Dear Reviewers:

Thank you for your comments on this manuscript. We tried to address each point and answer your questions one by one. Figures and Tables can be found at the end of the answers.

The numbers after '**Line**' are the line numbers in the manuscript **before revision**, whereas the underlined number in the bracket are the line numbers in the manuscript **after revision.** All revised sentences and paragraphs are marked in red in the manuscript.

Respond to 1st reviewer's comments:

Line 20 (20) and general - To improve readability I would use no abbreviations for the soils, there is enough space to use e.g. "limestone soils" instead of LS.

Answer: Yes. We replaced LSs and ASs by limestone soils and acid igneous rock soils in the abstract.

Line 30 (31) How much occluded OM was present in these soils? Thus is aggregation at all relevant for OM storage in these soils in contrast to mineral association?

Answer: We have no idea of the amount of occluded OM because the OM could not be separated using density fractionation for the acid igneous rock soils (ASs). The main reason is that the application of ultrasound caused severe dispersion of organic materials into dense solution (NaPT, 1.6 g cm^{-3}) for the ASs. We tried many ways (including long-time centrifuge) to separate the organic materials but always failed. The dispersion might be attributed to that Na$^+$ in the solution interacted with Al-OM complexes in the ASs and produced a stable suspension. A similar situation has been reported by Kaiser and Guggenberger (2007) but no solution was given.

Thus, we had to choose an alternative method (dry sieving plus incubating intact versus crushed aggregates) applied by Goebel et al. (2009), Juarez et al. (2013) and Wang et al. (2014). Aggregate destruction in the method homogenized soils and reduce the differences in substrate availability in SOC mineralization (Hartley et al., 2007). This way is indirect but still widely used to estimate OM protected by aggregates. As we found no difference in SOC mineralization between intact and crushed aggregates, we proposed that occlusion in aggregates was not the major mechanism for OM stabilization in our soils.

We added a discussion in **Line (323-332)** to explain this.

Line 40 (41) The Andes stretch over 7000 km, please be more specific on the location of your work.

Answer: To clarify the exact location, we modified the text to emphasized that the large SOC stocks were especially found in the Ecuadorian and Peruvian Andes in **Line (41-44).**

Line 44-47 (<u>46-48</u>) Again, the Andes stretch over vast distances, its clear that there are drastic climatic differences. But even at one location you get changes with exposition and elevation. Please be more specific!

Answer: We added information in this sentence to specify the study area, Andes in Northern Peru.

Line 50-51(<u>52-53</u>) This is redundant in itself, OM and OC is stabilized and of course is tightly linked.

Answer: We corrected the sentence to: "Specifically, SOC persistence and stabilization are controlled by…".

Line 54-56 (<u>57</u>) Again, this is highly dependent where you are in the Andes. In the Southern Andes you0ll have soils that are completely dominated by particulate OM rather than mineral-associated OM.

Answer: We specified this with: **"Peruvian and Ecuadorian Andes"**.

Line 93 (<u>97-100</u>) describe shortly Puna and Jalca

Answer: We modified the sentence to include information of wet Puna and Jalca: "The study areas belong to the Neotropical alpine grassland of the Andes, corresponding to the grassland ecosystem commonly referred as wet Puna or Jalca that is present between the tree line (3500 m asl) and the ice-covered region, having precipitation above 500 mm". More information is referred to the cited paper and the following contents in the M&M.

Line 103 (<u>110</u>) Are there records about a longer consistent land use at the sampling sites? Or do you have indices that show a longer sustained land use type?

Answer: Please see our answer to the next question (question of **Line 122**).

Line 122 (<u>131-134</u>) So there was a mixture of different land uses between the three site replicates? Was this detectable in the soil profiles or SOM properties?

Answer: Yes, samples were collected from grassland and abandoned cropland. A previous study showed that SOC stocks were not clearly affected by land use type (e.g. grassland vs. cultivation) (Yang et al. 2018). This is because the local farmers applied a special rotation to change land use in the order of cultivation, abandoned cultivation, cultivate grassland and grassland in a period of several years. They

repeated this cycle and it may keep the SOC stock high and in a dynamic balance. We added this information in the sentence in **Line (131-132)**.

Line 147 (158-160) How was the gravel content calculated, thus how did the authors differentiate between large aggregates (>2mm) and stones of this size range?

Answer: The aggregate-size fractionation was conducted by dry-sieving. For the fraction >5 mm and the fraction 2-5 mm, gravels (stones) were separated by sieving (2 mm) a sub-sample of the fraction after breaking aggregates. The gravel contents were calculated by gravimetric gravel contents, using the gravel weight divided by the sum of the fraction weight plus the gravel weight. In addition, gravels were also excluded in the calculations of mean weight diameters (MWD) and the incubation experiment.

We modified the sentence to "For all fractions larger than 2 mm, gravels were separated by sieving (2 mm) a subsample of the fraction after breaking aggregates. The gravel content (gravimetric) of each fraction was calculated using the gravel weight divided by the sum of the fraction weight plus the gravel weight." in **Line (158-160).**

Line 157-158 (173-174) Why you analyse in the one approach the fraction <63 μm, but don't use it in the incubation? Please describe here.

Answer: The finer fraction (<0.25 mm) were by far less abundant, especially for the limestone soils. The fraction was therefore not incorporated in the analysis. We added this in the revised manuscript.

Line 162 (175-176) By this approach you are not only crushing aggregates, but also rock fragments. How did you account for the different content of pure mineral constituents in relation to aggregates?

Answer: We replaced the word "grinding" with "crushing" here (**Line 176**), as this is actually what we did. If rock fragments are defined as size >2mm, this approach will not break rock fragments because rock fragments were removed before the aggregate crushing. We cannot account for the differences between mineral particles and aggregates. Nevertheless, our purpose was only crushing aggregates. Grinding using a porcelain mortar is unlikely to destruct mineral particles.

Line 164 (178) It was shown before that aggregate/soil disruption can lead to a rather fast spike in CO2 evolution within a few days. Did you in any way account for this CO2 loss between the different treatments during the first days of incubation before entering a sort of basal respiration?

Answer: Thank you for this question. We applied a 10-day pre-incubation, necessary because microbes in the air-dried soils need to be activated. We used slow wetting because we wanted to avoid aggregate destruction caused by fast-wetting.

For the spike in CO_2 at the beginning, data from Fig. R1 indicated that the fast pulse in CO_2 was not missed. This is because soils were too dry for microbes to start degradation during the early period of the pre-incubation. Furthermore, the comparisons in Table R1 showed no clear differences in early CO_2 production between intact and crushed aggregates. Thus, we think that we did not miss the fast CO_2 spike during the first few days, whereas our results do not support that aggregate/soil disruption caused a fast spike in CO_2 evolution at the beginning.

Line 208-215 (223-232) This is a nice exemplary paragraph to show how hard a text is to read for an outsider - let me summarize: "...LS is larger than AS, has more LM but minor Mi; AS has larger SM and Mi; LS were not different but wet-AS was slightly different from dry-AS..." I would really appreciate if you find a way to use even short words that are more descriptive and don0t ruin the flow of reading.

Answer: Thank you for this point. We improved the sentences to improve readability. Please read our modified paragraph in **Line (223-232**) in the result section 3.2**.**

Line 226-227 (243-244) Please also give mineralization rates normalized to the amount of OC in the individual samples. This will give a better mechanistic insight on the fate of OM with respect to aggregation. This might also level off possible differences in stone content etc.

Answer: We already have used SOC mineralization normalized for OC contents. We modified the relevant sentence in the method section **Line (186-187):** "Specific SOC mineralization rates (g CO2-C g^{-1} C), which were normalized for OC contents, were used as an indicator of the C stability of the soil fractions".

Line 233-234 (250-251) How is this relation if you normalize OC mineralization rates with sample amount OC?

Answer: See our previous answer to the question **Line 226-227** (SOC mineralization already normalized).

Line 239 (256) Also if normalized on the amount of OC in LM vs. SM?

Answer: See our previous answer to the question **Line 226-227** (SOC mineralization already normalized).

Line 253-256 (270-272) You are using two very contrasting parent materials which foster completely different soil biological communities and soil chemistry and thus of course yield different soil structure - so far its textbook knowledge. Such statement might be more interesting if comparing Granodiorite and a

Granite or Basalt etc. However, this comment is just about leaving out such "general textbook statements" and focus on the core of the story.

Answer: The statements concerning the effects of lithology on soil aggregate size distribution will be largely removed from the discussion part and moved, in a modified form, to the introduction in **Line (72-78)**.

Line 256-260 (270-272) This could possibly find its way into the Introduction as you could put this as a rational to take these two contrasting materials. In the discussion it appears again as a redundant textbook message.

Answer: We agree to move this part to the introduction in a modified form in **Line (72-78)**.

Line 262 (moved to 75-77) So basically the lack of fine material causes the lack of a more advanced aggregation.

Answer: This is correct.

Line 271(280) You are comparing a silicate rock and a carbonate rock - I would be more than surprised if precipitation would not have a less pronounced effect.

Answer: Based on this comment and the next comment concerning stoniness, we considered to shorten the discussion on precipitation in **Line (280-286)** and added an additional discussion on stoniness in **Line (287-298)**.

Line 275- 280 (**287-298**) There are in parts differences in aggregation and SOC stocks between wet and dry sites. Why are you neglecting those and talking them down as minor or biased by stoniness? If stoniness is the driving property, than how can you compare aggregate mineralization etc. at all?

Answer: Thank you for the very good questions. We agree that stoniness is a driving factor rather than a minor factor for aggregate-size distribution (Fig. 3). SOC stocks were also slightly higher (not significant) in the wet-ASs compared to the dry-ASs (Fig. 2). However, physicochemical properties of each aggregate fraction were not clearly affected by stoniness, and thus aggregate mineralization etc. can be compared. We incorporated discussions related to stoniness in **Line (292-298)**. Please check our detailed explanation as follows:

1. SOC stocks are affected by stoniness because we can see from the following equation that SOC stocks get lower when stoniness gets higher.

$$SOC\ stock = \sum_{i=1}^{i=k} BD_i \times C_i \times (1 - S_i) \times D_i$$

In which, BD_i = bulk density (g cm^{-3}) of the layer i (including gravels), C_i = SOC content (%) of the layer i (excluding gravels), S_i = stoniness of layer i, D_i= thickness (cm) of layer i.

2. Mean weight diameters (MWDs, i.e. aggregate-size distribution) gets lower when stoniness gets higher. As stones (gravels) are only distributed in fraction of >5 mm and that of 2-5 mm, the stoniness only has effects on $W_{>5} \times X_{>5}$ and $W_{2-5} \times X_{2-5}$. When the stoniness changed from 0% to 100%, the contribution of $W_{>5} \times X_{>5}$ and $W_{2-5} \times X_{2-5}$ declined and MWDs also decreased. Because the SOC distribution in aggregate fractions coincided with the aggregate-size distribution (Fig. 3), the SOC distribution affected by stoniness was also similar to aggregate-size distribution.

$MWD = W_{>5} \times X_{>5} + W_{2-5} \times X_{2-5} + W_{0.25-2} \times X_{0.25-2} + W_{0.063-0.25} \times X_{0.063-0.25} + W_{<0.063} \times X_{<0.063}$

In which, Xi = averaged diameter (mm) of the fraction i, Wi = weight percent (excluding gravels) of the fraction i.

3. The SOC mineralization in different aggregate fractions can be compared because the properties of each fraction were not clearly affected by stoniness. Stones (gravels) were excluded in the aggregate-size fractions and in the incubation experiments. The general idea came from the calculation of SOC stocks, in which gravels are considered SOC-free blocks or voids. Detailed explanation can be found in the 2nd reviewer's comments **Line 142** and relevant publications (Hobley et al., 2018; Poeplau et al., 2017). As analyses including SOC mineralization were conducted without gravels, we only need to ensure comparable gravel-free soil fractions. Our results showed that properties of aggregate fractions were not clearly affected by stoniness, as indicated by (1) no clear differences in vertical distribution of aggregate-related soil properties between wet-ASs and dry-ASs (Fig. 4) and (2) no clear differences in properties of aggregate fractions between wet-ASs and dry-ASs (Fig. S1). Thus, SOC mineralization rates using aggregate fractions were not biased by gravel contents.

Finally, we believe that it is necessary to discuss this in the discussion part in Line (**287-298**).

Line 282 (289-290) Given the high amount of stones and a some other constraints, the significant effects are worth taking them serious. Presumably as a result of altered soil biology and/or plant diversity / litter/root input.

Answer: In addition to the answer to the previous question of **Line 275-280**, we could elaborate on the effects of differences in stoniness: root distribution will be different in stones, differences in soil moisture redistribution affecting soil microbial activity and organic matter turnover. We added more explicitly discussions in **Line (289-290)**.

Line 294-295 (309-310) Which is a function of primary production and decomposition. Please give in the M&M more details on vegetation at the respective sites.

Answer: Information on vegetation were given in the M&M section in **Line (110-114):** "The vegetation in the wet site is a typical disturbed wet Puna (or Jalca) vegetation with dominant grass species: *Calamagrostis sp.,* but also *Festuca and Agrostis sp. as well as Rumex sp. on fallow land.* Similarly, the vegetation in the dry site is also a typical disturbed wet Puna (or Jalca) vegetation with *Calamogrostis sp., Stipa and Festuca sp. and Rumex sp. on fallow land".*

Line 299-304 (314-319) What soil horizons comprise the low SOC values with high CO2 evolution? Are those the low C/N ratio subsoils? If so, you are mixing two opposite factors, aggregation and soil material origin. Please give specific OC mineralization normalized per amount OC. And the very low C/N ratios under 5, would mean you have pure amino acid material in the sample. Could here values around the detection limit for N play a role?

Answer: The mineralization rates were already normalized (Questions of **Line 226-227, Line 233-234** and Line 239). In general, Dry-LS-A had the highest CO_2 evolution, whereas Dry-LS-B had the lowest SOC contents. For the C/N ratios, the values were 9.34±0.52 for the Dry-LS-A and 6.86±1.14 for the Dry-LS-B (Fig. 2). Thus, soil horizons with the highest CO_2 productions were not subsoils or the horizons with the lowest C/N ratios. In addition, we don't think the N contents reached the detection limit of the Elementar Analyzer because the detection limit of the Analyzer was 0.01% but the lowest N content was 0.16%.

Line 310-314 (334-338) How much OM is stored within the aggregates? Do you have estimates of amounts of e.g. occluded POM?

Answer: See our answer to the question of **Line 30** and also the question of **Line 307-326** from Reviewer 2.

Line 315 (339) The cited work showed a clear effect of aggregate disruption within the first days of incubation. You lack this information due to the late start after 10 days. So the low differences between crushed and intact might be due to fact that you missed the CO2 spike. Furthermore, how did you adjust comparable soil porosity/O2 diffusion and thus water contents between finely crushed/ground soil material and naturally aggregated soil?

Answer: We totally agree that there is a fast spike in CO_2 at the beginning of the incubation. However, we had to re-wet the air-dried soils to initiate the decomposition. We choose to slowly re-wet soil materials for 10 days because fast-wetting can significantly break soil aggregates. We just would like to avoid unnecessary destruction of aggregates. At the first few days of the incubation, soil materials are very dry and the SOC mineralization did not start. Thus, the fast spike in CO_2 did not appear in this period.

Although we applied the pre-incubation, we believe that we did not miss the massive CO2 production at the beginning. This is because of the much higher CO2 production rates in the first few days of the measurement (Fig. R1). In many studies, the pre-incubations were 14 days. Luckily, we anticipated the fast spike in CO2 at the beginning and we try to shorten the pre-incubation time. If we pre-incubated soils for 14 days as many studies did, we would be more likely missing the CO2 spike that was found in Day 1 and Day 2 (Fig. R1).

