Response to reviewer #1

We thank reviewer #1 for reviewing our manuscript. We have responded to each comment below.

1. Ensure the conclusions are not flawed, by recalculating SOC stocks by equivalent soil mass, which is common practice;

Response:

We do not agree with reviewer 1 that for this study, comparisons of SOC stocks between land-use types should be based on equivalent soil mass. It is important to differentiate between studies that look at the impact of land-use changes and studies that report on spatial variability in SOC stocks and its underlying controlling factors. In the first type of studies, comparisons between the land-use types should be based on equivalent soil mass and hence at the start the study must consider the immediate reference land use prior to the present land uses being investigated. The reason for this is that land-use change often coincides with change in soil bulk density as a result of management practices, which may cause compaction or loosening of the soil. In such studies, comparison of SOC stocks due to land-use change must be based on equivalent soil mass to avoid interference of altered bulk density on SOC stock changes. However, in the second type of studies, where our present study belongs to, it is not necessary to base comparisons between land-use types on equal soil mass. Since, our objective in not about land-use change effects on SOC stocks. We aimed to quantify the spatial variability of the actual SOC stocks and its controlling factors from subplot, plot to landscape scales. Calculating SOC stocks to an equal reference mass could possibly even lead to inaccurate results as the spatial variability in soil mass contributes to the spatial variability in SOC stocks. Moreover, we have sampled the entire soil profile down to 1.2 m and no significant amounts of carbon are expected below the lowest sampling depth, meaning that the biggest impacts of any differences in soil mass between the land-use types might have been accounted for within the soil profile (VandenBygaart and Angers, 2006).

2. Show the sampling design (plots) on a map;

Response:

Reviewer 2 had also suggested that we include a map with the sampling design. We added a new figure (Fig. 1) to the manuscript that will include: (1) the location of the study area in China, (2) the location of the sampling plots in the study area, and (3) a sketch of the one-ha sampling plot with the nine circular subplots arranged on a 50x50-m grid.

3. Better consider the impact of soil type (with discussion on its correlations with topography and land use) on SOCc and SOCs. Test of variance could for instance be added to Table 4.

Response:

Classification of a “soil type” is based on a range of quantitative soil properties. For instance ECEC, which is an important indicator of the presence of low or high activity clays and a key determinant parameter for soil group classification (IUSS Working Group WRB, 2014). According to the World Reference Base (IUSS Working Group WRB, 2014), soils with low activity clays like Acrisols and Ferralsols should have a subsoil CEC < 24 cmolc kg^{-1} clay whereas Cambisols and Umbrisol have a subsoil CEC > 24 cmolc kg^{-1} clay. Therefore, instead of including “soil type” as a categorical factor in the linear mixed effect models we choose to test for the impact of the relevant quantitative soil properties on SOC, like silt-plus-clay percentage and ECEC of the subsoil. These soil properties have been included as explanatory factors in the full linear mixed effect models. So, with our statistical analysis we actually considered the influence of soil type on SOC by including the quantitative soil properties “silt+clay” and ECEC and, because these are quantitative values rather than categorical variable as soil type, we are also able to quantify their influence on SOC. However, the included soil properties did not appear to have a statistically significant impact on SOC (Table 4). We also tested the impact of topography and land use on SOC, by including these factors as explanatory factors in the full linear mixed effects models.

Reviewer comment: Finally, the abstract structure is skewed to me with half of its length on methods. I would suggest the following to be considered: Abstract A. Topic sentence (s) on the subject (its importance) and research question(s): what is(are) the research gaps in this field of research? B. Objectives of the study C. Materials and methods used in the study D. Main results (with quantitative information, tests of significance) E. Conclusions: how these results respond to the objectives; general implications of the research

Response:

We agree with reviewer 1 that the quality of the abstract can be improved. We have revised the abstract by shortening the method section and following what the reviewer have outlined as the flow of the abstract. Furthermore, we provided the P values in the result's part of the abstract. We thoroughly checked that our revised abstract followed the structure described by reviewer 1.

References:

IUSS Working Group WRB: World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps., 2014.

VandenBygaart, A. J. and Angers, D. A.: Towards accurate measurements of soil organic carbon stock change in agroecosystems, Can. J. Soil Sci., 86(November 2015), 465–471, doi:10.4141/S05-106, 2006.

Response to reviewer #2

We appreciate the thorough review and the constructive comments and suggestions by reviewer #2, the comments helped us to improve the clarity of the manuscript. Below, we address each comment. Line numbers and figure numbers refer to the revised manuscript with track changes.

Specific issues:

1.) Reviewer comment: The title is rather unclear, the readers do not know what scale the paper refers to (spatial) and whether it's a micro scale study or a global study. Also in the abstract (l. 23) the reader need to get informed about which scales are investigated.

Response:
We agree that the title was rather unclear. To emphasize that we look at "spatial variability" of SOC, we changed the title into: "Spatial variability of soil organic carbon in a tropical montane landscape: Associations between soil organic carbon and land use, soil properties, vegetation and topography vary across plot to landscape scales". The title now explicitly state at which spatial scales we investigated.
In the abstract at l. 25-29, we replaced the following sentence:"..and key biophysical characteristics at multiple spatial scales." into this sentence: "….and the relationships of SOC with land-use types, soil properties, vegetation characteristics and topographical attributes at three spatial scales: (1) land-use types within a landscape (10,000 ha) (2) sampling plots (one ha) nested within land-use types (plot distances ranging between 0.5 - 12 km) and (3) subplots (10-m radius) nested within sampling plots."

2.) Reviewer comment: The term "biophysical characteristics" used throughout the manuscript (e.g. l. 20) is undefined and unclear. I suggest finding a better term. For example in figure 2 three parameters refer to soil organic matter, seven to soil characteristics, three to topography and three to vegetation. Instead, you combined the first to categories in fig 2a and the last two categories in 2b. I recommend to always use these three classes of drivers and one class of target variables and not to combine them randomly.

Response:

We do understand the point of reviewer 2 that the term biophysical characteristics is vague. Therefore, when describing our own data analysis and results, instead of using the term biophysical characteristics, we now refer to: soil properties, vegetation characteristics and topographical attributes. We will change Fig 3 according to the suggestions of reviewer 2, this will result in the following three Figures: Fig 3 (a) all soil properties, Fig 3(b) the 3 vegetation characteristics, and Fig 3 (c) the 2 topographical attributes. Regarding our target parameters, SOC stocks and SOC concentrations, we will refer to them as SOCs (for SOC stocks) and SOCc (SOC concentrations).

However, we do feel that there are multiple examples of general statements where the use of the term biophysical properties is appropriate, for example in the introduction in l. 81"…variability in biophysical factors that influence plant productivity and..", and in the discussion in l.334 "…with similar biophysical characteristics)…", and in l. 344 "….which are similar to the biophysical conditions in our study area.". In such cases, we prefer to stay with the term "biophysical characteristics".

3.) Reviewer comment: The "subplots" I did not understand. The variance analysis is conducted without the subplot scale (e.g. Fig. 2). Why? If not enough driver data are available at this scale you may have to delete the subplot aspect completely. For the moment the role of the subplots are unclear.

Response:

The variance analysis actually did include the subplots and this is referred to in Fig. 3 as 'within sampling plots'. The "subplot" in our study is the lowest level of the sampling design – defined in statistics as the unit where the actual measurement is conducted. In our study, the subplots are single observations and contain only one data point. Our hierarchical sampling design is as follows: we sampled four land-use types in a landscape, nested within each land-use type we sampled a certain number of plots, and nested within each sampling plot we sampled nine subplots (see l. 169-170, and l. 181-182). Hence, in this study the variance component analysis includes three components: (1) variability between land-use types, (2) variability between sampling plots nested within land-use types, and (3) the variability between subplots nested within sampling plots. Exactly these three components are shown in Fig 3, in which we referred to the subplot scale as "Within sampling plots" (See caption Fig 3, l. 649). In order to make Fig. 3 clearer, we changed the legend of Fig 3 into: (-) "Among land-use types", (-) "among plots nested within land-use types", (-) "among subplots nested within plots". Most of the driver data (soil properties, vegetation characteristics and topographical attributes) are available at the subplot level, as described in the respective methods sections l.181-182, 197-198, 200-201, 204.

Reviewer comment: Moreover, the different numbers of samples in different depth increments (l. 145-149) may hamper a proper analysis?

