total P was high in Mafic region as compared to both mixed sedimentary rocks and felsic regions. How could you justify your finding with the known situation of low available P in that region?”

Our response: This is an important question. Our rationale is the specific mineralogy and mafic geochemistry of alkaline basaltic rocks. Basalts consist of primary minerals like olivin, pyroxene and Ca-rich feldspars which contain P in their crystal structure. Compared to acid plutonics (i.e. granites) and mixed sedimentary rocks, basalt can contain up to 2.5 times more P. P-release from basalts into the soil matrix by chemical weathering is particularly high in humid areas with high temperatures like in our study sites (Hartmann et al., 2014). Furthermore, the content of bio-available P in highly weathered soil is increased when amended with basaltic material (Gillman et al., 2002) which again underlines the importance of basalts as a P-source for soils. This is further illustrated when comparing P content in bedrocks and soils. Bedrock geochemistry produces a strong difference in total P in unweathered rock samples (Figure R1) which is mirrored in the total P content in soils albeit to a lesser degree (Figure R2). This consolidates our interpretation, that parent material geochemistry leaves a footprint in soil geochemistry besides prolonged chemical weathering in the investigated soils. However, the amount of bio available P seems not solely dependent on bedrock geochemistry as shown by the similar content in bio available P between the mafic and felsic region as well by the much higher P fraction ratio in the latter (Figure R3, for referee and editor information only).

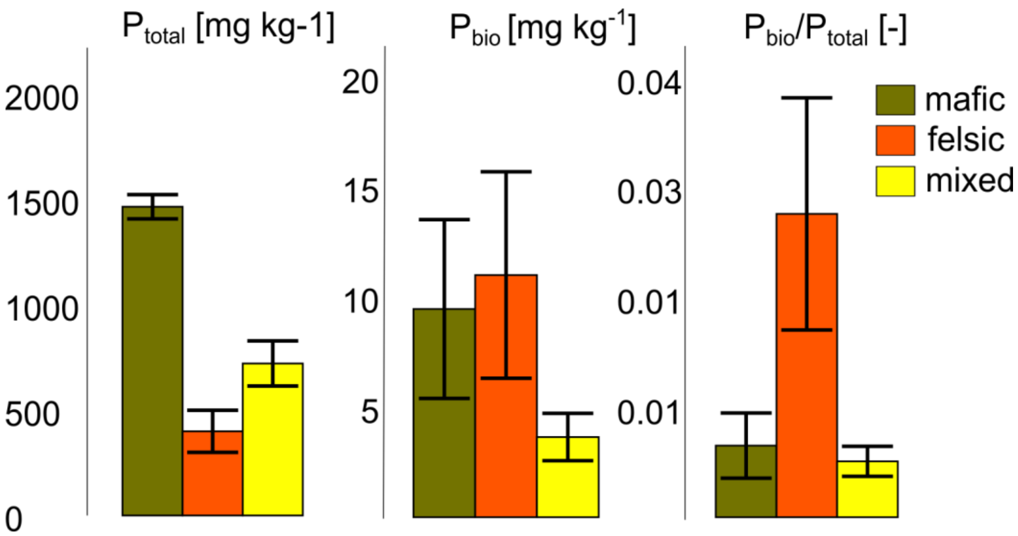

Figure R2: P fractions in the shallow subsoil (30 - 40 cm) of non-valley positions across geochemical regions. Left: total P; Right: bio available P; Right: Ratio of bio available P and total P. Bar represents mean and standard error shows standard deviation. Per bar n = 3.

Used Literature:

Gillman, G. P., Burkett, D. C., and Coventry, R. J.: Amending highly weathered soils with finely ground basalt rock, Appl. Geochem., 17, 987-1001, https://doi.org/10.1016/S0883-2927(02)00078-1, 2002.

Hartmann, J., Mossdorf, N., Lauerwald, R., Hinderer, M., and West, A. J.: Global chemical weathering and associated P-release - The role of lithology, temperature and soil properties, Chem. Geol., 363, 145-163, http://dx.doi.org/10.1016/j.chemgeo.2013.10.025, 2014.

REVIEWER#2 COMMENT 12: "8) At 365; How the reader could know that the study region is highly weathered without displaying soil data of all the three depths?"