For the adjustments of soil porosity and O_2 diffusion, we did not make them similar for crushed vs. naturally aggregated soils. OM stabilization through occluded in aggregates can be explained by physical inaccessibility to the decomposer. The inaccessibility is closely related to the microstructure of aggregates (e.g. soil porosity and O_2 diffusion). The objectives of crushing aggregates were to destruct soil structure (i.e. soil porosity, O_2 diffusion, etc.) that promote OM stabilization. If we made soil porosity and O_2 diffusion similar between intact and crushed aggregates, we were a bit like trying to eliminate what we want to compare.

Line 343(367) Do you have data on exchangeable ions?

Answer: Data on exchangeable ions is the focus of another paper (Yang, in revision, Envir. Earth Scie.). The paper investigated the effects of exchangeable ions, Fe and Al on SOM stabilization. Briefly, the OM in the ASs was stabilized by interacting with Fe- and Al-oxides, whereas the OM in the LSs was stabilized by Ca bridges in addition to Fe- and Al-oxides (Table R2). In addition, soil pH values were the key factor controlling OM stabilization mechanisms (Table R2). As the focus of this manuscript was aggregate size distribution and OM stability controlled by aggregates, it could be a better way that we proposed the OM stabilization mechanisms using the previous results (i.e. Fe, Al and Ca) and data from this manuscript (i.e. pH).

Line 358 (383) How is the vegetation at the sites, how is primary production, above and belowground OM input? The biggest control on SOC stocks besides soil properties are plant traits at comparable parent materials. So as stated above, please give information on vegetation data in M&M.

Answer: Information on vegetation were given in the M&M section in **Line (110-114).** See the answer to the question of **Line 294-295.** Based on the information, the vegetation is similar between the wet and the dry sites.

Line 368-370 (392-396) Or these compounds are just more stable at dry conditions. On top of that, plants produce e.g. more suberin in the roots as protection against drought. And without a baseline of the initial plant material above and belowground this data just tells you there are differences in these acids due to precipitation.

Answer: Addressing your first point whether these compounds are more stable in the dry site, our unpublished data showed that they are more vulnerable in the dry-LSs. This is evidenced by the Dry-LSs having a clearer trend in the depletion in α, ω-dioic acids and ω-hydroxyl alkanoic acids (maybe also long-chain fatty acids) than the Wet-LSs (Fig. R2). If these compounds are larger and meanwhile more vulnerable in the Dry-LSs compared to the Wet-LSs, the most probable explanation is that the dry-LSs have higher belowground OM input. As it is very difficult to estimate OM input in the puna grassland, we can only assess these potential differences using the data of SOM composition.

We added Fig. R2 in the supplement as Fig. S3 and modified the sentences in **Line (392-396).**

Line 376-377 (402-403) There is the same amount of work showing plant species and traits having these effects on SOC storage and stability. Thus to prove the solely precipitation effect you would have to work with comparable plant species and traits.

Answer: The vegetation between the two sites is slightly different, but consists of grasses of the same functional types and genera but with different (sub-)species (see M&M in **Line (110-114)**).Thus, we proposed that their impact on the soil is comparable. With regard to the primary production, we have no data and literature on this is also very scarce but we expect that NPP is also affected by the availability of moisture.

For more open discussion, it is impressive that vegetation has been reported having limited influence on SOC storage and chemical composition in Andean alpine grasslands. Tonneijck et al. (2010) and Zimmermann et al. (2009) showed that SOC stocks were not significantly different between forest and grassland in Ecuadorian and Peruvian Andes. Furthermore, molecular composition was also not clearly different between forest and grassland soils (Nierop et al., 2007). We are not sure whether this is unique for the Andes. This is an interesting topic for future research and also the reason that we focused on soil mineralogy and aggregates.

Line 381 (407) So how high is the OM input?

Answer: We do not know the exact OM input because it is very difficult to estimate OM input in the Andean Puna/Jalca grassland. In addition, literature on OM production or NPP is very limited. We only found that one publication for Peru on slightly drier sites indicates a NPP of about 5 Mg C / ha yr for grazed grassland and around 15 Mg C /ha yr (Oliveras et al., 2014), which might give an indication of the NPP at our sites. Thus, we have to emphasize that our statement is based on estimation rather than quantitative measurement. We added this point in the previous paragraph in **Line (399-400).**

Nevertheless, we believe that it is a good opportunity that future studies focus on finding a practical method to estimate OM input in the Andean grasslands.

Line 385 (411) You compare limestone with granodiorite, as mentioned above this of course outcompetes any effect of precipitation at same altitude and latitude.

Answer: We rephrased it by adding the sentence: "We did not find an important effect of precipitation on aggregation, which was probably overshadowed by the effect of lithology." in **Line (411-413).**

Line 385-387 (413-415) For this you would have to show that there is no occluded light fraction/POM, and you didn0t miss the fast pulses (>10 days) in CO2 after soil structure disruption found by others.

Answer: As density fractionation was not applicable for the acid rock soils, incubation with aggregate intact vs. crushed was used as an alternative method to estimate occluded OM. For the fast pulses, data from Fig. R1 indicated that the fast pulse in CO_2 was not missed, whereas the comparisons in Table R1 indicated that SOC production in the first days was not significantly higher for crushed aggregates than intact aggregates. Thus, we can propose that SOM is unlikely stabilized by occluded in aggregates. For details, please check the answers to the questions of **Line** 30, **Line** 164 and **Line** 315.

Figures and Tables:

Table R1 Comparisons in SOC mineralization rates (per day) between intact aggregates and crushed aggregates

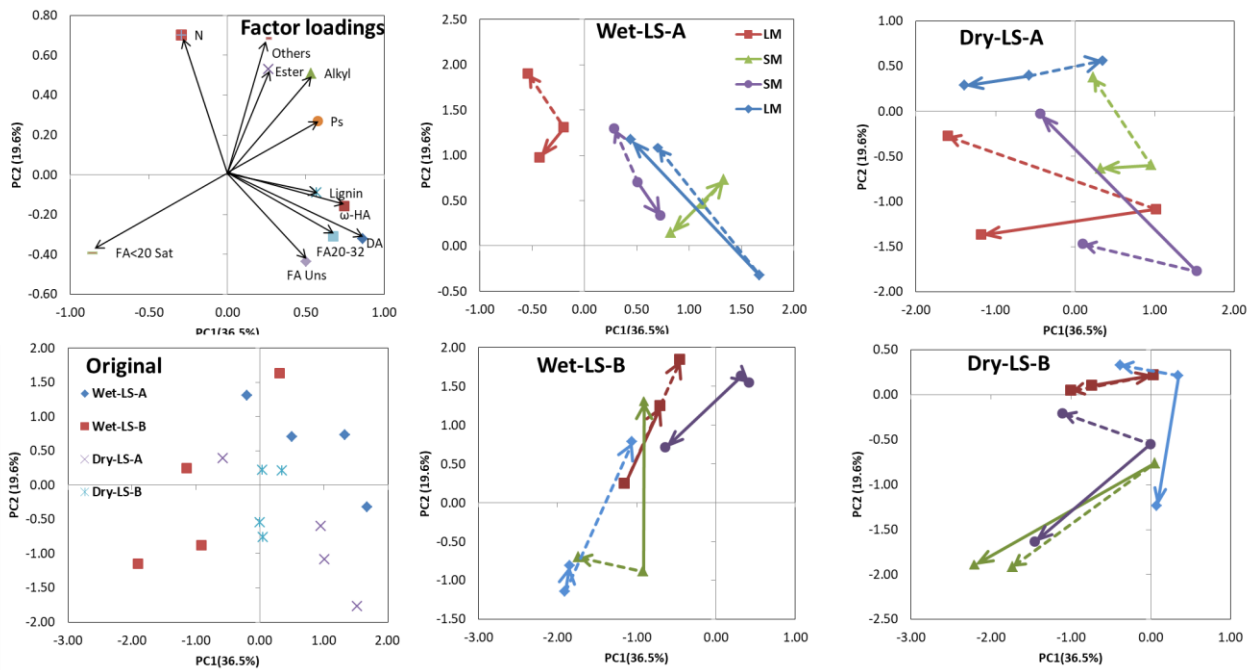|		Wet-LS-A		Wet-LS-B		Wet-AS-A		Dry-LS-A		Dry-LS-B		Dry-AS-A	
		LM	SM	LM	SM	LM	SM	LM	SM	LM	SM	LM	SM
Day1	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day2	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day6	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day9	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day13	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**In>Cr****
Day20	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day28	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day48	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day76	SMR	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	SMR per day	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

SMR: specified SOC mineralization rate Wet: the wet site, Dry: the dry site, LS: limestone soil, AS: acid igneous rock soil, A: A horizon, B: B horizon, LM: large macroaggregates (>2 mm), SM: small macroaggregates (0.25-2mm).
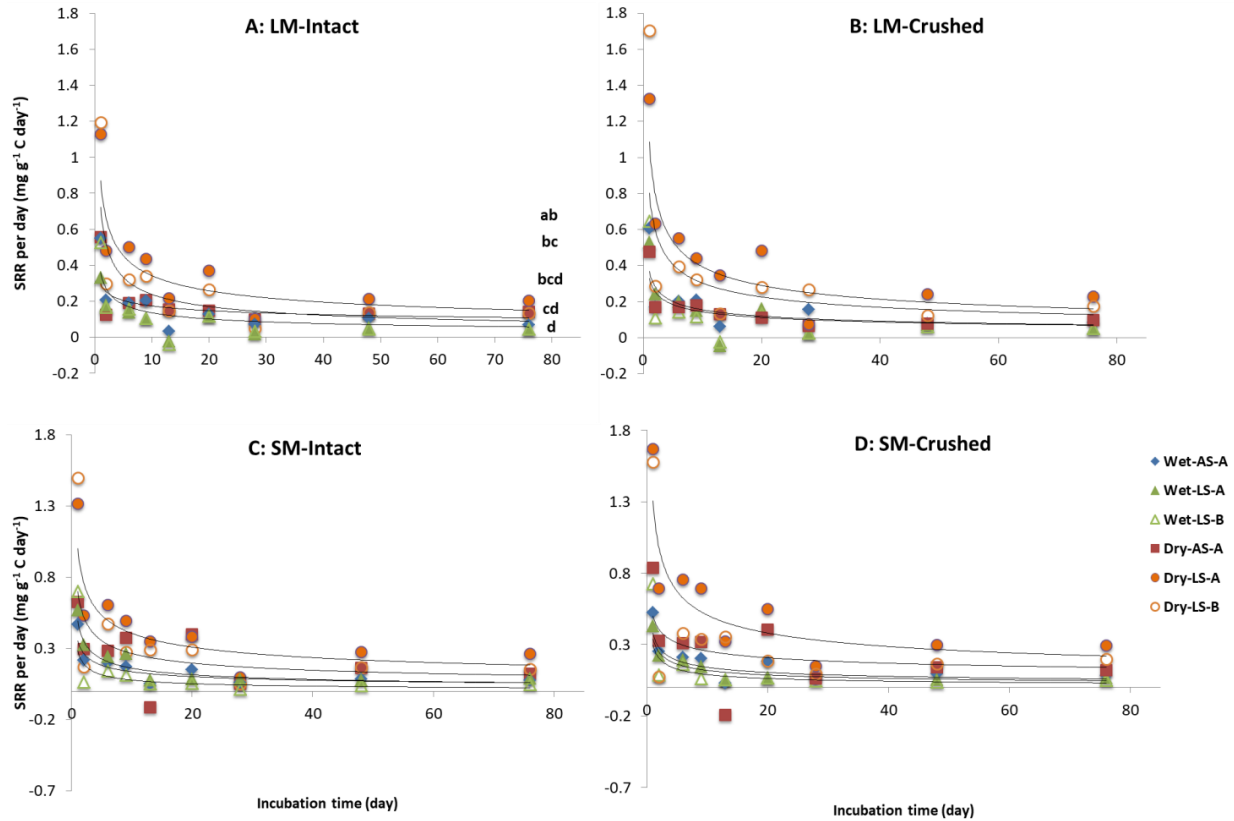
Fig. R1 Specific SOC mineralization rate per day (g C mineralized g^{-1} SOC day^{-1}). Wet: the wet site, Dry: the dry site, LS: limestone soil, AS: acid igneous rock soil, A: A horizon, B: B horizon, LM: large macroaggregates (>2 mm), SM: small macroaggregates (0.25-2mm).

Table R2 Correlations between SOC contents and selective extracted fractions, and between pH values and selective extracted fractions. The table shows the Fe, Al and Ca fractions contribution to SOC stabilization and the controls of soil pH on the Al and Ca fractions.

	Fe (pyrophosphate extracted)		Al (pyrophosphate extracted)		Ca (BaCl$_2$ extracted)	
	Correlation	P	Correlation	P	Correlation	P
Wet-LS (n=11)						
SOC content	**0.932**	**<0.001**	**0.816**	**0.002**	**0.750**	**0.008**
Wet-AS (n=7)						
SOC content	**0.687**	**0.088**	**0.736**	**0.059**	0.185	0.691
All (n=18)						
pH	0.063	0.805	**-0.704**	**0.001**	**0.532**	**0.023**

Fig. R2 (Fig. S3) Principal component analysis. DA: α, ω-dioic acid, ω-HA: ω-hydroxyl alkanoic acid, Alkyl: *n*-alkanes and *n*-alkenes, Ps: polysaccharides, N: nitrogen containing compounds, FA<20 Sat: saturated fatty acids with <20 carbon atoms, FA Uns: unsaturated fatty acids, FA20-32: saturated fatty acids with 20-32 carbon atoms, Wet: the wet site, Dry: the dry site, LS: limestone soil, AS: acid igneous rock soil, A: A horizon, B: B horizon. Arrows in solid line mean relative abundance change after incubation of intact aggregates; arrows in dotted line mean relative abundance change after incubation of crushed aggregates.

Respond to 2nd reviewers' comments:

The paper discusses the role of lithology and climate on the stabilization of organic matter. I like the choice of the sites on a clear precipitation transect. The approach is also straightforward, but I am not sure why the authors in contrast to the prevailing literature on the topic did not use wet sieving. After all, dry sieving does not result in water stable aggregates that occlude (to a certain extent) the organic matter. This choice for dry sieving needs to be justified and its implications discussed. Furthermore, details on the dry sieving method are lacking (line 159): agitation intensity and duration. Were the samples air-dried or field moist? The discussion section is speculative as many characteristics are mentioned in the discussion but neither the analytical methods nor the results are presented.

Answer in general: Thank you for the comments. In general, we used dry sieving instead of wet sieving because that (1) the method using wet-sieving to isolate occluded OM is not applicable for the acidic soils (ASs), and (2) aggregate stability determined by wet sieving does not explain SOC stocks or stability and is not helpful for to answer our research questions. For detailed information, please check the answer to the question of **Lines 307-326** (isolating occluded OM) and the question of **Line 144** (aggregate stability).

For other points, air-dried soils rather than moist soils were applied for the dry sieving. The sieving agitation intensity and duration were just the same as mentioned in the previous description of dry-sieving methods in **Line (155-161)**. To make this part clearer, we added the intensity and the duration in Line **(172)** "(30 Hz for 20 s)". For other soil characteristics, they were the focus of another publication. We addressed this in the question of **Line 328-330.**

Line 103 (109) Could you please explain the land use of the sites in somewhat more detail. As it stands, the land use is grassland, but you also mention cultivation and tree plantations. These activities would belong to cropland or forest land use classes.

Answer: The sampling rules were mentioned in **Line (131-134).** All sampling sites had the land use types of grassland, grassland with shrubs or fallow cropland. Tree plantation was avoided because tree litter can induce strong soil acidification.

The reason why we include three land use types is that a previous study in this area found that the spatial distribution of SOC stocks is not controlled by land use (Yang et al., 2018). The limited effects of land use on SOC stocks may be attributed to the special land use strategy in which a cycle of cultivation, land set-aside and grazing were repeated every 3-5 years. This suggests the SOC sequestration might be in a dynamical balance. Thus, it is reasonable to sample from these land use types.

We added information on vegetation in **Line (111-114)** and explained why we sampled on these land use types in **Line (131-132)**.