Response:

It is true that we have a different number of samples in different depth increments. This number of samples for different depths was decided very carefully based on our previous research works on SOC and based on the costs of labour and analysis. This varied number of samples for each depth is not a problem for the statistical analysis, as statistical tests were conducted for each sampling depth separately (see l. 220). Moreover, we used different types of statistical tests for data available at subplot level compared to data available at plot level.

For data available at subplot level (0-15, 15-30, 30-60, 60-90 cm, total SOC stocks 0-90 cm), we used linear mixed effect models (l. 223-226). For data that were only available at plot level, as is the case for depth increment 90-120, we used a one-way ANOVA or a Kruskal-Wallis ANOVA (l.249-252).

Reviewer comment: If still mentioned in the abstract you should provide the size of the subplots.

Response: We now included the size of the subplots within the rephrased sentence in the abstract l. 28 (see also answer to comment 1).

Reviewer comment: In l. 217 you even write about "subplot plots"- whats this?

Response: "subplot plots" was a typo error. We corrected this to "subplots".

4.) Reviewer comment: You should never use SOC without specifying if you talk about SOC stocks or SOC content (e.g. l. 33).

Response:

When talking about SOC quantities, it is indeed very important to know whether these quantities refer to SOC concentrations or stocks. We now checked our entire manuscript to make sure that when we report our results or findings from other studies on SOC quantities we clearly state whether we refer to stocks (SOCs) or concentrations (SOCc).
However, there are multiple examples of statements that are valid for both SOC stocks as well as SOC concentrations; for example, the paragraph in the introduction at lines 71-84. In those cases, we think it is appropriate to refer to "SOC" as a general term. We specify "SOC concentrations or stocks" wherever this particular variable is appropriate.

5.) Reviewer comment: It seems to be a contradiction that you state "SOC stocks did not differ among land use types" (l. 29) but "variability of SOC (stocks?) was influenced by land use type" (l. 35). Please rephrase.

Response:

l. 29 (original manuscript) is based on non-significant difference among land uses (mature forest, regenerating or highly disturbed forest, and open land, Table 3) in the entire landscape, whereas l.35 (original manuscript) was only referring to the open land category (used as tea plantations or rough grasslands, Table 4). We rephrased and restructured the abstract in order to clarify this. At l.35 (revised manuscript with Track changes), we now wrote: "SOC concentrations and stocks did not differ (P values range from 0.15 to 0.71) across the four land-use types. However, within the open-land category, SOC concentrations and stocks in grasslands were higher than in tea plantations ($P<0.01$ for 0-0.15-m, $P=0.05$ for 0.15-0.30-m, $P=0.06$ for 0-0.9-m depth)."

6.) Reviewer comment: You find different drivers for SOC stock variability among plots for different land use types due to a nested analysis of variance. Did you try the analysis without stratification by land use? (l. 207)

Response:

The reason we stratified into the categories "forest" and "open land" is to elucidate the controlling factors of SOC within a less disturbed strata "forests" versus a more human-impacted strata "open land".

As suggested by reviewer 2, we conducted the analysis for all land-use types combined (Supplement 1). We tested the same possible drivers, with the only difference that "land-use type" was not included in the linear mixed effect models to avoid multicolinearity between explanatory factors, as tree basal area and litter layer carbon stock differed between the forests and the open-land category (Table 1). This analysis showed that litter layer carbon stocks, tree basal area and elevation were positively related to SOC concentrations and stocks. These drivers (i.e. tree basal area and litter layer C stock) reflected the differences between the forest and open land categories (Table 1). The marginal R^2 for these relationships were, however, low: ranging from R^2=0.17 (total SOC stocks within 0.90-m depth) to R^2=0.32 (SOC concentration within 0-0.15 m). We think that the results obtained from stratifying by the forest and open land category are more meaningful. Therefore, we will not include the analysis for all land-use types combined in Table 4.

7.) Reviewer comment: Recommend to delete "with relevance for policy makers. . . .interest for" and write "for SOC accounting such as the Clean Development Mechanism. . ." in order to make it clearer.

Response:

Although we did not directly follow this recommendation of reviewer 2, we rephrased these lines in order to make it easier to understand. We changed l. 67-68 to:

"Understanding the drivers of this variability is essential for the development of management strategies that aim at enhancing soil functions, and for SOC accounting purposes with a relevance for policy makers. Examples of such SOC accounting purposes are the Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and Degradation (REDD+) initiatives that aim to generate financial compensation for local communities if they protect and enhance ecosystem carbon stocks (UNFCCC, 2009). "

8.) Reviewer comment: Please avoid the term "land-use cover" but only use "land-use" throughout the manuscript (e.g. 59). "Land cover" and "land use" are two different concepts.

Response:

We agree that land use and land-use cover are two different concepts. We replaced land-use cover with land use or land-use types. However in one case (l.94, "..more uniform land-use cover dominated by commercial crops and monoculture tree plantations..”), we would prefer to stay with land-use cover, as we think that the term land-use cover is appropriate here as this sentence refers to what actually covers the land.

9.) Reviewer comment: L. 62: Change clay type to clay mineralogy.

Response:

We changed this accordingly.

10.) Reviewer comment: L. 62 and throughout the manuscript: “soil group” should be replaced by “soil type” to make it easier to understand.

Response:

In all the sentences where we mentioned soil group, we meant here the uppermost level of soil classification, based on the FAO system World Reference Base (IUSS Working Group WRB, 2014). Soil group is the correct technical term for the meaning that we conveyed in these sentences. When you say soil type, it does not indicate which specific levels (in FAO system, subgroup to sublevel of the subgroup) of the soil classification you meant.

11.) Reviewer comment: L. 80-83: You mention several studies. For the reader they only make sense as introduction into the topic if you also mention the results of these studies in relation to SOC stocks variability.

Response:

We listed those studies to give an idea on the number of SOC assessments conducted in this region (SW China and the northern areas of Laos, Myanmar, Thailand and Vietnam), and to show that the number of studies conducted in this region is rather small. We found only three studies from this region conducted at a landscape- or larger scale that evaluated the impact of land use and biophysical factors on the spatial variation in SOC. In previous sections of the introduction (l. 82-84), we explained that such information is necessary to upscale SOC assessments to a larger area. To give a better idea of the focus of the cited studies we revised l. 96-100 to:

“There were only three studies so far that evaluated the impact of land use and various biophysical factors on the spatial variation in SOCc and SOCs at a landscape or larger scale in montane mainland southeast Asia; these were conducted in northern Thailand (Aumtong et al., 2009; Pibumrung et al., 2008) and Laos (Phachomphon et al., 2010).”

The results of the cited studies are discussed in detail and compared with our results in the discussion at l. 305-323.

12.) Reviewer comment: L. 84: Second objective is rather unclear; please rewrite and take into account comment 1, 2 and 4.

Response:

We rewrote the second objective as follows: "to determine the proportions of the overall variance of SOCc and SOCs as well as soil, vegetation and topographical properties that were accounted for by land-use types within the landscape (10,000 ha), by sampling plots (one ha) nested within land-use types (plot distances ranging between 0.5 - 12 km), and by subplots (10-m radius) nested within sampling plots,"

13.) Reviewer comment: I recommend deleting paragraph 86-93. Its Material and Methods that are described in the next chapter anyway.

Response:

We changed this by deleting l. 86-90 (original manuscript), but we retain the last sentence as this summarizes the contribution of our unique dataset in this under-studied region.

14.) Reviewer comment: L. 105-107: This sentence describing the forest vegetation should go to l. 132 were also the other land use types are described in detail.

Response:

We changed this accordingly.

15.) Reviewer comment: The studied landscape was between 800 and 2000 m asl. The plots were only between 1147 and 1867 m asl. Why did you exclude the valleys?

Response:

We did not exclude the valleys from our sampling design; however, the information on the elevation of the studied landscape was not precisely stated in the original manuscript and we have changed this to "The topography is mountainous with elevations of 1100-1900 m above sea level (asl).

16.) Reviewer comment: L. 117 and l.123-126: the sampling design is difficult to follow. I recommend a figure with the sampling scheme. What are the 12 units (l. 122)? How do they refer to 16 equal area units?

Response:

It was indeed not clearly described how the 12 units relate to the 16 equal-area units. The study area was divided in 16 equal-area units. From these 16 units, 12 were randomly selected, and within these 12 units, we randomly selected the sampling plots from the classified grid points. We added this clarification in l.144.

Reviewer 1 had also suggested that we include a map with the sampling scheme. Thus, we added a figure (Fig. 1 in the revised manuscript) that shows (1) the location of the study area in China, (2) the location of the sampling plots within the study area, and (3) a sketch of the 1-ha plot showing the nine circular subplots that were selected within the 50x50-m grid.