Our response: Thanks for this comment. We described the soil weathering stage by briefly presenting the chemical alteration index (CIA) in one sentence in the section "Parent material geochemistry and weathering stage" and by presenting the nutrient depletion as a result of weathering in greater detail both in the same section and in the appendix. Figure R3 shows the ratio of Fe_{dcb} versus Fe_{total}. This ratio is high in all regions and depth increments which reflects the highly advanced soil weathering stage. This corresponds with the pronounced reddish soil color and absence of rock fragments. To reduce redundancy, we would leave Figure R3 for reviewer and editor information only. However, if the referee and editors share the opinion it would enhance the clarity of the results, we are happy to add Figure R3 to the appendix.

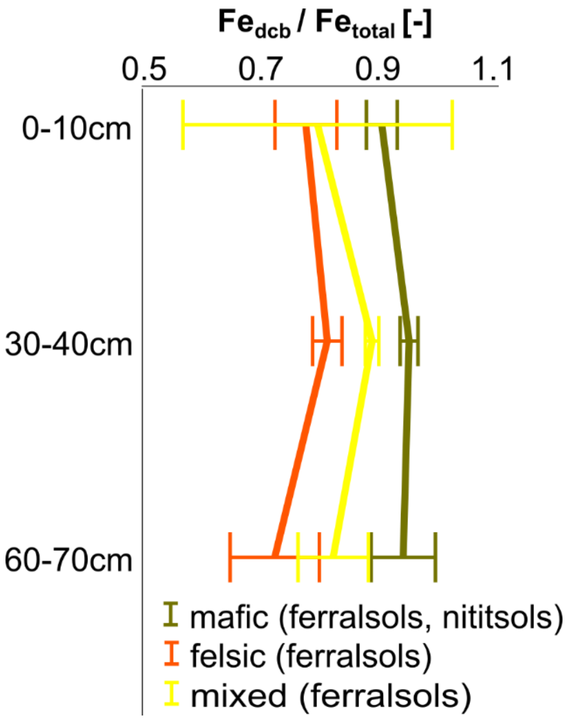

Figure R3: Fe_{dcb} / Fe_{total} ratio against soil depth for each geochemical region for non-valley positions. Datapoints represent mean and standard errors show standard deviation. For each data point n = 3.

REVIEWER#2 COMMENT 13: "9) at 375; How could you explain the high depletion of P (72 to 14 %) in parent material under natural conditions? (without any agricultural activity that could contribute to P removal)"

Our response: Thanks for this interesting question. The high P depletion in deeply leached tropical soils in the absence of geological (i.a. volcanism, tectonic uplift) and anthropogenic disturbances (i.a. soil erosion, fertilization) is best explained by progressive loss of P during long term soil development (Vitousek et al., 2010; Walker and Syers, 1976), but also via seasonally driven P leaching at the beginning of the rainy season (Campo et al., 1998). In addition, the P released from primary minerals into the soil matrix via weathering, can accumulate in biologically-available pools like litter and organic soil layers (Silver, 1994; Vitousek et al., 2010). These pools represent a sink, since P will be withdrawn from the mineral soil matrix by plant uptake and recycled between organic layers and plants (Vitousek et al., 2010; Wilcke et al., 2002).

Used Literature:

Campo, J., Jaramillo, C. J., and Maass, J. M.: Pulses of soil phosphorus availability in a Mexican tropical dry forest: effects of seasonality and level of wetting, Oecologia, 115, 167-172, 1998.

Silver, W. L.: Is nutrient availability related to plant nutrient use in humid tropical forests? Oecologia, 98, 336-343, 1994.

Vitousek, P. M., Porder, S., Houlton, B. Z. and Chadwick, O. A.: Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen-phosphorus interactions, Ecol. Appl., 20, 5-15, https://doi.org/10.1890/08-0127.1, 2010.

Walker, T. W., and Syers, J. K.: The fate of phosphorus during pedogenesis, Geoderma, 15, 1-19, https://doi.org/10.1016/0016-7061(76)90066-5, 1976.

Wilcke, W., Yasin, S., Abramowski, U., Valarezo, C., and Zech, W.: Nutrient storage and turnover in organic layers under tropical montane rain forest in Ecuador, European Journal of Soil Science, 53, 15-2, https://doi.org/10.1046/j.1365-2389.2002.00411.x, 2002.

We hope we have addressed all concerns and look forward to hearing from you.

Best regards,

The authors