Line 142 (153) The stoniness is not expressed in % but in fraction. Please also state that you use the gravimetric fraction. See the discussion on the role of coarse fragments for SOC stocks in SOIL by

Poeplau et al and Hobley et al (2017 if I am not mistaken). The Bulk density should include the coarse fragments. Was this the case? You mention in line 132 that the gravels were removed. Please revise carefully.

Answer: Thank you for the very good questions and the relevant references. We apologize for the unclear statement of bulk density. We read the recommended publications and agree that the bulk density should include the coarse fragments. We actually have included all coarse fragments for the bulk density determination. The weights of coarse fragments were used to revise the bulk density for the SOC stock calculation because the coarse fragments were considered free of organic carbon.

We made changes in **Line (143-146)** to emphasize that bulk densities were measured with coarse fragments involved and SOC contents were measured without coarse fragments involved. The changes were: "Soil samples collected every 10 cm were freeze-dried to determine bulk densities and SOC stocks. Soil bulk densities were measured by weighing samples after freeze-drying. Afterward, gravels (>2 mm) were removed from the samples. The rest of the samples were used to determine OC contents and to calculate SOC stocks."

We also made changes for the formula in **Line (152-154)** as follows:

$$SOC\ stock = \sum_{i=1}^{i=k} BD_i \times C_i \times (1 - S_i) \times D_i$$

In which, BD_i = bulk density (g cm^{-3}) of the layer i (including gravels), C_i = SOC content (%) of the layer i (excluding gravels), S_i = stoniness (gravimetric) of layer i, D_i = thickness (cm) of layer i.

Line 144 (155) In general wet sieving is used to determine aggregate stability. Why did you choose dry sieving?

Answer: We agree that wet sieving is more suitable to determine aggregate stability than dry sieving. We also have the dataset of aggregates stability, macroaggreagte stability determined using wet sieving and microaggregate stability determined using sonication and sedimentation, respectively (details in Fig. R3). However, the objectives of this paper were to have insights into aggregate-size distribution and the stability of SOC distributed in different-sized aggregates. For these objectives, we considered that wet sieving is less suitable than dry sieving for two reasons.

The first reason is that we need to apply incubation to estimate SOC stability in different-sized aggregates. Compared to wet sieving, dry sieving is less destructive and keep the aggregates more similar to the original statues. The second reason is that aggregate stability determined by wet sieving seem not significantly contribute to the paper's topic. Literature showed that aggregate stability is not very useful to estimate SOC stability or OM occluded in aggregates (e.g. Heckman et al., 2014). This is also indicated by our data that neither macroaggregate stability nor microaggregate stability significantly predicted SOC mineralization (Fig. R3). After evaluation, we believe that the aggregate stability determined by wet

sieving did not contribute to the topic of this manuscript. Thus, aggregate stability determined by wet sieving was not included.

We added a discussion to explain why we have chosen dry-sieving instead of wet-sieving in **Line (323-332)**.

Line 147 (158-160) Please specify that these are gravimetric gravel contents.

Answer: Corrected. We modified the sentence to "Gravels (>2mm) were removed for all fractions larger than 2mm and the gravel content (gravimetric) of each fraction was calculated using the gravel weight divided by the sum of the fraction weight plus the gravel weight." in **Line (158-160)**.

Lines 307-**326 (322-332)** I miss a discussion on the difference between wet and dry sieving. After all, the authors you cite all used wet sieving. It is possible that occlusion does not play an important role, because your aggregates are not water stable and therefore, there is no real occlusion of OM in stable aggregates. This possibility should at least be mentioned in a note of caution (see also general remark).

Answer: Thank you for this question. We added a discussion in **Line (323-332)** to explain the application of dry-sieving plus incubation instead of wet-sieving plus sonication. Please also see the detailed explanation as follows.

First, we have to explain why we chose dry sieving. In general, wet-sieving is used to get water-stable aggregates in which OM is occluded and stabilized. In order to isolate and quantify the occluded OM in water-stable aggregates (what we need), density fractionation plus sonication is generally applied. We had no problem for the wet-sieving but had problems for the sonication. The application of ultrasound caused severe dispersion of organic materials into dense solution (NaPT) for the acidic soils (ASs). The dispersed organic materials were extremely difficult to be isolated from the solution. A similar situation has been reported by Kaiser and Guggenberger (2007), but we could not find a solution. It is not enough to get insights into aggregate-protected OM if we only quantified water-stable aggregates. Thus we have to use an alternative method to estimate occluded OM.

We chose an alternative method (dry sieving plus incubating intact versus crushed aggregates) applied by Goebel et al. (2009) and Wang et al. (2014). In this method, OM occluded in water-stable aggregates and unstable aggregates was addressed. Our conclusion supports that aggregate occlusion did not clear promote SOC stabilization. This can be explained by either no occluded OM or occluded OM being not stabilized.

Section 4.3 It is not clear to what extent characteristics have been measured. For instance, **lines 328-330 (351-354)** I have not seen any analytical data on Fe and Al hydroxide or Ca bridges.

Answer: The data of Fe, Al and Ca has been used as the focus of another paper (*Yang et al. 2019 Revised version submitted to Environmental Earth Science*). Briefly, the OM in the ASs was stabilized by interacting with Fe- and Al-oxides, whereas the OM in the LSs was stabilized by Ca bridges in addition to Fe- and Al-oxides (Table R2). In addition, soil pH values were the key factor controlling OM stabilization mechanisms (Table R2). As the focus of this manuscript was aggregate size distribution and OM stability controlled by aggregates, it could be a better way that we proposed the OM stabilization mechanisms using the previous results (i.e. Fe, Al and Ca) and data from this manuscript (i.e. pH).

Lines 368-369 (392-394) How were these fatty acids analysed?

Answer: Relative abundances of all mentioned compounds (including fatty acids) were measured using a pyrolysis-GC/MS system. As the data was used for another publication paper (*Yang et al. 2019, under review in Geoderma*), we just gave a brief description to the analysis in the subtitle of Fig. S2 as follows:

"Pyrolysis-gas chromatography / mass spectrometry (GC/MS) was applied to estimate the molecular composition of the soil organic matter. Briefly, milled soil samples were hydrolyzed and methylated using tetra-methyl-ammonium hydroxide (25 % in water). Afterward, a Curie-point pyrolyzer was used for sample pyrolysis. Helium was used as the carrier gas. Initial temperature was kept at 40 °C for 1 min, followed by heating at the rate of 7 °C min^{-1} until 320 °C sustaining for 15 min. The products of the pyrolysis were analyzed by the GC/MS system. Relative abundance of each compound was calculated as the peak area of the compound divided by the sum of peak areas of all identified compounds."

Figures and Tables:
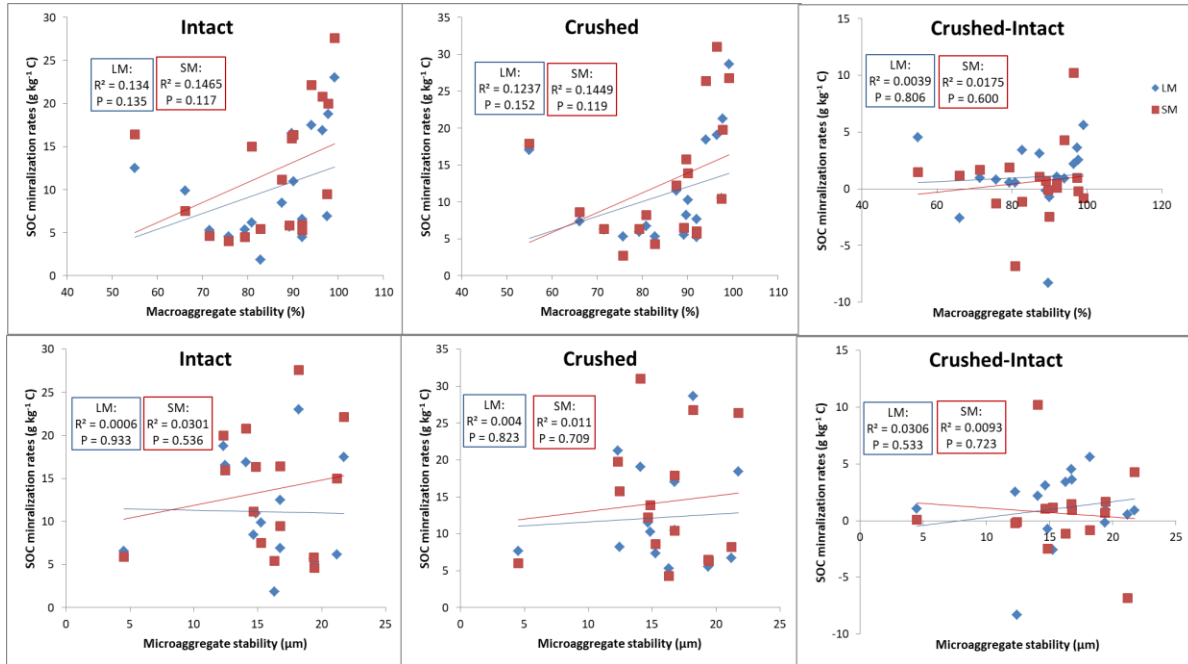
Fig. R3 SOC mineralization rates predicted by macroaggregate stability and microaggregate stability. Macroaggregate stability was measured by wet-sieving (20 Hz, 5 min) large macroaggreagtes (>2 mm) and determining the mass of remaining materials >2 mm. Microaggregate stability was determined by comparing the differences in mean weight diameters (MWD, μm) of microaggregates (<0.25 mm) between ultrasonic dispersion (20 W, 10 s) and non-dispersion applied.

Table R2 Correlations between SOC contents and selective extracted fractions, and between pH values and selective extracted fractions. The table shows the Fe, Al and Ca fractions contribution to SOC stabilization and the controls of soil pH on the Al and Ca fractions.

	Fe (pyrophosphate extracted)		Al (pyrophosphate extracted)		Ca (BaCl$_2$ extracted)	
	Correlation	P	Correlation	P	Correlation	P
Wet-LS (n=11)						
SOC content	**0.932**	**<0.001**	**0.816**	**0.002**	**0.750**	**0.008**
Wet-AS (n=7)						
SOC content	**0.687**	**0.088**	**0.736**	**0.059**	0.185	0.691
All (n=18)						
pH	0.063	0.805	**-0.704**	**0.001**	**0.532**	**0.023**

References:

Goebel, M. O., Woche, S. K. and Bachmann, J.: Do soil aggregates really protect encapsulated organic matter against microbial decomposition?, Biologia (Bratisl)., 64(3), 443–448, doi:10.2478/s11756-009-0065-z, 2009.

Hartley, I. P., Heinemeyer, A. and Ineson, P.: Effects of three years of soil warming and shading on the rate of soil

respiration: Substrate availability and not thermal acclimation mediates observed response, Glob. Chang. Biol., 13(8), 1761–1770, doi:10.1111/j.1365-2486.2007.01373.x, 2007.

Heckman, K., Throckmorton, H., Clingensmith, C., González Vila, F. J., Horwath, W. R., Knicker, H. and Rasmussen, C.: Factors affecting the molecular structure and mean residence time of occluded organics in a lithosequence of soils under ponderosa pine, Soil Biol. Biochem., 77, 1–11, doi:10.1016/j.soilbio.2014.05.028, 2014.

Hobley, E. U., Murphy, B. and Simmons, A.: Comment on "soil organic stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content" by Poeplau et al. (2017), Soil, 4(2), 169–171, doi:10.5194/soil-4-169-2018, 2018.

Juarez, S., Nunan, N., Duday, A. C., Pouteau, V., Schmidt, S., Hapca, S., Falconer, R., Otten, W. and Chenu, C.: Effects of different soil structures on the decomposition of native andadded organic carbon, Eur. J. Soil Biol., 58, 81–90, doi:10.1016/j.ejsobi.2013.06.005, 2013.

Kaiser, K. and Guggenberger, G.: Distribution of hydrous aluminium and iron over density fractions depends on organic matter load and ultrasonic dispersion, Geoderma, 140(1–2), 140–146, doi:10.1016/j.geoderma.2007.03.018, 2007.

Nierop, K. G. J., Tonneijck, F. H., Jansen, B. and Verstraten, J. M.: Organic Matter in Volcanic Ash Soils under Forest and Páramo along an Ecuadorian Altitudinal Transect, Soil Sci. Soc. Am. J., 71(4), 1119, doi:10.2136/sssaj2006.0322, 2007.

Oliveras, I., Girardin, C., Doughty, C. E., Cahuana, N., Arenas, C. E., Oliver, V., Huaraca Huasco, W. and Malhi, Y.: Andean grasslands are as productive as tropical cloud forests, Environ. Res. Lett., doi:10.1088/1748-9326/9/11/115011, 2014.

Poeplau, C., Vos, C. and Don, A.: Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content, Soil, 3(1), 61–66, doi:10.5194/soil-3-61-2017, 2017.

Tonneijck, F. H., Jansen, B., Nierop, K. G. J., Verstraten, J. M., Sevink, J. and De Lange, L.: Towards understanding of carbon stocks and stabilization in volcanic ash soils in natural Andean ecosystems of northern Ecuador, Eur. J. Soil Sci., 61(3), 392–405, doi:10.1111/j.1365-2389.2010.01241.x, 2010.

Wang, X., Cammeraat, E. L. H., Cerli, C. and Kalbitz, K.: Soil aggregation and the stabilization of organic carbon as affected by erosion and deposition, Soil Biol. Biochem., 72, 55–65, doi:10.1016/j.soilbio.2014.01.018, 2014.

Yang, S., Cammeraat, E., Jansen, B., den Hann, M., van Loon, E. and Recharte, J.: Soil organic carbon stocks controlled by lithology and soil depth in a Peruvian alpine grassland of the Andes, Catena, 171(June), 11–21, doi:10.1016/j.catena.2018.06.038, 2018.

Zimmermann, M., Meir, P., Silman, M. R., Fedders, A., Gibbon, A., Malhi, Y., Urrego, D. H., Bush, M. B., Feeley, K. J., Garcia, K. C., Dargie, G. C., Farfan, W. R., Goetz, B. P., Johnson, W. T., Kline, K. M., Modi, A. T., Rurau, N. M. Q., Staudt, B. T. and Zamora, F.: No Differences in Soil Carbon Stocks Across the Tree Line in the Peruvian Andes, Ecosystems, 13(1), 62–74, doi:10.1007/s10021-009-9300-2, 2009.

Changes in manuscript

(All line numbers corresponds to the revised manuscript)

Changes based on Reviewer 1:

Line (20-28): We replaced LSs and ASs by limestone soils and acid igneous rock soils in the abstract.

Line (41-44, 46-48 and 57): We specified the place as Ecuadorian and Peruvian Andes.

Line (72-78): A part of the discussion (first paragraph of section 4.1) on aggregate size distribution controlled by lithology was moved to the introduction in a modified form.

Line (97-100): We added a short description of wet Puna and Jalca.

Line (111-114): We added information on vegetation.

Line (131-132): We added that the SOC stocks were not controlled by land use in the studied area.

Line (158-160): We modified the sentence on how gravel contents were measured.

Line (173-174): We added a sentence to explained why the finer fraction was not analyzed.

Line (176): We replaced the word "grinding" with "crushing".

Line (186-187): We changed the sentence to emphasize that the SOC mineralization was normalized for OC contents.

Line (223-232): We re-wrote the paragraph to make it easier to understand.

Line (270-275): The original paragraph was largely shortened and a part of it was moved to the introduction in a modified form in **Line (72-78)**.

Line (280-298): We split the original paragraph into two: one on precipitation in **Line (280-286)** and the other on stoniness in **Line (287-298).**

Line (323-332): We added a discussion to explain why we did not separate occluded OM.

Line (392-396): We modified the explanation of the higher underground OM input in the dry-LS. **Line (399-400):** We added a discussion based on a publication on OM input in the Andes.

Line (411-413): We added the sentence "We did not find an important effect of precipitation on aggregation, which was probably overshadowed by the effect of lithology" in the conclusion.

Changes based on Reviewer 2:

Line (131-132): We added that the SOC stocks were not controlled by land use in the studied area.

Line (143-146 and 153-154): We made changes to emphasize that bulk densities were measured including gravels.