17.) Reviewer comment: L. 140: The fire aspect is interesting. Was the mature forest also burned? Was there a difference in burning frequency between land use types? (l. 291). To which soil depth did you detect charcoal pieces (l. 141)?

Response:

All land-use types have been burnt at some point in the past, as is inherent for areas with a long history of swidden agriculture. This information is given in l. 163. We do not have quantitative information on fire frequencies. Charcoal pieces were observed in soil samples from all depths, and we added this information in l. 165.

18.) Reviewer comment: L. 147: Provide the diameter of the auger.

Response:

We used an Edelman auger with 4-cm diameter. We added this information in l. 171.

19.) Reviewer comment: L. 171: Write the full word for ECEC the first time it appears.

Response:

ECEC was written full the first time it appeared in line 133: "…, and the effective cation exchange capacity (ECEC) in the subsurface soil ranged…."

20.) Reviewer comment: L. 186: The equation is wrong, since it does not take into account the stones. Stones are almost C-free and thus need to be subtracted.

Response:

We corrected the soil bulk density samples for gravel content (pebbles > 2mm) (see l. 175). By doing this, we ensured that carbon stocks are not over-estimated as in cases where soils contained gravels and soil BD was not corrected for stone content. To improve clarity, we changed the BD definition in l. 211 to 'where BD is the soil bulk density, corrected of stone content'. Since the soils at the sampling plots were stone poor (average stone content in BD samples was 2.8 volume %, and no big stones observed in the soil profiles) we did not correct for the volume of stones in the soil profile.

21.) Reviewer comment: L. 197: Specify to which soil characteristics you are referring to.

Response:

We referred to "sand, silt plus clay, bulk density, pH (H_2O), pH (KCl), ECEC, Al saturation and base saturation". We added this information in the text (l. 224) in order to make this clearer.

22.) Reviewer comment: L. 205: Why was silt and clay analysed separately but taken into account for the statistical analysis only as silt-plus-clay?

Response:

In order to determine accurately the clay and silt contents in soils, which contain iron oxides like in highly weathered Ferralsol soils, the soil must be pre-treated with a dispersing reagent (e.g. sodium dithionite) to remove iron oxides. Chemical dispersion minimizes the presence of pseudo-particles (pseudo-silt) in the particle size analysis. Although organic material had been removed prior to the soil texture analysis, our soil samples were analysed in a laboratory in China for soil texture and have not been dispersed with sodium dithionite. Therefore, we could not assure that the pseudo-particles, formed via iron oxides binding, had been dispersed, which could have resulted in an overestimation of the silt- and underestimation of the clay content. Therefore, we decided to use the sum of silt and clay content.

23.) Reviewer comment: L. 205: Why was ECEC from topsoil no explanatory variable for SOC stocks but only subsoil ECEC?

Response:

We tested ECEC as an explanatory variable of SOC, as ECEC is an important indicator of the presence of low or high activity clays and a key determinant parameter for soil group classification (IUSS Working Group WRB, 2014). However, the topsoil ECEC is not a good indicator for soil group and clay mineralogy because the topsoil's ECEC is more largely influenced by soil organic matter (that contributes also to ECEC) than the deeper soil depths. Hence, in the WRB classification system, the ECEC is specified to be based from the deeper soil depths. For example, soils with low activity clays like Acrisols and Ferralsols should have a subsoil CEC < 24 cmolc kg^{-1} clay whereas Cambisols and Umbrisol have a subsoil CEC > 24 cmolc kg^{-1} clay. Thus, we decided to use the subsoil ECEC as an explanatory variable of SOC in the linear mixed effect models instead of topsoil ECEC. We did not add an extensive clarification in the manuscript about why we used the subsoil's ECEC, as we assumed this is common knowledge to those who are familiar of what ECEC-to-SOC relationship is based on mechanistically.

24.) Reviewer comment: L. 209: correlated "with each other"?

Response:

We changed this accordingly.

25.) Reviewer comment: L. 229 and l. 239: Change “differences” to “significant differences”.

Response:

We changed this accordingly.

26.) Reviewer comment: L. 234: Change “lower” to “narrower”

Response:

We changed this accordingly.

27.) Reviewer comment: L.241 and 247: To what does the R2 refers to? To the model efficiency of the regression model? If yes, you may need to rewrite this or use EF as model efficiency or the explained variance as indicator for the model performance.

Response:

R^2 in the original manuscript referred to the proportion of the variance explained by the fixed effect terms of each LME (linear mixed effect model), defined by Nakagawa and Schielzeth (2013) as marginal R^2, we explained this in the method section in l.242. Therefore, we decided to replace the term R^2 in the text by “marginal R^2”. Moreover, to make it easier to understand, we added the definition of mariginal R^2 the first time marginal R^2 appears in the results section at l. 272.

28.) Reviewer comment: L. 249: Was SOC content decreasing with increasing slope for all land use types? Thus, was erosion similar among land use types (l. 336)?

Response:

We stated in l.390 that the relationships of SOC concentrations and total SOC stocks with slope were only found for the open land category (used as grasslands and tea plantations). The lines (l. 384- l. 386) previous to this also clearly stated what controls the SOC in the forest sites, and the factors were largely vegetation-related and slope did not show significant relationship.

29.) Reviewer comment: L. 258: Please rewrite this sentence. It is unclear.

Response:

In order to make the message of the sentence clearer, we revised the sentences l.290-295 to: “Variance partitioning showed that in the top 0.3 m of the soil, with the exception of soil pH H_2O, land-use type did not contribute significantly to any of the variation in soil characteristics (Figure 3a; for 0.15-0.3 m, data not shown). Instead, the variability among plots (nested within land-use type) and among subplots (nested within plots) contributed relatively equally to the variances in SOCc, total SOCs down to 0.9 m and all other soil characteristics (except for soil texture)."

30.) Reviewer comment: L. 270-282 and 315-317: Several other studies are mentioned here. You should also add and discuss why some other studies found other results than you.

Response:

In l.305-318, we described that our values of SOC stocks in the studied land-use types were at the high end of the range of SOC stocks reported for these land-use types by others studies in the region. Compared to the cited studies, our study site was located at a higher elevation (1100-1900 m asl), had a relatively low MAT (18 °C) and a relatively high MAP (1600-1800 mm) (Table 5). Elevation and MAP have commonly been observed to positively affect SOCs (Amundson, 2001; Chaplot et al., 2010; Dieleman et al., 2013) while MAT is known for being negatively associated with SOCs (Amundson, 2001; Powers et al., 2011). These factors may have contributed to the large total SOCs we observed. We added this explanation in l319.

In l.358-365, we compared our findings with other studies; in our study, the overall variance in SOCc and SOCs was accounted by the variability within plots and only a smaller proportion was accounted by the variability among plots. In the revised manuscript, we explain why Allen et al (2016) found other results compared to the findings from our study and that of Paul et al.(2013) and Chaplot et al. (2009) as follows: "Paul et al. (2013) related the high within plot variability in SOCc to the heterogeneous nature of vegetation and microclimate in their plots. Chaplot et. al. (2009) attributed the large small-scale variation in SOCs and SOCc to land use, clay content and hill-slope surface morphology. The study of Allen et al. (2016) was on well-drained areas of the landscape with gentle slopes and stratified by soil group, which may have resulted in the small within-plot variability they observed. Our study was in a montane landscape, wherein large within-plot variability in SOCc and SOCs may have been due to a large heterogeneity in vegetation characteristics and slope within the one-ha plots (and therein the possible microclimate variability)." We elaborated on these drivers in the subsequent paragraphs l.374-376, and l.384-393, l.395-403.

31.) Reviewer comment: L. 294-296: Provide an explanation for this reported finding.

Response:

The findings of van der Kamp et al. (2009) and Yonekura et al. (2010) that SOC stocks in *Imperata* grasslands were higher than in primary forests were attributed to charcoal inputs and higher root biomass in grasslands compared to forests. We added this information in l.331-332.

32.) Reviewer comment: L. 371-374 and 37-40: The conclusions are rather weak – please rewrite them. It is nothing new that requires this additional study to find out that for the detection of land-use change effects paired plot designs are better that stratified, random or grid sampling designs. Much more interesting is where the variability of SOC stocks comes from at which scales. At which sampling plot size do we achieve representative sampling for the field site?

Response:

We revised the conclusions to focus on where the variability of SOC stocks comes from at which scales and its implication on achieving representative sampling in the field. The modified conclusion is:

"In this tropical montane landscape in SW China, the spatial variability in SOCc and SOCs was largest at the plot scale. This high within-plot variability in SOC reflected the variability in litter layer carbon stocks and slope in open land, and the variability in litter layer carbon stocks and tree basal area in forests. Therefore, to achieve a reliable estimate of SOCc and SOCs within plots, it is important to have a plot size that encompasses the inherent slope and vegetation variability. Furthermore, since the variability in SOCc and SOCs among plots was related to elevation in forests, and to land-use type in open land, sampling designs for similar montane landscapes should stratify by elevation and land-use types as the principal drivers of SOC at the landscape scale. These scale-dependent relationships between SOC and controlling factors demonstrate that sampling designs must consider the controlling factors at the scale of interest in order to elucidate their effects on SOC, to control for the variability within and between plots, and to detect any possible differences in SOC between land-use types."

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SUPPLEMENT 1 – for response to reviewer 2

Table: Coefficient estimates[a] (± SE) of effects of soil texture, vegetation characteristics and topographical attributes on SOC concentrations and total SOC stocks in all land-use types (regenerating or highly disturbed forest and mature forest combined, tea plantation and grassland combined) in a tropical montane landscape in SW China.

Response	Effect	All land-use types combined (n=27)	
		Estimate	**P value**
SOC concentration (%) at 0-0.15 m	Intercept	1.52 (1.02)	0.14
	Land-use type[b]	Not included	Not included
	Silt-plus-clay percentage (%)	0.01 (0.01)	0.34
	ECEC[c] at 0.6-0.9 m ($cmol_c$ kg^{-1} clay)		ns
	Litter layer carbon stock (Mg C ha^{-1})	0.17 (0.04)	<0.01
	Litter layer C:N ratio		
	Tree basal area (m^2 ha^{-1})	0.04 (0.01)	<0.01
	Slope (%)		ns
	Relative elevation[d] (m)	0.003 (0.001)	<0.01
	Compound Topographic Index		ns
SOC concentration (%) at 0.15-0.30 m	Intercept	1.41 (0.80)	0.08
	Land-use type[b]	Not included	Not included
	Silt-plus-clay percentage (%)	0.008 (0.01)	0.38
	ECEC[c] at 0.6-0.9 m ($cmol_c$ kg^{-1} clay)		ns
	Litter layer carbon stock (Mg C ha^{-1})	0.17 (0.03)	<0.01
	Litter layer C:N ratio		ns
	Tree basal area (m^2 ha^{-1})	0.009 (0.01)	<0.01
	Slope (%)		ns
	Relative elevation[d] (m)	0.002 (0.001)	0.04
	Compound Topographic Index		ns
Total SOC stock (Mg C ha^{-1}) at 0-0.9 m	Intercept	120.61 (22.29)	<0.01
	Land-use type[b]	Not included	Not included
	Silt-plus-clay percentage (%)		ns
	ECEC[c] at 0.6-0.9 m ($cmol_c$ kg^{-1} clay)		ns
	Litter layer carbon stock (Mg C ha^{-1})	5.21 (1.39)	<0.01
	Litter layer C:N ratio		ns
	Tree basal area (m^2 ha^{-1})	0.79 (0.31)	0.01
	Slope (%)		ns
	Relative elevation[d] (m)	0.07 (0.04)	0.08
	Compound Topographic Index		ns

[a]Linear mixed effects models with sampling plot as random intercept. All effects were included in the full model, and model simplification resulted in the minimum adequate model. ns - not significant (i.e., the effects excluded by model simplifications)

[b]Land-use type has not been included as a categorical factor in the full model.

[c]ECEC, Effective Cation Exchange Capacity.

[d]Relative elevation is the change in elevation compared to the lowest situated sampling plot.

~~Scale-dependent relationships~~Spatial variability of soil organic carbon in a tropical montane landscape: Associations between soil organic carbon ~~stocks,~~and land~~-~~ use~~ types~~, soil properties, vegetation and ~~biophysical characteristics in a tropical montane~~topography vary across plot to landscape scales.

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Abstract. Presently, the lack of data on soil organic carbon (SOC) stocks in relation to land-use types and biophysical characteristics prevents reliable estimates of ecosystem carbon stocks in montane landscapes of mainland SE Asia. Our study, conducted in a 10,000-~~hectare~~ha landscape in Xishuangbanna, SW China, aimed at assessing the spatial variability in SOC ~~and its~~concentrations and stocks, and the relationships of SOC with land-use ~~cover and key biophysical~~types, soil properties, vegetation characteristics and topographical attributes at ~~multiple~~three spatial scales~~.~~: (1) land-use types within a landscape (10,000 ha) (2) sampling plots (one ha) nested within land-use types (plot distances ranging between 0.5 - 12 km) and (3) subplots (10-m radius) nested within sampling plots. We sampled 27 one-~~hectare~~ha plots including 10 plots in mature forests, 11 plots in regenerating or highly disturbed forests, and six plots in open land including tea plantations ~~or~~and grasslands. We used a sampling design with a hierarchical structure. The landscape was first classified according to land-use types. Within each land-use type, sampling plots ~~of 100 m x 100 m each~~ were randomly selected, and within each plot we sampled within nine subplots. ~~This hierarchical sampling design allowed partitioning of the overall variance in SOC, vegetation, soil properties and topography that was accounted for by the variability among~~SOC concentrations and stocks did not differ significantly across the four land-use types~~, among plots nested within land-use types, and~~. However, within ~~plots.~~the open-land category, SOC concentrations and stocks ~~did not differ significantly across land-use types.~~in grasslands were higher than in tea plantations (P<0.01 for 0-0.15-m, P=0.05 for 0.15-0.30-m, P=0.06 for 0-0.9-m depth). The SOC stocks to a depth of 0.9 m were 177.6 ± 19.6 (SE) Mg C ha^{-1} in tea plantations, 199.5 ± 14.8 Mg C ha^{-1} in regenerating or highly disturbed forests, 228.6 ± 19.7 ~~(SE)~~ Mg C ha^{-1} in mature forests, and 236.2 ± 13.7 Mg C ha^{-1} in grasslands. In this montane landscape, variability within plots accounted for more than 50% of the overall variance in SOC~~.~~ stocks to a depth of 0.9 m, and the topsoil SOC concentrations. The relationships ~~between SOC, biophysical~~of SOC concentrations and stocks with land-use types, soil properties, vegetation characteristics and ~~land-use types~~topographical attributes varied across spatial scales. Variability in SOC within plots was determined by ~~tree basal area,~~ litter layer carbon stocks ~~and slope.~~(P<0.01 for 0-0.15-m and P=0.03 for 0.15-0.30-m and 0-0.9-m depth) and slope (P≤0.01 for 0-0.15-m, 0.15-0.30-m and 0-0.9-m depth) in open land, and by litter layer carbon stocks (P<0.001 for 0-0.15-m, 0.15-0.30-m and 0-0.9-m depth) and tree basal area (P<0.001 for 0-0.15-m and P=0.01 for 0-0.9-m depth) in forests. Variability in SOC among plots in open land was ~~influenced by land-use type~~ related to the differences in SOC concentrations and stocks ~~in~~between grasslands ~~were higher than in~~and tea plantations. In forests, the variability in SOC among plots was ~~related to~~ associated with elevation~~.~~ (P<0.01 for 0-0.15-m and P=0.09 for 0-0.9-m depth). The scale-dependent relationships between SOC and its controlling factors demonstrate that studies ~~which~~that aim to investigate the land-use effects on SOC need an appropriate sampling design reflecting the controlling factors of SOC so that land-use effects will not be masked by the variability between and within sampling plots.

1. Introduction

Soils are the largest pool of terrestrial organic carbon, storing more carbon than the combined total of carbon stocks in the atmosphere and vegetation (Schlesinger, 1997). The carbon pools in soil and atmosphere are tightly linked to the photosynthetic activity of plants and decomposition of soil organic matter by soil fauna. The flux from the soil organic carbon (SOC) pool to atmospheric CO_2 is one of the largest in the global carbon cycle and is sensitive to changes in land use (e.g., Powers et al., 2011) and climate (Amundson, 2001). Apart from the important role of the SOC pool in the global carbon cycle, SOC is a dominant controlling factor of important soil functions such as soil fertility, soil structure, and soil water-holding capacity. SOC stocks typically ~~displays~~display considerable spatial variability across landscapes~~, and understanding~~. Understanding the drivers of this variability is essential for the development of management strategies that aim at enhancing soil functions, and for SOC accounting purposes with a relevance for policy makers. Examples of such SOC ~~assessments~~accounting purposes are ~~of particular interest for~~ the Clean Development Mechanism (CDM) and ~~for~~ Reducing Emissions from Deforestation and Degradation (REDD+) initiatives that aim to generate financial compensation for local communities if they protect and enhance ecosystem carbon stocks (UNFCCC, 2009).