Line (155-161 and 172): We modified the description on dry-sieving.

Line (158-160 and 165): We modified the sentence on how gravel contents were measured and calculated.

Line (323-332): We added a discussion to explain why we have chosen dry-sieving instead of wet-sieving.

Others:

We added Fig. S3 (PCA) in the Supplements.

We added two references in **Line (464-466)** and **Line (496-498).**

Lithology and climate controlled soil aggregate size distribution and organic carbon stability in the Peruvian Andes

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10

Abstract

Recent studies indicate that climate change influences soil mineralogy by altering weathering processes, and thus impacts soil aggregation and organic carbon (SOC) stability. Alpine ecosystems of the Neotropical Andes are characterized by high SOC stocks, which are important to sustain ecosystem services. However, climate change in the form of altered precipitation patterns can potentially affect soil aggregation and SOC stability with potentially significant effects on the soil's ecosystem services. This study aimed to investigate the effects of precipitation and lithology on soil aggregation and SOC stability in the Peruvian Andean grasslands, and assessed whether occlusion of organic matter (OM) in aggregates controls SOC stability. For this, samples were collected from soils on limestone and soils on acid igneous rocks from two sites with contrasting precipitation levels. We used a dry-sieving method to quantify aggregate size distribution, and applied a 76-day soil incubation with intact and crushed aggregates to investigate SOC stability in dependence on aggregation. SOC stocks ranged from 153±27 to 405±42 Mg ha^{-1}, and the highest stocks were found in the limestone soils of the wet site. We found lithology rather than precipitation to be the key factor regulating soil aggregate size distribution, as indicated by coarse aggregates in the limestone soils and fine aggregates in the acid igneous rock soils. SOC stability estimated by specific SOC mineralization rates decreased with precipitation in the limestone soils, but minor differences were found between wet and dry sites in the acid igneous rock soils. Aggregate destruction had a limited effect on SOC mineralization, which indicates that occlusion of OM in aggregates played a minor role in OM stabilization. This was further supported by the inconsistent patterns of aggregate size distribution compared to the patterns of SOC stability. We propose that OM adsorption on mineral surfaces is the major OM stabilization mechanism controlling SOC stocks and stability. The results highlight the interactions between precipitation and lithology on SOC stability, which are likely controlled by soil mineralogy in relation to OM input.

1 Introduction

Soil organic carbon (SOC) is the largest terrestrial carbon (C) pool and plays an important role in global C dynamics (Carvalhais et al., 2014; Lal, 2004). However, the distribution of SOC at a global scale is highly variable (Batjes, 2014; Lal, 2004). Alpine grasslands of the Andes are characterized by large SOC stocks,

especially for the Ecuadorian and Peruvian Andes (Muñoz García and Faz Cano, 2012; Rolando et al., 2017a; Tonneijck et al., 2010). The Andean grasslands play a crucial role in agricultural production, water provision and sustaining the high biodiversity (Buytaert et al., 2011; Rolando et al., 2017a). The large

45   SOC stocks contribute to crucial ecosystem services, and act as a potential C sink or source for atmospheric CO_2 in the context of global change (Buytaert et al., 2011). However, the studied region, the Andes in Northern Peru, is characterized by heterogeneity in climate, vegetation, agricultural activities and geological formations (Buytaert et al., 2006b; Rolando et al., 2017a), which potentially introduces spatial variability in SOC storage and stability.

50   Recent views on SOC persistence have shifted from chemical recalcitrance of soil organic matter (OM) to progressive decomposition of soil OM dependent on the surrounding biotic and abiotic environment (Lehmann and Kleber, 2015; Schmidt et al., 2011). Specifically, SOC persistence and stabilization are controlled by: (1) OM adsorption on mineral surfaces that controls long-term stabilization, and (2) physical occlusion of OM within soil aggregates that regulates intermediate-term stabilization with

55   heterogeneous OM composition and residential time (Lützow et al., 2006; Schrumpf et al., 2013). Adsorption of OM on mineral surfaces was reported as an important stabilization mechanism for soil OM underlying the large SOC stocks in the Peruvian and Ecuadorian Andes (Buytaert *et al.*, 2006a; Tonneijck *et al.*, 2010; Yang *et al.*, submitted). However, studies focusing on aggregate-controlled OM stabilization in relation to climate in the Andes are rare (e.g. Rolando *et al.*, 2017b). Aggregates promote soil OM

60   stabilization against decomposition by regulating the availability of oxygen and water as well as the accessibility of OM itself (Kong et al., 2005). Thus, the formation and turnover of soil aggregates are crucial for SOC storage and OM stabilization (Six et al., 2004; Six and Paustian, 2014). As soil aggregates are formed with monomers of clay minerals, polyvalent cations and OM, their formation and the underlying OM stabilization largely depend on various biotic and abiotic factors (e.g. climate and

65   lithology) (Bronick and Lal, 2005; Doetterl et al., 2015).

Lithology is the key factor controlling soil OM stabilization and soil aggregation, mainly attributed to its controls on soil mineralogy and texture (Angst et al., 2018; Homann et al., 2007; Wiesmeier et al., 2019). In soils formed on acidic bedrocks, OM is generally considered to be stabilized by ligand exchange with non-crystalline Fe and Al oxides, whereas in soils formed on alkaline-rich bedrocks, OM is thought to be

70   stabilized by interaction with the mineral surface through polyvalent cation bridges (e.g. Ca^{2+}) (Lützow et al., 2006). Soil texture also has effects on OM stabilization because OM-mineral association is dominantly controlled by clay-sized minerals (Kaiser and Guggenberger, 2003; Kleber et al., 2007). In addition, soil mineralogy and texture are crucial factors for soil aggregation (Bronick and Lal, 2005). In soils developed on base-rich or calcareous materials, the high clay and calcium (Ca) contents promote the

3

75   formation of large-sized aggregates. In soils developed on sand-rich or acidic materials, the lack of alkaline cations (e.g. Ca^{2+}) and the coarse texture hinder the formation of coarse aggregates (Bronick and Lal, 2005; Six et al., 2004). The differences in aggregation can potentially affect soil OM stabilization as controlled by occlusion of OM within aggregates (Lützow et al., 2006).

Climate factors, comprising temperature and precipitation, act as the primary drivers regulating SOC
80   storage and OM stabilization by controlling OM input and decomposition (Schmidt et al., 2011; Wiesmeier et al., 2019). Recent studies indicated that climate factors also control OM persistence by regulating soil mineralogy (Chaplot et al., 2010; Doetterl et al., 2015, 2018). The soil mineralogy and OM persistence controlled by climate can be dependent on lithology due to their inherent properties (Jenny, 1994; Wagai et al., 2008). Given the importance of climate and lithology, the heterogeneity in
85   precipitation and lithology in the Andes can potentially cause spatial variation in OM stabilization and consequently SOC stocks. In addition, shifts in e.g. precipitation patterns as a result of global change may impact SOC stocks in different parts of the Andes in different ways.

The objectives of our study were to assess the controls of precipitation and lithology on SOC stocks and stability in the Peruvian Andes. Specifically, we aimed to investigate whether the effects of precipitation
90   and lithology on SOC stability are through the controls of OM stabilization governed by aggregate occlusion and/or mineral adsorption. For this, we applied a combination of aggregate-size fractionation with a 76-day incubation for soil samples collected from the Peruvian Andes with two contrasting bedrocks and two precipitation levels.

95   **2 Materials and methods**

2.1 Site description

Basic information of the sampling sites is shown in Fig. 1. The study areas belong to the Neotropical alpine grassland of the Andes, corresponding to the grassland ecosystem commonly referred as wet Puna or Jalca that is present between the tree line (3500 m asl) and the ice-covered region, having an annual
100   precipitation over 500 mm (Rolando et al., 2017a). Two sampling sites were selected with similar altitudes but with different lithologies and precipitation levels. The wet site is located in the western Cordillera mountain chain of the Peruvian Andes, to the west of Cajamarca, Peru (7°11` S, 78°35` W). The altitudes of the sites range from 3500 m to 3720 m asl. The temperature shows a large daily variation and minor seasonal variation, with an estimated annual mean of 11°C. The sites receive 1100mm
105   precipitation per year and have a wet season between October and April (Sánchez Vega et al., 2005). The

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dry site is located in the mountain chain of the Cordillera Blanca, to the northeast of Carhuaz (9°22` S, 77°59` W), with altitudes ranging between 3490 and 3700 m asl. The annual temperature and precipitation were estimated as 11 °C and 680 mm, and had similar annual and daily variations as the wet site (Merkel, 2017). Typical land use in both sites is grassland with human activities including cultivation,

110 grazing and plantation of pine trees and eucalyptus (Rolando et al., 2017a; Sánchez Vega et al., 2005). The vegetation in the wet site is a typical disturbed wet Puna (or Jalca) vegetation with dominant grass species *Calamagrostis sp.,* but also *Festuca and Agrostis sp. as well as Rumex sp.* on fallow land. Similarly, the vegetation in the dry site is also a typical disturbed wet Puna (or Jalca) vegetation with *Calamogrostis sp., Stipa and Festuca sp. and Rumex sp.* on fallow land.

115 For the wet site, the geology consists of a basement of Cretaceous sedimentary formations, which is composed of limestone, marl, shale and quartzite. Neogene igneous bedrocks consisting of granite and ignimbrite intrude or cover parts of the basement (Reyes-Rivera, 1980). For the dry site, intrusive igneous rocks (mainly granodiorite) belonging to the Neogene Cordillera Blanca batholith are present in the western part of the Cordillera Blanca (Coldwell et al., 2011; Portes et al., 2016). The foot slopes consist

120 of fluvio-glacial and glacial sediments partly covering andesitic ignimbritic rocks of the Neogene Yungay formation, as well as the sedimentary Cretaceous Carhuaz and Santa formations that are dominated by folded limestones, sandstones and shales (Coldwell et al., 2011). Soils developed on the limestone were classified as Phaeozems or Umbrisols, whereas soils on acid igneous rocks were classified as Andosols and Umbrisols (WRB, 2014).

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2.2 Sampling procedures

For both the wet and dry sites, we selected three soil sampling plots from limestone and three plots on acid igneous rocks. For limestone soils (LSs) in both sites and acid igneous rock soils (ASs) in the wet site, all soils were directly developed on the bedrock. For ASs in the dry site, one sampling site was

130 directly developed on granodiorite, whereas the other two sites were located on the glacier deposits on lateral moraines with a granodioritic composition. As a previous study in the study area showed that SOC stocks are not significantly controlled by land use (Yang et al., 2018), all sampling sites were selected based on the criteria of (1) grassland, grassland with shrubs or abandoned cropland, (2) gentle slopes, (3) no intensive human activities, and (4) similar soil development status.

135 For the determination of bulk density and calculation of SOC stocks through the soil profile, samples were collected every 10 cm in duplicate to the depth of the C horizon using Kopecky rings (100 cm^3). For the determination of basic soil properties, aggregate-size fractionation and incubation, soil samples were

collected per horizon in triplicate (e.g. A_{h1}, A_{h2} and B_{tg} horizons). To minimize aggregate destruction during transportation, soil samples were transferred into sealed plastic bags and protected by hard plastic

140   boxes.

2.3 Laboratory analyses

Soil samples collected every 10 cm were freeze-dried to determine bulk densities and SOC stocks. Soil bulk densities were measured by weighing samples after freeze-drying. Afterward, gravels (>2 mm) were

145   removed from the samples. The rest of the samples was used to determine OC contents and to calculate SOC stocks. Soil samples collected per horizon were air-dried, followed by taking 5-10 g of sub-samples milled for the determination of basic soil properties. For these samples, total C and N contents were analyzed using a VarioEL Elementar analyzer (Elementar, Germany). As inorganic C contents were negligible in all the samples, the total OC contents were equal to total C contents. Soil pH was determined

150   with a glass electrode in suspensions of soil material in demi-water (w:v=1:5, Bates, 1973).

Total SOC stocks were calculated using the following equation:

$$SOC\ stock = \sum_{i=1}^{i=k} BD_i \times C_i \times (1 - S_i) \times D_i$$

In which, BD_i = bulk density (g cm^{-3}) of the layer i (including gravels), C_i = SOC content (%) of the layer i (excluding gravels), S_i = stoniness (gravimetric) of layer i, D_i = thickness (cm) of layer i.

155   Dry-sieving was applied to fractionate soil samples into 5 aggregate-size groups: >5mm, 2-5mm, 0.22-2 mm, 0.063-0.25 mm and <0.063 mm, respectively. Briefly, 170-230 g sub-samples (<16 mm) of each horizon were fractionated using 4 mesh sieves (5, 2, 0.25 and 0.063 mm) by shaking for 20 s at 30 Hz at a horizontal shaker. For all fractions larger than 2 mm, gravels were separated by sieving (2 mm) a subsample of the fraction after breaking aggregates. The gravel content (gravimetric) of each fraction was

160   calculated using the gravel weight divided by the sum of the fraction weight plus the gravel weight. For each fraction, fraction weights as well as total C and N contents were determined.

The mean weight diameter (MWD) of the bulk soil was calculated by:

$$MWD = \sum_{i=1}^{i=5} \frac{x_{i\ max} + x_{i\ min}}{2} \times w_i$$

In which, $x_{i\,max}$ = maximum diameter (mm) of the fraction i, $x_{i\,min}$ = minimum diameter (mm) of the
fraction i, w_i = weight percent (excluding gravels) of the fraction i (Klute and Dinauer, 1986).

Sample materials collected from different horizons were used for the incubation. All materials from
individual A horizons in the same soil profile were merged (e.g. Ah1 and Ah2 horizons merged to A
horizon), based on the weight distribution of the horizons as estimated by their bulk densities and depths.
Original B horizons were used because each soil profile only had a single B horizon. Prior to the
incubation, all samples were fractionated into large macroaggregates (LM, > 2mm), small
macroaggregates (SM, 0.25-2 mm) and microaggregates (Mi, <0.25 mm), following the dry-sieving
procedure (30 Hz for 20 s). The LM and SM fractions were used for the incubation with intact and
crushed aggregates. The finer fractions (<0.25 mm) were by far less abundant, and thus were not
incubated. The variation in SOC mineralization between intact and crushed aggregates was used as a
measure of C stabilization by occlusion within aggregates (Goebel et al., 2009). Aggregates were
destructed by crushing the fractions using a porcelain mortar, and all crushed materials could pass a 0.125
mm sieve (Wang et al., 2014). Before incubation, intact and crushed fractions were rewetted at pF 2.0 for
10 days to activate soil microbes. Approximate 10 g dry-weight equivalent fractions were incubated for
76 days at 20 °C in sealed glass jars (120 ml). All soil fractions were incubated in duplicate. The
headspace of incubating jars was sampled on days 1, 2, 6, 9, 13, 20, 28, 48 and 76. During the sampling
period, CO_2-free air was injected into the jars to maintain pressure and avoid too high CO_2 concentrations.
The CO_2 concentration was analyzed using a gas chromatograph with a flame ionization detector (GC-
FID, Thermo Scientific, Trace GC Ultra) with packed columns (RESTEK Packed Column, Part Nbr:
PC7130, Serial Nbr: C34216-01, HayeSep Q, 1/8" 80/100 2m and HayeSep Q, 1/8" 80/100 1m). A
methanizer was situated in front of the FID, as the detector can only measure hydrocarbons instead of
CO_2. Specific SOC mineralization rates (g CO_2-C g^{-1} C), which were normalized for OC contents, were
used as an indicator of the C stability of the soil fractions.

2.4 Statistics

Statistical comparisons of soil properties and SOC stocks were made using a one-way ANOVA. *Post hoc*
analyses were conducted using the Fisher's Least Significant Difference (LSD) test. Principal component
analysis (PCA) was applied to investigate potential differences between different soil profiles and
horizons. Before conducting the PCA, Kaiser-Meyer-Olkin tests and Bartlett's tests were used to
guarantee that sampling adequacy and the sphericity were suitable for the analysis. Linear regressions
were applied to investigate relationships of specific SOC mineralization rates with SOC and C/N ratios.