Spatial variability in SOC is the result of soil-forming factors acting and interacting across various spatio-temporal scales (Trangmar et al., 1986). Soil-forming factors affecting SOC are soil parent material, ~~topography~~topographical attributes, biota, human activity (which includes land-use ~~cover~~type and land management), time, and climate (Jenny, 1941). The importance of these controlling factors differs with spatial scale and environmental setting (Chaplot et al., 2010; Liu et al., 2013; Powers and Schlesinger, 2002). At the landscape scale, parent material (which often affects soil group, and clay ~~type~~minerology and content) is an important driver of SOC (e.g. de Koning et al., 2003; Schimel et al., 1994; Six et al., 2002). Within the same soil group, SOC is mainly influenced by land-use ~~cover~~type and management (e.g. de Blécourt et al., 2013; de Koning et al., 2003; Mekuria et al., 2009; Post and Kwon, 2000), and geomorphological characteristics such as slope and slope position (Chaplot et al., 2005; Corre et al., 2015; Pennock and Corre, 2001). Spatial patterns of SOC~~ stocks~~ are also greatly influenced by small-scale variability in biophysical factors that influence plant productivity and decomposition of soil organic matter (Hook et al., 1991; Stoyan et al., 2000). A comprehensive understanding of the sources of spatial variability of SOC and its key drivers at multiple scales is an important prerequisite for upscaling SOC data to larger areas.

In this study, we used a hierarchical sampling design to examine spatial variability in SOC concentrations (SOCc) and stocks (SOCs) and its relationships with land-use ~~cover and key biophysical~~types, soil properties, vegetation characteristics, and topographical attributes at multiple spatial scales in a tropical montane landscape in Xishuangbanna, SW China. For centuries the area's land-~~-~~ use~~ cover~~ has been characterized by swidden agriculture (also called slash-and-burn agriculture, or shifting cultivation) (Xu, 2006). The long history of swidden agriculture has resulted in a mosaic of secondary forests, agricultural fields, paddy rice, tea plantations, and rough grasslands (i.e. grasslands invaded with shrubs). Similar multi-use landscapes extend throughout SW China and the northern areas of Laos, Myanmar, Thailand and Vietnam (Garrity, 1993). In recent decades, large areas, formerly under swidden agriculture, have been transformed into landscapes with a more uniform land-use cover dominated by commercial crops and monoculture tree plantations (Rerkasem et al., 2009). The impact of the demise of swidden agriculture on ecosystem carbon stocks remains hard to predict, which is caused, among other factors, by limited SOC data (Fox et al., 2014). ~~The few~~There were only three studies ~~available for this region~~so far that evaluated the impact of land use and various biophysical factors on ~~SOC assessments~~the spatial variation in SOCc and SOCs at a landscape or ~~national~~larger scale in montane mainland southeast Asia; these were conducted in northern Thailand (Aumtong et al., 2009; Pibumrung et al., 2008) and Laos ~~(Chaplot et al., 2009, 2010; Phachomphon et al., 2010).~~(Phachomphon et al., 2010).

Our specific objectives were (i) to quantify the ~~SOC stocks~~SOCs of the four dominant land-use types~~, (ii) to determine the proportions of the overall variance in SOC and key biophysical characteristics across multiple spatial scales, and (iii) to assess the relationships between SOC, land-use types and biophysical characteristics. We sampled SOC stocks, vegetation- and soil properties, and recorded topographical parameters along a disturbance gradient ranging from~~: tea plantation ~~(strongly disturbed),~~, rough grasslands, regenerating or highly disturbed forests, ~~to~~and mature forests ~~(minimally disturbed). Our hierarchical sampling design allowed us~~, (ii) to ~~partition~~determine the proportions of the overall variance of ~~SOC~~SOCc and SOCs as well as soil, vegetation~~-~~ and ~~soil~~topographical properties ~~into the variability~~that were accounted for by land-use types~~,~~ within the landscape (10,000 ha), by sampling plots (one ha) nested within land-use types (plot distances ranging between 0.5 - 12 km), and by subplots (10-m radius) nested within ~~the one-hectare sampling plots.~~sampling plots, and (iii) to assess the relationships between SOCc and SOCs with land-use types, soil properties, vegetation characteristics and topographical attributes. Our data provide important information on ~~SOC stocks~~SOCs for an understudied region, give insights into factors that drive ~~SOC~~SOCs at multiple spatial scales, and will help to design better sampling strategies for ~~SOC stocks~~SOCs.

2. Material and Methods

2.1 Study area

The studied landscape covered an area of about 10,000 ~~hectare~~ha and was located in Mengsong township, Xishuangbanna prefecture, Yunnan province, China (21˚29'25.62"N, 100˚30'19.85"E) (Figure 1a), bordering with Myanmar. The topography is mountainous with elevations of ~~800-2000~~1100-1900 m above sea level (asl). The climate is tropical monsoon and has a mean annual temperature (MAT) of 18 °C (at 1600 m asl). Mean annual precipitation (MAP) ranges from 1600-1800 mm, of which 80 % falls in the wet season lasting from May to October (Xu et al., 2009).

Land-use types in the area cover a disturbance gradient ranging from intensively managed tea plantation, rough grasslands, regenerating or highly disturbed forests, to mature forests, with minimal human influence. Forests in the area are classified as seasonal tropical montane rainforest in valleys, with transitions to seasonal evergreen broadleaf forest on hill slopes and ridges (Zhu et al., 2005). ~~Dominant tree families in the forest are Lauraceae, Fagaceae, Pentaphylaceae, Euphorbiaceae, and Rubiacea (Paudel et al., 2015).~~ Our sampling plots ranged in elevation from 1147 to 1867 m asl, with slopes up to 49% (Table 1). The soils at the sampling plots varied from Haplic and Ferralic Cambisols in narrow valleys, to Cambic and Ferralic Umbrisols and Umbric and Haplic Acrisols and Ferralsols at both midslope and upslope positions (IUSS Working Group WRB., 2006). Soil texture ranged from sandy clay loam to clay, soil pH (H_2O) from 3.2-6.2, and the effective cation exchange capacity (ECEC) in the subsurface soil ranged from 4.8-45.8 $cmol_c$ kg^{-1} clay (Table 2).

2.2 Sampling design

We selected 27 one-~~hectare~~ha sampling plots of which 10 plots were in mature forests, 11 plots in regenerating or highly disturbed forests, and six plots were categorized as open land used as tea plantations or rough grasslands~~.~~ (Figure 1b). In each sampling plot, we established nine circular subplots with a 10-m radius on a square grid with 50-m spacing~~.~~ (Figure 1c). Plots were selected using double sampling for stratification, also known as two-phase sampling (Fleischer, 1990). In phase 1, we classified the land-use types of the 10,000-~~hectare~~ha landscape based on grid points (400 points with 500-m spacing) that were placed on satellite images (SPOT5 acquired in 2009 and RapidEye acquired in 2010) of the study area. Each point was identified as mature forest, regenerating or highly disturbed forest, open land, or other. In phase 2, the study area was divided in 16 equal-area units. ~~Within~~From these 16 units, 12 were randomly selected, and within these 12 units we randomly selected the sampling plots from the classified grid points. Minimum distance between the sampling plots was 500 m. The land-use classification of the selected sampling plots was verified through field validations and interviews with local informants. Of the selected sampling plots, three sampling plots included a maximum of four out of the nine subplots, which did not belong to the original land-use classifications. To reduce noise in the dataset we removed these subplots from the dataset. The fieldwork, which included soil, litter and vegetation sampling, was done in 2010 and 2011.

We defined mature forests as forest sites dominated by trees with stem diameters more than 30 cm that did not show signs of recent disturbances due to timber extraction or fire. Regenerating or highly disturbed forests included both younger forest sites dominated by smaller trees, and older forest sites that had been strongly disturbed due to timber extraction or recent burning. Dominant tree families in the forest are Lauraceae, Fagaceae, Pentaphylaceae, Euphorbiaceae, and Rubiacea (Paudel et al., 2015). The selected open land plots included three plots in tea plantations and three plots in rough grasslands. Sampled tea plantations consisted of tea bushes planted in rows parallel to the slopes with few or no trees. One of the sampled tea plantations was terraced. Management practices applied in the tea plantations involved weeding and the use of chemical fertilizers and pesticides. Weeded plants were typically left between or under the tea bushes. Rough grasslands were dominated by *Imperata cylindrica* (L.) Raeusch grass, some small shrubs and a few trees. These grasslands are typically used for extensive cattle grazing and are maintained by regular burning. We observed that some of our grassland plots burnt at least two times between 2010 and 2013. According to local informants, sampling plots in each land-use type had been burnt in the past, as is inherent to the areas with a long history of swidden agriculture. Evidence of fire in the past was also observed by pieces of charcoal in the collected soil samples~~.~~ down to the deepest sampling depth of 0.9-1.2 m.