An independent *t*-test was applied to check effects of precipitation, lithology, soil horizon, aggregate size and aggregates destruction on SOC mineralization rates.

Before the *t*-test and the one-way ANOVA, data normality and variance homogeneity were examined using a Shapiro-Wilk test and a Levene's test. When the assumption of normality was violated, the
200   Kruskal-Wallis H test was applied instead of the one-way ANOVA, while the Mann-Whitney U-test was used instead of the *t*-test. When the homogeneity of the variance could not be assumed, the Robust Welch test was used for the one-way ANOVA. All analyses were conducted using SPSS 24.0 (SPSS Inc., USA).

3 Results

205   *3.1 Soil properties*

Average soil depths were 61cm for limestone soils (LSs) in both wet and dry sites, and 49 cm and 51 cm for acid igneous rock soils (ASs) in the wet and the dry sites (Fig. 1). SOC stocks were highest in LSs of the wet site (wet-LSs, 405.3 ± 41.7 Mg ha^{-1}), followed by ASs of the wet site (wet-ASs), ASs of the dry site (dry-ASs) and dry-LSs. SOC stocks in the wet-LSs were significantly higher compared to other soils
210   (Fig. 2). SOC contents in the A horizons were significantly higher in the wet-LSs both with regard to bedrock and precipitation. No significant differences were present for the ASs with regard to precipitation (Fig. 2). The LSs had no significant difference in C/N ratios compared to the ASs for the A horizons in the wet sites, however, the LSs had significantly lower C/N ratios in the dry site (Fig. 2). With decreasing precipitation, C/N ratios significantly decreased in the LSs and increased in the ASs (Fig. 2). pH values
215   were significantly higher in the LSs compared to the ASs in the wet site, but were not significantly different in the dry site (Fig. 2). In addition, significantly lower pH values with lower precipitation were only found in the LSs (Fig. 2). With regard to the differences between horizons in the LSs, B horizons were characterized by significant lower SOC contents, lower C/N ratios and higher pH compared to A horizons, except for SOC contents and pH values in the dry sites (Fig. 2).

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3.2 Aggregate-size fractionation

The weight distribution of the aggregate-size fractions is shown in Fig 3A and 3C. The LSs had larger aggregate sizes than the ASs in both wet and dry sites, as indicated by that LSs had more LM fraction (> 60%) and less Mi fraction (< 10%) when compared to the AS (Fig 3A and 3C). When comparing the wet
225   and dry sites, the aggregate-size distribution was not clearly different in the LSs. In contrast, the wet-ASs

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had larger aggregate sizes (more LM fraction) than the dry-ASs (Fig. 3A and 3C). When comparing the A and B horizons in the LSs, B horizons had larger aggregates sizes compared to A horizons for both wet-LSs and dry-LS (Fig. 3A and 3C). The SOC distribution in different fractions is similar to the weight distribution as shown in Fig. 3B and 3D. The LSs had more SOC located in large-sized aggregates than the ASs , whereas the wet-ASs had more SOC distributed in large aggregates than the dry-ASs. For the LSs, B horizons had more SOC distributed in large-sized aggregates when compared to A horizons (Fig 3A-3D).

Soil properties of different horizons are shown in Fig. 4. PC1 and PC2 explained 67.0 % and 17.9 % of the total variation. PC1 had positive contributions of the SM and Mi fractions and negative loadings of the LM fractions and MWD, whereas PC2 had positive contributions of C and N contents. The LSs were separated from the ASs as indicated by coarser aggregates, higher pH values and lower C/N ratios (Fig. 4). In addition, wet-LSs were separated from dry-LSs by higher C and N contents, whereas ASs were not clearly separated by precipitation (Fig. 4). The LSs were characterized by increasing coarse aggregate fractions and decreasing C and N contents as well as C/N ratios with increasing soil depth, whereas the ASs had no clear pattern in soil property change with increasing depth (Fig. 4).

3.3 SOC mineralization

After the 76-day incubation, specific SOC mineralization rates were the highest in A and B horizons of the dry-LSs, when compared to the other soil horizons (Fig. 5A-5D). For comparisons between two lithologies, SOC mineralization rates were not significantly different in the wet site, but were generally higher in the LSs compared to the ASs in A horizons of the dry site (Table 1). For effects of precipitation, SOC mineralization rates were significantly higher in the dry site compared to the wet site for the LS-A horizons in most sampling days, but were not significantly different for the AS-A horizons (Table 1). For comparisons between A and B horizons in the LSs, SOC mineralization rates were not significantly different in the wet site. In the dry site, A horizons had significantly higher SOC mineralization rates than B horizons only in the aggregate-crushed SM fraction (Table 1).

SOC mineralization rates were slightly stimulated (up to 19.4 %) when aggregates were crushed compared to that when aggregates were intact, with exceptions of the LM fraction in dry-AS-A horizons and the SM fraction in dry-AS-A horizons and wet-LS-A horizons (Fig 6A and 6B). However, the stimulation caused by aggregate destruction was never significant (Fig. 6A and 6B). In addition, no significant difference in SOC mineralization rates was found between LM and SM fractions. Exclusively,

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slightly higher SOC mineralization rates (not significant) were found in the SM fraction compared to LM fraction in A horizons of the wet-LS, the dry-LSs and the dry-ASs (Fig. 6C and 6D).

Overall, SOC mineralization rates had significant negative relationships with SOC contents and C/N ratios, and the negative relationships did not differ between intact and crushed aggregates (Fig. 7A and 7B). Exclusively for the dry-LSs, positive relationships were found between SOC mineralization rates and SOC contents when aggregates were intact and crushed, and between SOC mineralization rates and C/N ratios when aggregates were crushed (Fig. 7C-7F). In the dry-LSs, SOC contents and C/N ratios explained 38.2 % and 24.9 % of the variation of specific SOC mineralization rates when aggregates were intact. When aggregates were crushed, SOC contents and C/N ratios explained 48.0 % and 33.3 % of the total variation (Fig. 7C-7F).

4 Discussion

4.1 Aggregate size distribution

Lithology is the key factor controlling soil aggregate-size distribution in our soils, as indicated by larger aggregates in the LSs when compared to the ASs (Fig. 3). The larger aggregates in the LSs are consistent with the literature (Bronick and Lal, 2005; Six et al., 2004). The lithology-controlled aggregate-size distribution can be further supported by the physicochemical properties of aggregate fractions (Fig. S1). Compared to the LSs, the ASs had higher C/N ratios in all fractions than the LSs and had a larger increase in OC contents with decreasing fraction size when aggregate size was smaller than 2 mm (Fig. S1). Furthermore, increasing aggregate sizes with soil depth were found in the LSs exclusively (Fig. 4), which can be explained by the better aggregation promoted by clay illuviation in deep soils. In contrast, no clear vertical differences in the ASs may be related to the lack of the clay fraction in the ASs (Yang *et al.*, submitted).

Unlike lithology, precipitation plays only a minor role in the soil aggregate size distribution for our soils. This is indicated by small differences in properties related to soil aggregation between the wet and the dry sites for the same bedrock types (Fig. 3, Fig. 4 and Fig. S1). Although precipitation potentially controls the OM input and further affects soil aggregation (Bronick and Lal, 2005, Wiesmeier et al., 2019), similar vegetation between wet and dry sites (see *2.1 site description*) might alleviate the controls of precipitation on OM input and soil aggregation. In addition, the effects of precipitation might be superimposed by the strong effect of lithology in our study.

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Notably, the dry-ASs had smaller aggregates than the wet-ASs (Fig. 3). This is probably attributed to their greater gravel contents in the dry-ASs (Fig. 1 and Table S1) because abundant gravels occupy the space and hinder the formation of large-sized aggregates. Furthermore, gravel contents may affect soil

290 aggregation by controlling root distribution, OM input or soil biological activity. The greater gravel contents in the dry-ASs are likely to be attributed to the terrain conditions (steep mountains and glacial deposits) rather than precipitation (Portes *et al.* 2016). Although aggregate-size distribution is controlled by gavel contents, the physicochemical properties of each aggregate fraction were not clearly affected. This is corroborated by: (1) no clear differences in vertical distribution of aggregate-related soil properties

295 between wet-ASs and dry-ASs (Fig. 4), and (2) no clear differences in properties of aggregate fractions between wet-ASs and dry-ASs (Fig. S1). An important reason for this is that gravels were always removed from all fractions >2 mm. Thus, analyses conducted for aggregates fractions (e.g. SOC mineralization) are not biased by gravel contents.

300   *4.2 SOC stocks and stability*

SOC stocks were controlled by interactions between lithology and precipitation, as indicated by increased stocks with precipitation in the LSs and no significant changes in the ASs (Fig. 2). Lithology had significant effects on SOC stocks in the wet sites (Fig. 2), which is consistent with the findings of Yang *et al.* (2018) showing that lithology is the key factor controlling SOC stocks. In the wet site, the high SOC

305 stocks in the LSs compared to the ASs can be explained by deeper soils and higher SOC contents in A horizons (Fig. 1 and 2). In the dry site, no difference in SOC stocks between the LSs and the ASs can be explained by that the LSs had lower SOC contents but deeper profiles (Fig. 1 and 2). Precipitation had significant effects on SOC stocks of the LSs, as indicated by the wet-LSs having greater SOC stocks than the dry-LSs (Fig. 2). This is consistent with the consensus that SOC stocks generally increase with

310 precipitation (Homann et al., 2007; Wiesmeier et al., 2019). The higher SOC stocks in the wet-LSs can be also explained by SOC contents because of (1) similar soil depths in the wet-LSs and the dry-LSs (Fig. 1) and (2) lower soil bulk densities in the wet-LSs (Table S2). Hence, patterns of SOC stocks controlled by lithology and precipitation are mainly explained by SOC contents.

The negative correlations between SOC contents and SOC mineralization rates (Fig. 7A and 7B) reflect

315 SOC contents controlled by SOC stability. The SOC stability is significantly controlled by precipitation and lithology (Table 1) rather than soil horizon, aggregate size or aggregate destruction (Fig. 6). For horizons, although SOC stability was different between A and B horizons in the crushed SM fraction of

the dry-LSs (Table 1), the small contribution of the SM fraction (Fig. 3) suggests that horizon is not an important factor controlling the SOC stability.

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4.3 Organic matter stabilization mechanisms

SOC stability is largely controlled by two mechanisms: (1) OM adsorption on the mineral surfaces and (2) physical occlusion of OM within soil water-stable aggregates (Lützow et al., 2006; Six et al., 2002). In general, OM occluded in water-stable aggregates is isolated using wet-sieving followed by density

325   fractionation plus sonication (Cerli et al., 2012; Moni et al., 2012). However, these methods were not applicable for our ASs because the application of ultrasound caused severe dispersion of OM into the dense solution (i.e. NaPT). The dispersed OM was difficult to be separated from the solution and thus occluded OM could not be isolated. A similar situation has been reported and a potential explanation is that Na$^+$ in the solution interacted with Al-OM complexes in the ASs and produced a stable suspension

330   (Kaiser and Guggenberger 2007). As the problem could not be solved, we applied an alternative method, which has been conducted by Goebel et al. (2009) and Wang et al. (2014), to estimate aggregate-occluded OM using a combination of dry-sieving and incubating intact versus crushed aggregates.

Overall, aggregate-occlusion is not a major OM stabilization mechanism in our soils, as indicated by no or insignificant stimulation in SOC mineralization after aggregate destruction (Fig. 6). The minor role of

335   aggregate-occlusion is further supported by the minor changes in correlation patterns of SOC mineralization rates with SOC contents and C/N ratios, when aggregates were intact and crushed (Fig. 7A and 7B). The limited effects of OM occlusion in aggregates are not consistent with the general view of aggregate-controlled OM stabilization (Lehmann and Kleber, 2015; Wiesmeier et al., 2019), as well as other studies revealing aggregate-protected OM using similar aggregate destruction methods (Mueller et

340   al., 2012; Wang et al., 2014). However, Goebel *et al.* (2009) and Juarez *et al.* (2013) reported limited roles of soil aggregates in protecting OM from decomposition. For the ASs, the limited role of aggregates-occlusion in OM stabilization can be explained by the lack of large-sized aggregates (Fig. 3), which suggests the restricted formation of microaggregates within macroaggregates. This potentially weakens the OM protection controlled by occlusion in aggregates (Six et al., 2002; Six and Paustian,

345   2014). For the LSs, the minor contribution of aggregates might be related to the strong adsorption of OM on less-saturated mineral surfaces (Yang *et al.*, submitted). Because of the limited contribution of OM occlusion in aggregates, OM adsorption on mineral surfaces is most likely the dominant stabilization mechanism. Similar to our results, mineral-controlled OM stabilization mechanisms have been reported in

other studies in alpine grassland soils of the Andes (Yang *et al.,* submitted; Buytaert *et al.*, 2006a;
350   Tonneijck *et al.*, 2010; Rolando *et al.*, 2017b).

Lithology is an important factor for OM stabilization related to mineral surfaces. Yang *et al.* (submitted) found that OM stabilization in the wet-LSs was controlled by OM complexed and/or adsorbed with Fe and Al (oxides) as well as by Ca^{2+} bridges. In contrast, OM stabilization in the wet-ASs was only controlled by Fe and Al (oxides) complexation (Yang *et al.* submitted). In the wet site, SOC stability
355   between LSs and ASs was not significantly different (Table 1). This may be attributed to the mineral surfaces in both LSs and ASs having a large capability for OM stabilization, although their OM stabilization mechanisms are slightly different. In the dry site, lower SOC stability in the LSs compared to the ASs (Table 1) suggests the lower capacity of the mineral surfaces to stabilize OM in the LSs. Similarly, Heckman *et al.* (2009) found lower SOC stocks and stability in LSs compared to soils formed
360   on felsic and basaltic igneous rocks, in a region with similar temperature and precipitation to our dry site. They explained this by a lack of active Fe and Al fractions to stabilize OM (Heckman et al., 2009), which might be an explanation for the less stable SOC in our dry-LSs as well.

Precipitation is also an important factor to explain the low SOC stability in the dry-LSs, as precipitation has a potential effect on soil mineralogy by controlling weathering processes (Doetterl et al., 2015, 2018;
365   Wiesmeier et al., 2019). Compared to the wet-LSs, the lower pH values in the dry-LSs indicate that a part of exchangeable base cations (e.g Ca^{2+}) are replaced by exchangeable H^+. The replacement results in lower adsorption capacity of the mineral surfaces because H^+ is a monovalent cation that does not promote OM stabilization (Jenny, 1994; Lützow et al., 2006). In addition, positive correlations between SOC mineralization rates and SOC contents, and between SOC mineralization and C/N ratios in the dry-
370   LSs (Fig. 7) indicate that SOC mineralization is dominantly dependent on SOC contents and quality. This also suggests a lower sorption capacity of the mineral adsorption sites. Similarly, Wagai *et al.* (2008) reported positive correlations between SOC mineralization and C/N ratios, and used the positive correlations as an indication of inert mineral surfaces. Furthermore, the lowest C/N ratios in the dry-LSs (Fig. 2) indicate a depletion of plant-derived C and a rapid SOC decomposition process (Moni et al.,
375   2012), which suggests the low SOC stability and the low capacity of mineral surfaces to stabilize OM.

4.4 Interactions between precipitation and lithology

The effects of precipitation and lithology on SOC stocks and stability are unlikely through the controls of soil aggregation, which is supported by the weak controls of OM stabilization via occlusion in aggregates

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380 (Fig. 6 and 7) and inconsistent patterns of aggregate size distribution compared to the patterns of SOC stability (Fig. 3, Fig. 4 and Table 1). In contrast, the interactions between precipitation and lithology on SOC stocks and stability are likely explained by soil mineralogy. This is supported by (1) the contrasting OM stabilization mechanisms controlled mineral surfaces between the wet-LS and the wet-AS (Yang *et al.*, submitted), and (2) shifts in pH values, C/N ratios and correlations between SOC mineralization rates

385 and SOC contents that suggest variations in properties of the mineral surfaces (Fig. 2 and Fig. 7).

Recent studies indicate that controls of climate factors and soil mineralogy are crucial to the persistence and stabilization of soil OM (Chaplot et al., 2010; Doetterl et al., 2015; Homann et al., 2007). For the LSs, we proposed that the lower SOC stability in the dry site is explained by the weaker interactions between OM and mineral surfaces due to the lower pH when compared to the wet site. However, the lower pH in

390 the dry-LSs is not consistent with the general soil formation process. The lower pH in the dry-LSs might be explained by soil acidification induced by higher belowground OM input compared to the wet-LSs. The higher OM input in the dry-LSs is supported by (1) more abundant α, ω-dioic acids, ω-hydroxyl alkanoic acids and long-chain fatty acids, especially in B horizons (Fig. S2), and (2) low stability of these compounds against decomposition in the dry-LSs (Fig. S3). As these compounds are mainly derived from

395 root input (Kögel-Knabner, 2002), the lower pH in the dry-LSs can be explained by the higher belowground OM input because plants need more developed root systems for the low precipitation. By contrast, no clear difference is found between the wet-ASs and the dry-ASs (Fig. 1 and Table 1). This may be attributed to the limited acidification induced by OM input because the bedrocks are already acidic. Notably, our statement on OM input is based on estimation because quantification of OM input in

400 Andean grasslands is difficult and only a few studies have addressed this (Oliveras et al., 2014).

Similar to our results, Wagai et al. (2008) reported that the controls of altitude (temperature and precipitation) on OM stoichiometry (indicating mineral surface activity) are dependent on soil bedrocks. Furthermore, Doetterl et al. (2015, 2018) indicated that climate factors in relation to soil mineralogy control the potential of soil matrix to stabilize OM. Our findings also support their views that the OM

405 persistence is controlled by climate factors and soil mineralogy. We further propose that the interactions between precipitation and lithology on OM stabilization in our study are through the controls of soil mineralogy in relation to OM input.

5 Conclusion

410   Our findings highlighted (1) SOC stocks and stability controlled by interactions between precipitation and lithology, and (2) soil aggregate size distribution controlled by lithology only. We did not find an important effect of precipitation on aggregation, which was probably superimposed by the effect of lithology. As the assumption that aggregate occlusion contributes to OM stabilization is not supported by our data, we conclude that OM adsorption on mineral surfaces is the major OM stabilization mechanism

415   in these soils. We propose that the controls of precipitation and lithology on SOC stocks and OM stabilization are through the controls of soil mineralogy in relation to OM input.

Further studies are required for more lithology types and more precipitation levels. In addition, primary effects of precipitation on OM dynamics are not limited to the controls of soil mineralogy. Potential effects of precipitation on quantity and quality of input OM suggest that investigations in OM molecular

420   composition may contribute to a better understanding of the processes governing SOC sequestration in the Neotropical grasslands of the Andes.

Author contribution. SY, BJ, KK and EC conceived and designed the study; RvH contributed to the experiments related to aggregate-size fractionation and analyses of soil properties; SA contributed to the

425   soil incubation and the SOC mineralization measurement; SY wrote the paper. All authors contributed to the manuscript revision.

Competing interests. The authors declare that they have no conflict of interest.

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Reference

Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., Kögel-Knabner, I., Leuschner, C., Rethemeyer, J. and Mueller, C. W.: Soil organic carbon stocks in topsoil and subsoil controlled by

parent material, carbon input in the rhizosphere, and microbial-derived compounds, Soil Biol. Biochem.,

440   122(July 2017), 19–30, doi:10.1016/j.soilbio.2018.03.026, 2018.

Bates, R. G.: Determination of pH: theory and practice, J. Electrochem. Soc., 120(8), 3C–263C, 1973.

Batjes, N. H.: Total carbon and nitrogen in the soils of the world, Eur. J. Soil Sci., 65(1), 1,
doi:10.1111/ejss.12120, 2014.

Boix-Fayos, C., Calvo-Cases, A., Imeson, A. C. and Soriano-Soto, M. D.: Influence of soil properties on

445   the aggregation of some Mediterranean soils and the use of aggregate size and stability as land
degradation indicators, Catena, 44(1), 47–67, doi:10.1016/S0341-8162(00)00176-4, 2001.

Bronick, C. J. and Lal, R.: Soil structure and management: a review, Geoderma, 124(1–2), 3–22,
doi:10.1016/j.geoderma.2004.03.005, 2005.

Buytaert, W., Deckers, J. and Wyseure, G.: Description and classification of nonallophanic Andosols in

450   south Ecuadorian alpine grasslands (páramo), Geomorphology, 73(3–4), 207–221,
doi:10.1016/j.geomorph.2005.06.012, 2006a.

Buytaert, W., Celleri, R., Willems, P., Bièvre, B. De and Wyseure, G.: Spatial and temporal rainfall
variability in mountainous areas: A case study from the south Ecuadorian Andes, J. Hydrol., 329(3–4),
413–421, doi:10.1016/j.jhydrol.2006.02.031, 2006b.

455   Buytaert, W., Cuesta-Camacho, F. and Tobón, C.: Potential impacts of climate change on the
environmental services of humid tropical alpine regions, Glob. Ecol. Biogeogr., 20(1), 19–33,
doi:10.1111/j.1466-8238.2010.00585.x, 2011.

Carvalhais, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., Mu, M., Saatchi, S.,
Santoro, M., Thurner, M., Weber, U., Ahrens, B., Beer, C., Cescatti, A., Randerson, J. T., Reichstein, M.,

460   Mu, M., Saatchi, S., Santoro, M., Thurner, M., Weber, U., Ahrens, B., Beer, C., Cescatti, A., Randerson, J.
T., Reichstein, M., Mu, M., Saatchi, S., Santoro, M., Thurner, M., Weber, U., Ahrens, B., Beer, C.,
Cescatti, A., Randerson, J. T. and Reichstein, M.: Global covariation of carbon turnover times with
climate in terrestrial ecosystems, Nature, 514, 213–217, doi:10.1038/nature13731, 2014.

Cerli, C., Celi, L., Kalbitz, K., Guggenberger, G. and Kaiser, K.: Separation of light and heavy organic

465   matter fractions in soil — Testing for proper density cut-off and dispersion level, Geoderma, 170, 403–
416, doi:10.1016/j.geoderma.2011.10.009, 2012.

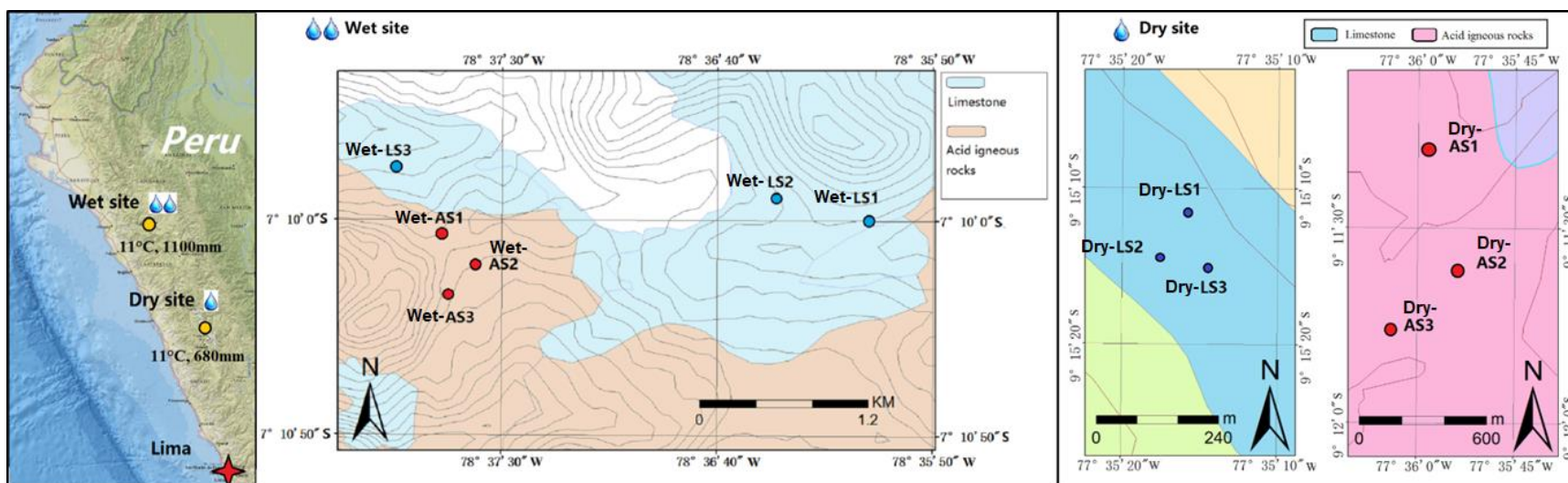Chaplot, V., Bouahom, B. and Valentin, C.: Soil organic carbon stocks in Laos: Spatial variations and

controlling factors, Glob. Chang. Biol., 16(4), 1380–1393, doi:10.1111/j.1365-2486.2009.02013.x, 2010.

Coldwell, B., Clemens, J. and Petford, N.: Deep crustal melting in the Peruvian Andes: Felsic magma

470   generation during delamination and uplift, Lithos, 125(1–2), 272–286, doi:10.1016/j.lithos.2011.02.011,
2011.

Doetterl, S., Stevens, A., Six, J., Merckx, R., Oost, K. Van, Pinto, M. C., Casanova-katny, A., Muñoz, C.,
Boudin, M., Venegas, E. Z. and Boeckx, P.: Soil carbon storage controlled by interactions between
geochemistry and climate, Nat. Geosci., 8(10), 780–783, doi:10.1038/NGEO2516, 2015.

475   Doetterl, S., Berhe, A. A., Arnold, C., Bodé, S., Fiener, P., Finke, P., Fuchslueger, L., Griepentrog, M.,
Harden, J. W., Nadeu, E., Schnecker, J., Six, J., Trumbore, S., Van Oost, K., Vogel, C. and Boeckx, P.:
Links among warming, carbon and microbial dynamics mediated by soil mineral weathering, Nat. Geosci.,
11(8), 589–593, doi:10.1038/s41561-018-0168-7, 2018.

Esri. "Topographic" [basemap]. Scale Not Given. "World Topographic Map". June, 2013.

480   http://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f. (June, 2019).

GEO GPS PERÚ, 2014. "GEO GPS PERÚ: Base De Datos Perú - Shapefile - *.Shp - MINAM - IGN -
Límites Políticos.", https://www.geogpsperu.com/2014/03/base-de-datos-peru-shapefile-shp-minam.html.

Goebel, M. O., Woche, S. K. and Bachmann, J.: Do soil aggregates really protect encapsulated organic
matter against microbial decomposition?, Biologia (Bratisl)., 64(3), 443–448, doi:10.2478/s11756-009-

485   0065-z, 2009.

Heckman, K., Welty-Bernard, A., Rasmussen, C. and Schwartz, E.: Geologic controls of soil carbon
cycling and microbial dynamics in temperate conifer forests, Chem. Geol., 267(1–2), 12–23,
doi:10.1016/j.chemgeo.2009.01.004, 2009.

Homann, P. S., Kapchinske, J. S. and Boyce, A.: Relations of mineral-soil C and N to climate and texture:

490   Regional differences within the conterminous USA, Biogeochemistry, 85(3), 303–316,
doi:10.1007/s10533-007-9139-6, 2007.

Jenny, H.: Factors of soil formation: a system of quantitative pedology, Courier Corporation., 1994.

Juarez, S., Nunan, N., Duday, A. C., Pouteau, V., Schmidt, S., Hapca, S., Falconer, R., Otten, W. and
Chenu, C.: Effects of different soil structures on the decomposition of native andadded organic carbon,

495   Eur. J. Soil Biol., 58, 81–90, doi:10.1016/j.ejsobi.2013.06.005, 2013.

Kaiser, K. and Guggenberger, G.: Distribution of hydrous aluminium and iron over density fractions depends on organic matter load and ultrasonic dispersion, Geoderma, 140(1–2), 140–146, doi:10.1016/j.geoderma.2007.03.018, 2007.

Kaiser, K. and Guggenberger, G.: Mineral surfaces and soil organic matter, Eur. J. Soil Sci., 54(2), 219–

500 236, doi:10.1046/j.1365-2389.2003.00544.x, 2003.

Kleber, M., Sollins, P. and Sutton, R.: A conceptual model of organo-mineral interactions in soils: self-assembly of organic molecular fragments into zonal structures on mineral surfaces, Biogeochemistry, 85(1), 9–24, doi:10.1007/s10533-007-9103-5, 2007.

Klute, A. and Dinauer, R. C.: Methods of Soil Analysis Part 1. Physical and Mineralogical Methods, 2nd

505 ed., edited by A. Klute, Madison., 1986.

Kögel-Knabner, I.: The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter: Fourteen years on, Soil Biol. Biochem., 34(2), 139–162, doi:10.1016/S0038-0717(01)00158-4, 2002.

Kong, A. Y. Y., Six, J., Bryant, D. C., Denison, R. F. and van Kessel, C.: The Relationship between

510 Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems, Soil Sci. Soc. Am. J., 69(4), 1078, doi:10.2136/sssaj2004.0215, 2005.

Lal, R.: Soil carbon sequestration impacts on global climate change and food security, Science (80-.)., 304(5677), 1623–1627 [online] Available from: //000221934300036, 2004.

Lehmann, J. and Kleber, M.: The contentious nature of soil organic matter., Nature, 528(7580), 60–8,

515 doi:10.1038/nature16069, 2015.

Lützow, M. V., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B. and Flessa, H.: Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review, Eur. J. Soil Sci., 57(4), 426–445, doi:10.1111/j.1365-2389.2006.00809.x, 2006.

520 Merkel, A.: Climate-data, [online] Available from: https://en.climate-data.org/south-america/peru-27/, 2017.

Moni, C., Derrien, D., Hatton, P.-J., Zeller, B. and Kleber, M.: Density fractions versus size separates: does physical fractionation isolate functional soil compartments?, Biogeosciences, 9(12), 5181–5197, doi:10.5194/bg-9-5181-2012, 2012.

525   Mueller, C. W., Schlund, S., Prietzel, J., Kögel-Knabner, I. and Gutsch, M.: Soil Aggregate Destruction by Ultrasonication Increases Soil Organic Matter Mineralization and Mobility, Soil Sci. Soc. Am. J., 76(5), 1634, doi:10.2136/sssaj2011.0186, 2012.

Muñoz García, M. A. and Faz Cano, A.: Soil organic matter stocks and quality at high altitude grasslands of Apolobamba, Bolivia, Catena, 94, 26–35, doi:10.1016/j.catena.2011.06.007, 2012.

530   Portes, R. D. C., Spinola, D. N., Reis, J. S., Ker, J. C., Costa, L. M. Da, Fernandes Filho, E. I., Kühn, P. and Schaefer, C. E. G. R.: Pedogenesis across a climatic gradient in tropical high mountains, Cordillera Blanca - Peruvian Andes, Catena, 147, 441–452, doi:10.1016/j.catena.2016.07.027, 2016.

Reyes-Rivera, L.: Geología de los cuadrángulos de Cajamarca, San Marcos y Cajambamba 15-f, 15-g, 16-g-[Boletín A 31]., 1980.

535   Rolando, J. L., Turin, C., Ramírez, D. A., Mares, V., Monerris, J. and Quiroz, R.: Key ecosystem services and ecological intensification of agriculture in the tropical high-Andean Puna as affected by land-use and climate changes, Agric. Ecosyst. Environ., 236, 221–233, doi:10.1016/j.agee.2016.12.010, 2017a.

Rolando, J. L., Dubeux, J. C., Perez, W., Ramirez, D. A., Turin, C., Ruiz-Moreno, M., Comerford, N. B., Mares, V., Garcia, S. and Quiroz, R.: Soil organic carbon stocks and fractionation under different land

540   uses in the Peruvian high-Andean Puna, Geoderma, 307(March), 65–72, doi:10.1016/j.geoderma.2017.07.037, 2017b.