2.3 Soil and litter sampling

Soils were sampled down to 1.2 m at five depth intervals: 0-0.15 m, 0.15-0.3 m, 0.3-0.6 m, 0.6-0.9 m and 0.9-1.2 m. At each of the nine subplots per plot, we collected samples for the top three depths from four systematically (2 m east, 2 m north, 2 m west and 2 m south of the subplot center) positioned points using a ~~Dutch~~Edelman auger~~.~~ (4-cm diameter). Soil samples collected from each subplot were mixed thoroughly in the field to form one composite sample per sampling depth per subplot. Soil samples at 0.6-0.9-m and 0.9-1.2-m depth were taken in soil pits at four subplots and one subplot per sampling plot, respectively. These pits were also used to measure soil bulk density for each sampling depth using the core method (Blake and Hartge, 1986). The bulk density measurements were corrected for gravel content (pebbles > 2 mm). The litter layer (including leaves, seeds, and twigs with a length < 0.2 m) was collected at each subplot with a 0.04-m^2 quadrant sampling frame. Samples of the litter layer were collected between May-August 2010. This one-time sampling of the litter layer coincided with the start of the rainy season and does not reflect seasonal or annual fluctuations in litterfall (Paudel et al., 2015). The litter layer mainly consisted of fresh and partly decomposed plant material.

2.4 Tree inventory and topographical attributes

At all nine subplots (10-m radius) per plot we measured the diameter at breast height (DBH), at 1.3 m above the soil surface, of all trees with a DBH ≥ 10 cm. Within a 5-m radius of the subplot center we also measured the DBH of all trees with a DBH ≥ 2 cm. Tree basal area at each subplot was calculated as the sum of the basal area of all measured trees. Topographical data obtained for each subplot included slope, elevation, and compound topographic index (CTI). We measured the slope from the center of each subplot to a target point situated 5-m downslope of the subplot center using a clinometer. Elevation was derived from a SRTM digital elevation model with a 90-m resolution resampled to 30-m resolution. The CTI, also known as steady state wetness index, quantifies landscape positions based on slope and upstream contributing area orthogonal to flow direction (Gessler et al., 1995; Moore et al., 1993). High CTI values refer to valleys with large catchments and low CTI values denotes to ridges or steep slopes. We calculated the CTI from the 30-m SRTM digital elevation model using ArcGIS.

2.5 Laboratory analyses and calculations

We analyzed the soil samples for total organic carbon and nitrogen concentrations, soil pH, soil texture and ECEC. Litter layer samples were analyzed for total organic carbon and nitrogen concentrations. Prior to analyses, the soil samples were air dried (5 days) and sieved (< 2 mm). Litter layer samples were oven dried at 60 °C for 48 hours and weighed. Total organic carbon and nitrogen concentrations were analyzed by dry combustion for ground subsamples of each soil and litter sample using a CNS Elemental analyzer (Elementar Vario EL, Hanau, Germany). Since soil pH (H_2O) was below 6.2, we did not expect carbonates in these soils and carbonate removal was not necessary. Soil pH (H_2O), pH (KCl) and soil texture were measured on each sample from the 0-0.15-m, 0.15-0.3-m, and 0.9-1.2-m depth intervals, and on a pooled sample per sampling plot for the 0.6-0.9 m depth interval. Soil pH (H_2O) and pH (KCl) were measured in a 1:2.5 soil-to-solution ratio. Soil texture was determined using the pipette method distinguishing the fractions clay (<0.002 mm), silt (0.002-0.063 mm), and sand (0.063-2 mm). ECEC was measured on soil samples of the 0-0.15 m depth interval and on a pooled sample from each sampling plot for the 0.6-0.9 m depth interval. The soil samples were percolated with unbuffered 1 M NH_4Cl and the percolates were analyzed for exchangeable cations using ICP-EAS (Spectroflame, Spectro Analytical Instruments, Kleve, Germany).

We calculated the litter layer organic carbon stocks using the carbon concentration, the mass of the litter layer and the sample frame area. ~~The SOC stock for~~SOCs of each sampling depth was calculated using:

$$\sout{SOC\ \text{stocks}}\,SOCs\,(\text{Mg C ha}^{-1}) = \frac{\%C}{100} \times BD\ (Mg\ m^{-3}) \times \Delta\ \text{D}\ (m) \times 10{,}000\ m^2 ha^{-1},$$

where BD is the soil bulk density (corrected for gravel content, pebbles > 2mm) and ΔD is the thickness of the sampling depth. Since the soil depth of some sampling plots did not reach down to 1.2 m, we reported both the total ~~SOC stocks~~SOCs down to 0.9 m and the total ~~SOC stocks~~SOCs down to 1.2 m. ~~Total SOC stocks were~~The total SOCs of each subplot was calculated as ~~the~~ sum of SOCs of the constituent soil depths per subplot, the mean ~~SOC stocks per~~ SOCs of the 0.6-0.9-m depth of the respective sampling plot ~~of the relevant sampling depths~~, and the SOCs of the 0.9-1.2-m depth obtained at the plot level.

2.6 Statistical analyses

Statistical analyses were carried out using the statistical software R version 3.2.3 (R Core Team, 2015). Statistical tests were conducted for each sampling depth separately. Prior to analyses, we tested the data for normality (Shapiro-Wilk test) and equality of variances (Levene's test). Significant differences were accepted at $P \leq 0.05$, and differences at $P \leq 0.1$ were considered as marginally significant.

Data at the subplot level (~~SOC concentrations~~SOCc and ~~stocks~~SOCs, soil C:N ratio, other soil characteristics (sand, silt plus clay, bulk density, pH (H_2O), pH (KCl), ECEC, Al saturation and base saturation) down to 0.3 m, tree basal area, litter layer characteristics and topographical attributes) were analyzed using linear mixed effects models (LME) with sampling plot included as random intercept, using the package nlme (Pinheiro et al., 2012). We tested if land-use types (fixed effect term) differed in ~~SOC~~SOCc and SOCs, tree basal area, soil, litter and topographical attributes (response variables). Multiple comparisons of the means of each land-use type were done using Tukey's ~~HSD~~ test in the package multcomp (Hothorn et al., 2008). We conducted multiple regression analyses, using LMEs with sampling plot as random intercept, to test the relationships between ~~SOC concentrations~~SOCc or ~~stocks~~SOCs (response variables) with the following potential explanatory variables (fixed effect terms): land-use type, silt-plus-clay percentage, ECEC of the subsurface soil (0.6-0.9-m depth), litter layer carbon stock, litter layer C:N ratio, tree basal area, slope, relative elevation (change in elevation relative to the lowest situated sampling plot), and CTI. We conducted regression analyses separately for forests (mature forest and regenerating or highly disturbed forest combined) and open land (tea plantation and grassland combined). Correlation tests showed that the explanatory variables included in the LMEs were not strongly correlated with each other (Spearmans Rho < 0.44). Minimum adequate LMEs were selected using a stepwise model selection based on the Akaikes Information Criterion with the function stepAIC in the package MASS (Venables and Ripley, 2002). Residuals of the selected LMEs were examined for normality and equality of variances. In cases where we detected unequal variances, we included variance functions and if the assumption of normality was violated we used a logarithmic transformation of the response variable. The proportion of the variance explained by the fixed effect terms (marginal R^2) of each LME was calculated according to Nakagawa and Schielzeth (2013). We used a variance component analysis to partition the overall variance of each response variable into the variability among land-use types, among sampling plots within land-use types, and among ~~subplot plots~~subplots within plots. For the variance partitioning, we refitted the LME with sampling plot nested within land-use type as random intercept. Subsequently, we tested if both random factors were required in the LMEs by leaving out the random effect for land-use type, and comparing the two LMEs using a likelihood ratio test (Crawley, 2007).

For data that were only available at plot level (soil characteristics below 0.3-m depth other than ~~SOC,~~SOCc and ~~SOC~~SOCs, and SOCc of the 0.9~~-1.2-m depth, 0-0.9-m depth and 0~~-1.2-m depth), we tested the effect of land-use type using either one-way analysis of variance (ANOVA) (parametric test) followed by Tukey's HSD test, or Kruskal-Wallis ANOVA (non-parametric test) followed by a pairwise Wilcoxon test with Holm's correction for multiple comparisons.

3. Results

3.1 Soil properties, vegetation~~, and topographic~~ characteristics and topographical attributes

Comparison of soil characteristics across land-use types revealed significant differences in soil pH and ECEC (Table 2). The soil pH (H_2O) down to 0.3 m was lowest in mature forest (data 0.15-0.3 m not shown), and the pH (KCl) down to 0.15 m was lower in mature forests than in the tea plantations. Compared to grasslands, the ECEC of the top 0.15 m was lower in tea plantations. Tree basal area and litter layer carbon stocks were higher in regenerating or highly disturbed forests and mature forests than in tea plantations and grasslands (Table 1). Litter layer C:N ratios were ~~lower~~narrower in mature forest compared to grassland. Comparison of topographical attributes showed that the land-use types were located on similar altitudes and topographical positions (reflected by CTI). However, the tea plantations had more gentle slopes compared to the other land-use types (Table 1).

3.2 Soil organic carbon concentrations and stocks

We did not detect differences in ~~SOC concentration~~SOCc and ~~stocks among~~SOCs across the four land-use types for any of the sampling depths nor for the total ~~SOC stock~~SOCs down to 0.9 m and 1.2 m (Figure ~~1~~2, Table 3). In forests, ~~SOC concentrations~~SOCc and total ~~SOC stocks~~SOCs were positively associated with litter layer carbon stock, tree basal area, and elevation (marginal R^2 = 0.51 for 0-0.15~~-~~-m, marginal R^2 = 0.25 for 0.15-0.3~~-~~-m, marginal R^2 = 0.18 for 0-0.9~~-~~-m depth, marginal R^2 refers to the variance explained by the fixed effect terms of each LME) (Table 4). However, the effect of elevation on total ~~SOC stocks~~SOCs was only marginally significant, and for the 0.15-0.3-m depth litter layer carbon stock was the only controlling factor of ~~SOC~~SOCc that was statistically significant. The effect of silt-plus-clay percentage on ~~SOC~~SOCc was included in the regression LME for the 0.15-0.3-m depth but was not statistically significant (Table 4).

In open land, the most important controls of ~~SOC concentrations~~SOCc and total ~~SOC stocks~~SOCs were land-use type, vegetation characteristics (litter layer carbon stocks, litter layer C:N ratio and tree basal area) and slope (marginal R^2 = 0.57 for 0-0.15~~-~~-m, marginal R^2 = 0.54 for 0.15-0.3~~-~~-m~~,~~, and marginal R^2 = 0.60 for 0-0.9~~-~~-m depth) (Table 4). ~~SOC concentrations~~SOCc and total ~~SOC stocks~~SOCs increased with increasing litter layer carbon stocks and decreased with increasing slope. Furthermore, ~~SOC concentrations~~SOCc and total SOCs in grasslands were higher than tea plantations when controlling for the variability related to other explanatory variables (Table 4). Litter C:N ratio was included as explanatory variable for ~~SOC~~SOCc at 0.15-0.3-m depth; however, this effect was marginally significant (Table 4). Tree basal area was included as explanatory factor for ~~SOC concentrations~~SOCc in open land at 0.15-0.3 m and for total ~~SOC stock~~SOCs, but its effects on ~~SOC~~

~~concentrations~~SOCc was marginally significant at 0.15-0.3 m and not significant on total ~~SOC stocks~~SOCs (Table 4).

3.3 Variance partitioning of soil properties, vegetation~~, litter~~ characteristics and topographical attributes

Variance partitioning showed that in the top 0.3 m of the soil, with the exception of soil pH ~~H_2O (P=0.02),~~H_2O, land-use type did not contribute ~~significant~~significantly to any of the variation in soil ~~characteristics~~ properties (Figure ~~2a~~3a; for 0.15-0.3 m, data not shown). ~~Variability~~Instead, the variability among plots (nested within land-use type) and among subplots (nested within plots ~~largely constituted the overall variance for SOC concentration~~) contributed relatively equally to the variances in SOCc, total ~~SOC stocks~~SOCs down to 0.9 m and ~~soil characteristics~~all other ~~than~~ soil properties (except for soil texture) (Figure ~~2a~~3a). For soil texture, the variability among plots was the most important component of the overall variance. Most of the overall variance in the litter layer carbon stocks and litter layer C:N ratio was accounted for by the variability among subplots within plots (Figure ~~2b~~3b). For tree basal area, the variability among land-use types was the most important component of the overall variance followed by the variability within plots. The main proportion of the overall variance in slopes was covered by the variability among subplots within plots, and the overall variance in elevation was almost completely due to the variability among plots (Figure ~~2b~~3c).

4. Discussion

4.1 Effects of land-use type on soil organic carbon concentrations and stocks

Our values of ~~SOC stocks~~SOCs in mature forest, regenerating or highly disturbed forests, tea plantations and grasslands (Table 3) were at the high end of the range of ~~SOC stocks~~SOCs reported for these land-use types in other studies from montane areas of mainland SE Asia (Table 5, our comparisons are based on equivalent sampling depths). ~~SOC stocks~~SOCs to a depth of 0.3 m in mature forest and regenerating or highly disturbed forest were comparable to national estimates of ~~SOC stocks~~SOCs in forests in Laos (Chaplot et al., 2010). However, our total ~~SOC stocks~~SOCs within 0-0.9-m and 0-1.2-m depth were higher than the regional estimates of ~~SOC stocks~~SOCs within 1-m depth in subtropical forests in China (Yu et al., 2011), and ~~then~~than the ~~SOC stocks~~SOCs within the same depths in other tropical forests in Xishuangbanna, SW China, ~~(de Blécourt et al., 2013; Lü et al., 2010)~~(de Blécourt et al., 2013; Lü et al., 2010) and northern Thailand (Aumtong et al., 2009; Pibumrung et al., 2008). Data on ~~SOC stocks~~SOCs in tea plantations and grasslands in the montane regions of SE Asia are scarce. Our observed ~~SOC stocks~~SOCs in tea plantations within 0-0.6 m were in the range of the regional estimates of ~~SOC stocks~~SOCs in tea plantations reported for SW China (Li et al., 2011). However, our values of ~~SOC stocks~~SOCs within 0-1.2-m depth in grasslands were higher than the amounts reported for fallow fields with a vegetation consisting of grasses and shrubs in northern Thailand (Aumtong et al., 2009). Compared to the cited studies, our study site was located at a higher elevation (1100-1900 m asl), had a relatively low MAT (18 °C) and a relatively high MAP (1600-1800 mm) (Table 5). Elevation and MAP have commonly been observed to positively affect SOCs (Amundson, 2001; Chaplot et al., 2010; Dieleman et al., 2013) while MAT is known for being negatively associated with SOCs (Amundson, 2001; Powers et al., 2011). These factors may have contributed to the large total SOCs we observed.

~~Although land-use type is often considered an important controlling factor of SOC, we did not observe differences in SOC concentrations and stocks among land-use types (Table 3, Figure 1). There are several possible explanations for the high SOC levels in grasslands, which were similar to SOC levels in mature forests. First, *Imperata* grasslands may have a higher belowground net primary production (NPP) compared to forests, resulting in greater inputs of organic matter to the soil.~~Although land-use type is often considered an important controlling factor of SOC, we did not observe differences in SOCc and SOCs among land-use types (Table 3, Figure 2). Possible explanations for the high total SOCs in grasslands, which were similar to SOCs in mature forest, are higher belowground net primary production and charcoal inputs compared to forests (van der Kamp et al., 2009; Yonekura et al., 2010). Higher belowground NPP in *Imperata* grasslands compared to forests may result in greater inputs of organic matter to the soil. To our knowledge, no comparable data (i.e. from sites with similar biophysical characteristics) exists on belowground NPP in these land-use types. Belowground NPP of regularly burnt *Imperata* grasslands in northeast India ranges from 973.8 to 1326.7 g m^{-2} y^{-1} (Astapati and Das, 2010) and is far greater than the reported 111 and 379 g m^{-2} y^{-1} for tropical forests on Ultisols and Oxisols, respectively (Vogt et al., 1996). ~~Second, charcoal~~Charcoal input in grasslands is probably relatively high due to the high fire frequencies. However, results from field measurements on impacts of fire and charcoal additions on SOC quantities are contradicting, ranging from SOC losses (Bird et al., 2000; Fynn et al., 2003) to no change or increases in the SOC pool (Eckmeier et al., 2007; Ojima et al., 1994). Studies conducted in Kalimantan, Indonesia (van der Kamp et al., 2009; Yonekura et al., 2010) reported even higher ~~SOC stocks~~SOCs in *Imperata* grasslands compared to primary forests. Similarly, a meta-study of tropical land-use conversions (Powers et al., 2011) reported an increase in ~~SOC stocks~~SOCs of 26% following forest-to-grassland conversions on soils with low activity clays and annual precipitation of 1501-2500 mm, which are similar to the biophysical conditions in our study area. However, this meta-study also included managed grasslands as opposed to the semi-managed (mainly by regular burning) grasslands in our study.