Sánchez Vega, I., Cabanillas Soriano, M., Miranda Leiva, A., Poma Rojas, W., Díaz Navarro, J. and Terrones Hernández, F Bazán Zurita, H.: La jalca: el ecosistema frio del noroeste peruano, fundamentos biologicos y ecologicos., 2005.

545   Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D. A. C., Nannipieri, P., Rasse, D. P., Weiner, S. and Trumbore, S. E.: Persistence of soil organic matter as an ecosystem property., Nature, 478(7367), 49–56, doi:10.1038/nature10386, 2011.

Schrumpf, M., Kaiser, K., Guggenberger, G., Persson, T., Kögel-Knabner, I. and Schulze, E.-D.: Storage

550   and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals, Biogeosciences, 10(3), 1675–1691, doi:10.5194/bg-10-1675-2013, 2013.

Six, J. and Paustian, K.: Aggregate-associated soil organic matter as an ecosystem property and a measurement tool, Soil Biol. Biochem., 68, A4–A9, doi:10.1016/j.soilbio.2013.06.014, 2014.
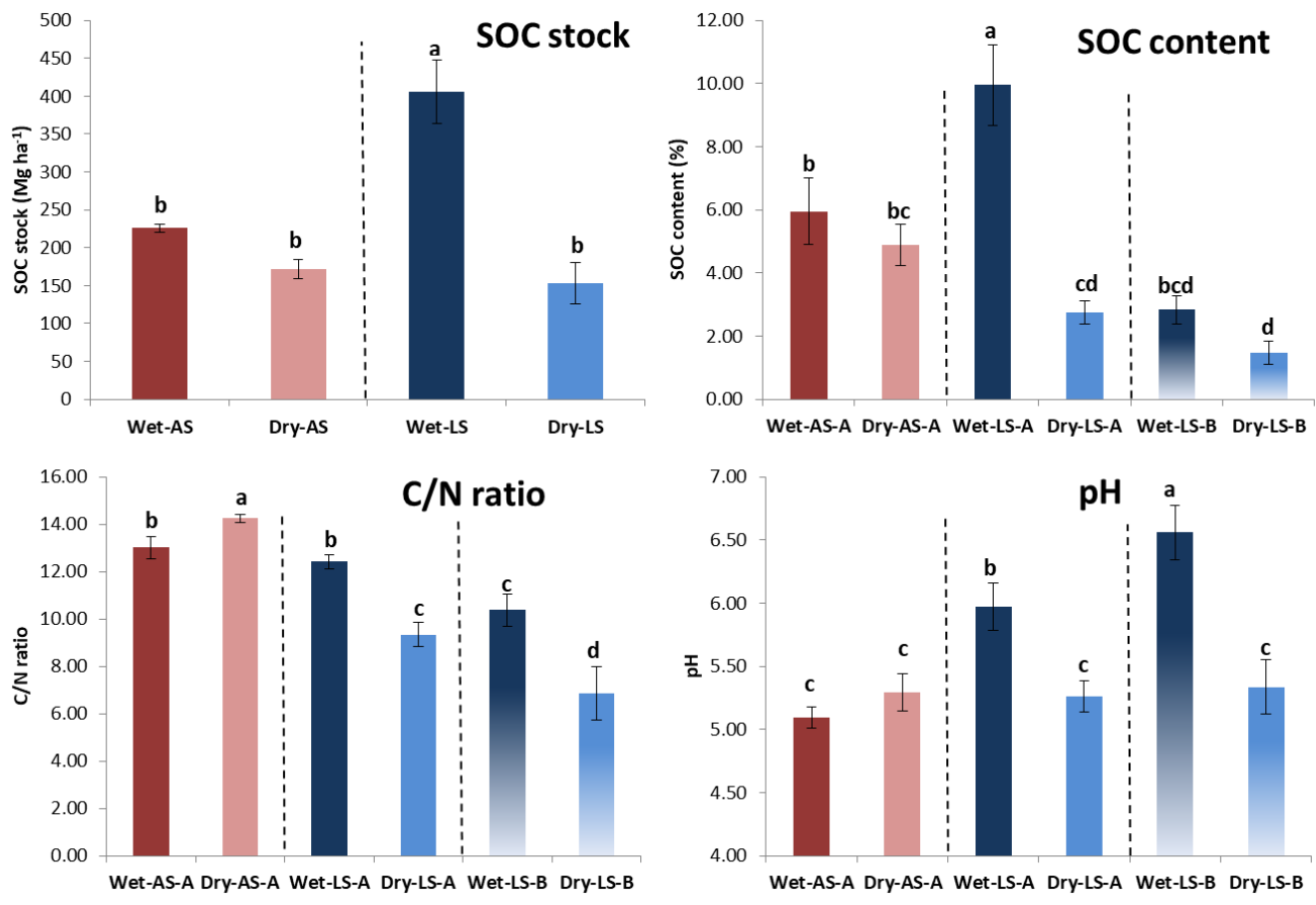
Six, J., Conant, R. T., Paul, E. A. and Paustian, K.: Stabilization mechanisms of soil organic matter :
555   Implications for C-saturation of soils, , 155–176, 2002.

Six, J., Bossuyt, H., Degryze, S. and Denef, K.: A history of research on the link between
(micro)aggregates, soil biota, and soil organic matter dynamics, Soil Tillage Res., 79(1), 7–31,
doi:10.1016/j.still.2004.03.008, 2004.

Tonneijck, F. H., Jansen, B., Nierop, K. G. J., Verstraten, J. M., Sevink, J. and De Lange, L.: Towards
560   understanding of carbon stocks and stabilization in volcanic ash soils in natural Andean ecosystems of
northern Ecuador, Eur. J. Soil Sci., 61(3), 392–405, doi:10.1111/j.1365-2389.2010.01241.x, 2010.

Wagai, R., Mayer, L. M., Kitayama, K. and Knicker, H.: Climate and parent material controls on organic
matter storage in surface soils: A three-pool, density-separation approach, Geoderma, 147(1–2), 23–33,
doi:10.1016/j.geoderma.2008.07.010, 2008.

565   Wang, X., Cammeraat, E. L. H., Cerli, C. and Kalbitz, K.: Soil aggregation and the stabilization of
organic carbon as affected by erosion and deposition, Soil Biol. Biochem., 72, 55–65,
doi:10.1016/j.soilbio.2014.01.018, 2014.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B.,
Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H. J. and Kögel-Knabner, I.: Soil
570   organic carbon storage as a key function of soils - A review of drivers and indicators at various scales,
Geoderma, 333(July 2018), 149–162, doi:10.1016/j.geoderma.2018.07.026, 2019.

WRB, I. W. G.: World reference base for soil resources 2014. International soil classification system for
naming soils and creating legends for soil maps, FAO, Rome., 2014.

Yang, S., Cammeraat, E., Jansen, B., den Hann, M., van Loon, E. and Recharte, J.: Soil organic carbon
575   stocks controlled by lithology and soil depth in a Peruvian alpine grassland of the Andes, Catena,
171(June), 11–21, doi:10.1016/j.catena.2018.06.038, 2018.

Yang, S., Jansen, B., Kalbitz, K., Chunga Castro, F. O., van Hall, R. L. and Cammeraat, E. L. H.:
Lithology controlled soil organic carbon stabilization in an alpine grassland of the Peruvian Andes,
Submitt to Environ. Earth Sci.

Fig. 1 Sampling site description. LS: limestone soil, AS: acid igneous rock soil, LM: large macroaggregates (>2 mm). The ArcGIS Online World Topographic Map basemap (Esri., 2013) was used for the map of Peru on the left, whereas the data for the contour lines in the maps of the wet site and the dry site was derived from Geo GPS Perú, (2014).

|	Wet site				Dry site				
Site	Parent material	Altitude	Soil depth	Ave. depth	Gravels in LM fractions	Parent material	Altitude	Soil depth	Ave. depth	Gravels in LM fractions
		m	cm		%		m	cm		%
LS1	Limestone	3716	57		6.86	Limestone	3573	56		8.70
LS2	Limestone	3717	66	61	3.13	Limestone	3532	54	61	5.42
LS3	Limestone	3517	60		0.16	Limestone	3560	73		13.01
AS1	Granite/ignimbrite	3583	68		10.86	Granodiorite	3667	44		50.28
AS2	Granite/ignimbrite	3585	45	49	14.12	Granodiorite-rich glacier materials	3521	60	51	39.57
AS3	Granite/ignimbrite	3586	35		28.60	Granodiorite-rich glacier materials	3495	50		61.05

Fig. 2 Soil organic carbon stocks in the whole soil profile and soil properties in diagnostic horizons (Mean±SE). Wet: the wet site, Dry: the dry site, LS: limestone soil, AS: acid igneous rock soil, A: A horizons, B: B horizons

21
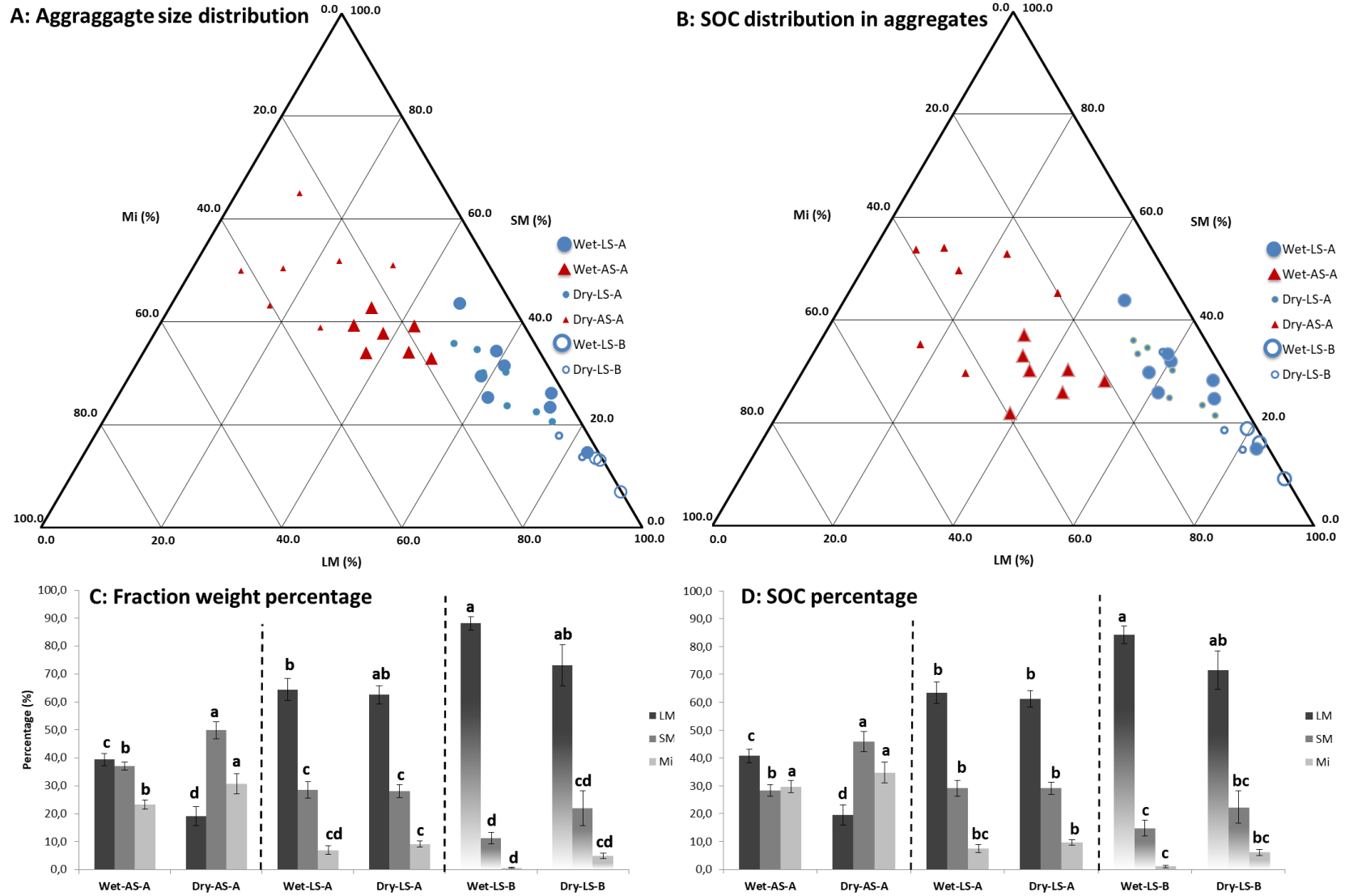
Fig. 3 Distribution of fraction weight and soil organic carbon in aggregate size fractions. A: Fraction weight distribution in aggregate size fractions, B: SOC distribution in aggregate size fractions, C: percentages of fraction weights in soil horizons (Mean±SE), D: SOC percentage in soil horizons (Mean±SE). Wet: the wet site, Dry: the dry site, LS: limestone soil, AS: acid igneous rock soil, A: A horizons, B: B horizons, LM: large macroaggregates (>2 mm), SM: small macroaggregates (0.25-2 mm), Mi: microaggreagtes (<0.25 mm)
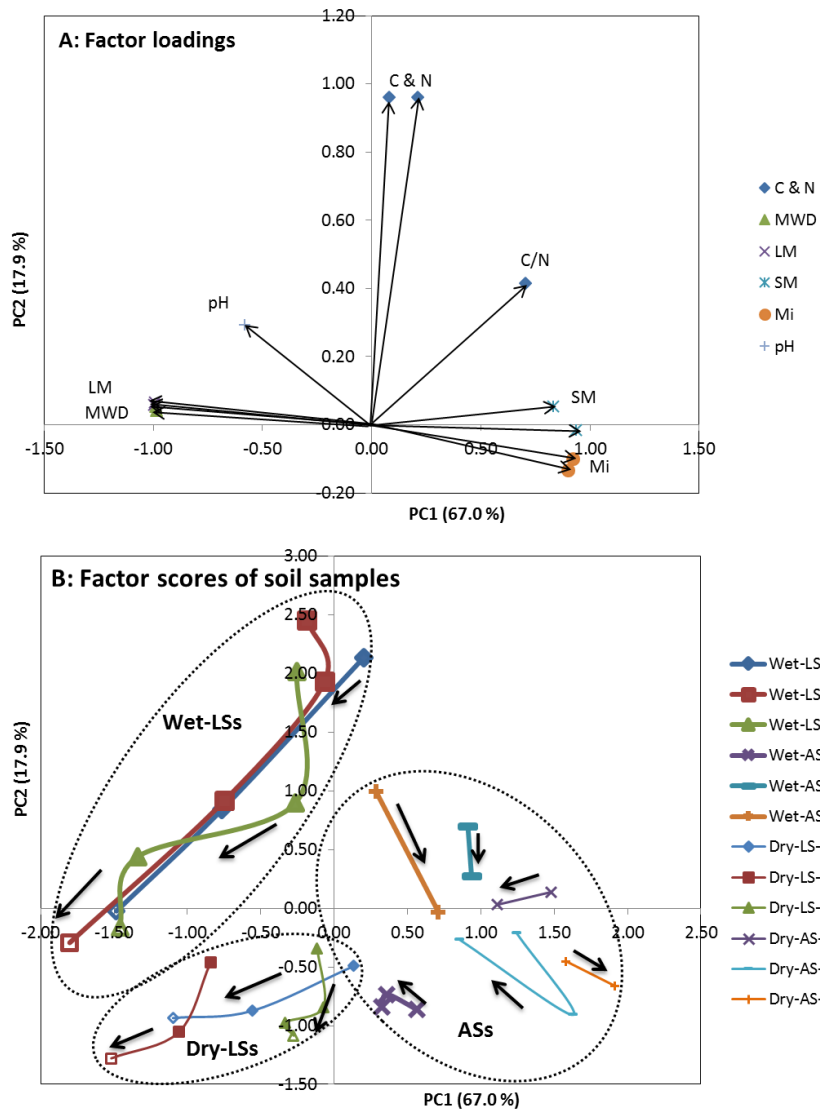
Fig. 4 Principal component analysis (PCA) indicating vertical distribution of aggregate-related soil properties in both limestone soils (LSs) and acid igneous rock soils (ASs). Solid points are A horizons, and hollow points are B horizons. Black arrows are pointing to the direction of soil horizons with increasing soil depth. Wet: the wet site, Dry: the dry site, LS: limestone soil, AS: acid igneous rock soil, MWD: mean weight diameter, C: SOC content, N: total nitrogen content, C/N: C/N ratio, LM: large macroaggregates, SM: small macroaggregates, Mi: microaggregates.

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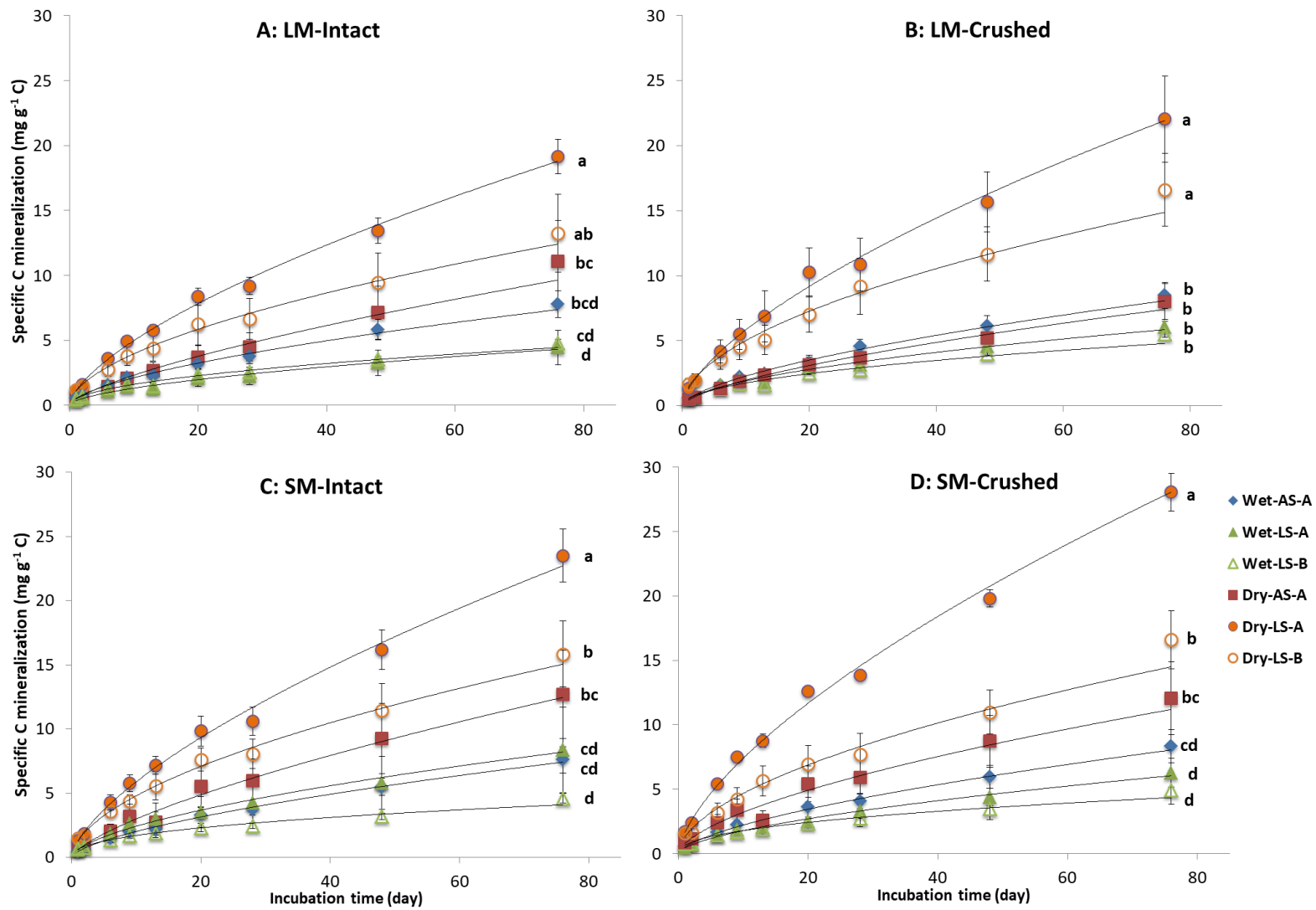
Fig. 5 SOC mineralization in the large macroaggregats (LM) and small macroaggregates (SM) in a period of 76-day incubation, with aggregate intact and crushed (Mean ± SE). Letters on the right of each plots indicate significant differences of cumulative C mineralization between different groups on Day 76. LM: large macroaggregates (>2 mm), SM: small macroaggregates (0.25-2 mm), Intact: incubation with aggregates intact, Crushed: incubation with aggregates crushed, Wet: the wet site, Dry: the dry site, AS-A: acid igneous rock soil - A horizon, LS-A: limestone soil - A horizon, LS-B: limestone soil - B horizon.

Table 1 Comparison in SOC mineralization rates between bedrock, precipitation and horizon with combinations of aggregate sizes and aggregate destruction. Abbreviations in the table indicating the group with significant higher SOC mineralization than the other group.

	A horizon: LS vs. AS				A horizon: Wet vs. Dry				LS: A vs. B horizon			
	LM-In	LM-Cr	SM-In	SM-Cr	LM-In	LM-Cr	SM-In	SM-Cr	LM-In	LM-Cr	SM-In	SM-Cr
	Wet				**LS**				**Wet**			
Day 1	n.s.	n.s.	n.s.	n.s.	Dry**	Dry*	Dry*	Dry**	n.s.	n.s.	n.s.	n.s.
Day 2	n.s.	n.s.	n.s.	n.s.	Dry**	Dry*	n.s.	Dry**	n.s.	n.s.	n.s.	n.s.
Day 6	n.s.	n.s.	n.s.	n.s.	Dry*	n.s.	n.s.	Dry**	n.s.	n.s.	n.s.	n.s.
Day 9	n.s.	n.s.	n.s.	n.s.	Dry**	n.s.	n.s.	Dry**	n.s.	n.s.	n.s.	n.s.
Day 13	n.s.	n.s.	n.s.	n.s.	Dry*	n.s.	Dry*	Dry**	n.s.	n.s.	n.s.	n.s.
Day 20	n.s.	n.s.	n.s.	n.s.	Dry*	n.s.	Dry*	Dry**	n.s.	n.s.	n.s.	n.s.
Day 28	n.s.	AS*	n.s.	n.s.	Dry**	n.s.	Dry*	Dry**	n.s.	n.s.	n.s.	n.s.
Day 48	n.s.	n.s.	n.s.	n.s.	Dry**	Dry*	Dry*	Dry**	n.s.	n.s.	n.s.	n.s.
Day 76	n.s.	n.s.	n.s.	n.s.	Dry**	Dry*	Dry*	Dry**	n.s.	n.s.	n.s.	n.s.
	Dry				**AS**				**Dry**			
Day 1	LS*	n.s.	LS*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day 2	LS*	LS*	LS*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Day 6	LS*	n.s.	n.s.	LS*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	A*
Day 9	LS*	n.s.	n.s.	LS*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	A*
Day 13	n.s.	n.s.	LS*	LS**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	A**
Day 20	n.s.	LS*	n.s.	LS*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	A*
Day 28	n.s.	n.s.	n.s.	LS**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	A**
Day 48	n.s.	LS*	n.s.	LS**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	A**
Day 76	n.s.	LS*	n.s.	LS**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	A**

LS: limestone soil, AS: acid igneous rock soil, LM: large macroaggregates (>2 mm), SM: small macroaggregates (0.25-2 mm), MA: macroaggregates (>0.25 mm), A: A horizon, In: aggregate intact, Cr: aggregate crushed, Wet: the wet site, Dry: the dry site, *: $P<0.05$ **: $P<0.01$, n.s.: not significant.
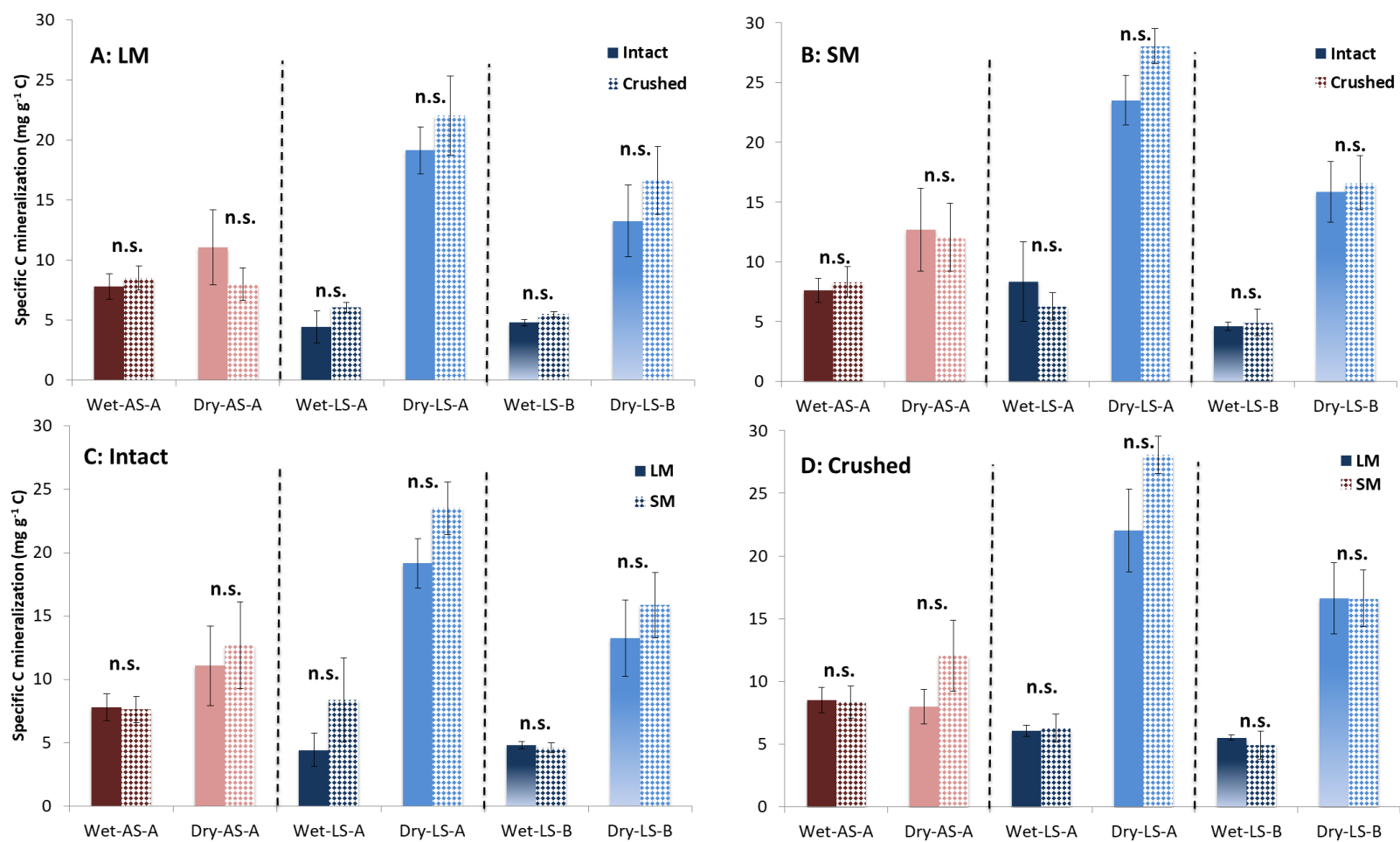
Fig. 6 Effects of aggregate destruction and aggregate size on specific SOC mineralization rates in the sampling day 76 (Mean ± SE). A: comparing aggregates intact and crushed in large macroaggregates, B: comparing aggregate intact and crushed in small macroaggregates, C: comparing large and small aggregates with aggregates intact, D: comparing large and small aggregates with aggregates crushed. LS: limestone soil, AS: acid igneous rock soil, LM: large macroaggregates (>2 mm), SM: small macroaggregates (0.25-2 mm), Intact: incubation with aggregates intact, Crushed: incubation with aggregates crushed, A: A horizon, Wet: the wet site, Dry: the dry site, n.s.: not significant.
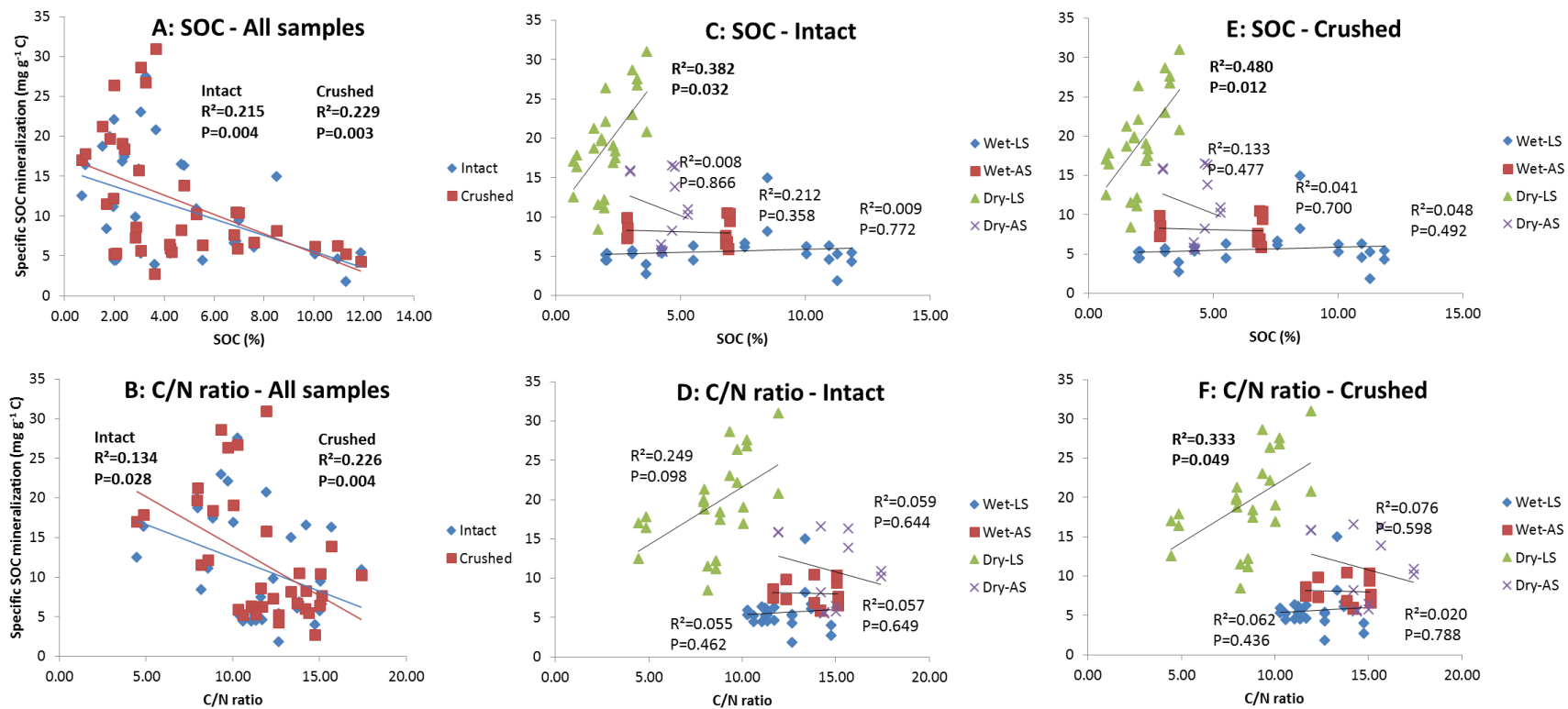
Fig. 7 Relationships of specific C mineralization rates (Day 76) with organic carbon contents and C/N ratios when soil aggregates were intact and crushed. Wet: the wet site, Dry: the dry site, LS: limestone soil, AS: acid igneous rock soils, SOC: soil organic carbon content.