The large proportion of variability within and among plots from the overall variance in ~~SOC~~SOCc and SOCs (Figure ~~2a~~3a) reflects our probability sampling technique (double sampling for stratification) for selecting plot locations. Studies with sampling designs based on prior knowledge of factors controlling SOC at a specific spatial scale of investigation (e.g. using space-for-time substitution, chronosequences, or stratification based on soil groups) generally result in smaller variability among plots nested within land-use types, as opposed to probability sampling designs. Results of the variance component analysis showed that large variability in ~~SOC~~SOCc and SOCs, other soil properties, vegetation characteristics, and ~~topography~~topographical attributes within and among sampling plots (Figure ~~2~~3) masked possible land-use effects on SOC in our study area.

4.2 Effects of ~~biophysical~~ soil properties, vegetation characteristics and ~~vegetation~~ topographical attributes on ~~SOC~~soil organic carbon concentrations and stocks

Our findings that the majority of the overall variance in ~~SOC~~SOCc and total SOCs down to 0.9 m was accounted by the variability within sampling plots and a smaller proportion was accounted by the variability among plots (Figure ~~2a~~3a), is similar to the findings of a study in subtropical northern New South Wales, Australia with plots of 30 m x 30 m (Paul et al., 2013). A large small-scale variability was also observed on a hill slope in Laos, where 85% of the variance in ~~SOC~~SOCc and SOCs occurred at a 20-m scale (Chaplot et al., 2009). In contrast, in lowland landscapes of Sumatra, Indonesia, where plots of 50 m x 50 m had slopes ranging from 3-16 %, only a small proportion of the overall variance in ~~SOC~~SOCs was accounted by the variability within plots (Allen et al., 2016).

~~The substantial~~Paul et al. (2013) related the high within plot variability in SOCc to the heterogeneous nature of vegetation and microclimate in their plots. Chaplot et al. (2009) attributed the large small-scale variability ~~that we detected in SOC~~in SOCs and SOCc to land use, clay content and hill-slope surface morphology. The study of Allen et al. (2016) was on well-drained areas of the landscape with gentle slopes and stratified by soil group, which may ~~reflect the~~have resulted in the small within-plot variability they observed. Our study was in a montane landscape, wherein large within-plot variability in SOCc and SOCs may have been due to a large heterogeneity in slope and vegetation characteristics~~,~~ especially tree basal area and litter layer carbon stocks, within ~~our~~the one-~~hectare sampling plots~~ha plots (and therein the possible microclimate variability) (Table 4 and Figure ~~2b~~3). We base this on the associations of SOC with tree basal area and litter layer carbon stocks in forest, and with litter layer carbon stocks and slope in open land (Table 4), in combination with the high proportion of within-plot variability of these parameters from the overall variances (Figure ~~2b~~3). We attributed the variability in ~~SOC~~SOCc and SOCs among plots in open land to land-use effects (tea plantations versus grasslands) whereas in forests, elevation was the most important factor controlling the variability in ~~SOC~~SOCc and SOCs among plots (Table 4, Figure ~~2b~~3). The low marginal R^2 of our SOC-models in forests, for 0.15-0.3-m and 0-0.9-m depths, indicated a large amount of unexplained variance and suggests that other controlling factors may have contributed which we did not include in our measurements. These factors could include vegetation composition and land-use history, which we tried to document but which proved difficult to categorize meaningfully.

The observed increase in ~~SOC~~SOCc and SOCs in forests and open land with increasing tree basal area and litter layer carbon stocks (Table 4) was in accordance with findings from previous studies (de Blécourt et al., 2013; Powers and Schlesinger, 2002; Woollen et al., 2012) and is attributed to biomass productivity. Enhanced biomass productivity may increase SOC input through increases in litterfall and root residues. The use of tree basal area and litter layer carbon stocks as a proxy for biomass productivity is supported by positive associations between yearly litterfall and increases in tree basal area and litter layer carbon stocks, observed in a subset of our forest plots (Table A1, Paudel et al., 2015). The decrease in ~~SOC~~SOCc and SOCs in open land with increasing slope (Table 4) was most likely related to surface erosion, which is common in montane landscapes (e.g., Arrouays et al., 1995; Corre et al., 2015). The importance of erosion and sedimentation processes on the redistribution of SOC was shown in studies conducted in Laos (Chaplot et al., 2005) and Ecuador (Corre et al., 2015); soil erosion was highest at the upper slopes and most of the eroded soil and SOC was deposited within a short distance at the lower slopes. The observed increase in ~~SOC~~SOCc and SOCs in forests with increase in elevation is consistent with other studies (Chaplot et al., 2010; Dieleman et al., 2013; Powers and Schlesinger, 2002). Elevation effects on SOC are often related to changes in precipitation, temperature, soil characteristics, and biomass productivity. However, despite the large elevation gradient of the forest plots in our study (1147-1867 m asl) we did not observe any elevation effects on silt-plus-clay percentage, ECEC of the subsurface soil (reflecting clay mineralogy), soil pH H_2O, soil C:N ratio or tree basal area (data not shown). Although microclimatic data for our plots were not available, the commonly occurring reduction in temperatures with increase in elevation may influence SOC decomposition rates, which could possibly explain the positive trend between elevation and SOC in our forest plots. Soil texture within a similar soil group is regarded as an important control for plant productivity, decomposition of soil organic matter, and SOC stability (Silver et al., 2000). In our study area, silt-plus-clay percentage did not influence ~~SOC concentrations~~SOCc and ~~stocks~~SOCs (Table 4). Possibly the influence of soil texture on SOC was masked by the large variability in soil groups (and thus clay mineralogy) in our study area.

4.3 Implications for sampling soil organic carbon stocks

Probability sampling techniques as applied in our study are appropriate for assessing spatial variability of SOC and its driving factors across scales (subplot to plot and landscape scale) but fall short in detecting land-use effects on SOC. In montane landscapes, large variability in SOC due to variability in vegetation characteristics, slope and elevation within and among plots (Figure ~~2~~3) may conceal the land-use effects on SOC, unless sample sizes are very large. An often used approach that has proven to be effective in detecting land-use effects on SOC is space-for-time substitution (e.g., de Blécourt et al., 2013; de Koning et al., 2003; van Straaten et al., 2015; Veldkamp, 1994). This approach aims to select plots that mainly differ in land-use type, with soil group and thus clay ~~type~~mineralogy and content, and topographical and climatic characteristics being comparable. However, in contrast to our probability sampling technique, plot selection using the space-for-time substitution approach is non random in order to meet the criteria for comparison, and thus SOC ~~stocks~~levels measured in those studies can only be extrapolated to larger scales under similar soil ~~group~~type and biophysical characteristics.

5. Conclusions

~~We show that, in~~In this tropical montane landscape in SW China, the spatial variability in ~~SOC~~SOCc and SOCs was largest at the plot scale~~ of one hectare. The relationships between SOC, biophysical characteristics and land-use types varied across spatial scales. The~~. This high within-plot variability in SOC reflected the variability in ~~slope and in vegetation characteristics (~~litter layer carbon stocks and slope in open land, and the variability in litter layer carbon stocks and tree basal area~~). SOC variability among plots~~ in forests~~.~~. Therefore, to achieve a reliable estimate of SOC stocks within plots, it is important to have a plot size that encompasses the inherent slope and vegetation variability. Furthermore, since the variability in SOCc and SOCs among plots was related to elevation in forests, and to land-use type in open land~~.~~, stratification of similarly montane landscapes, should be based on elevation and land-use types as the principal drivers of SOC at the landscape scale. These scale-dependent relationships between ~~SOC~~SOCc and SOCs with controlling factors demonstrate that ~~studies which investigate land-use effects on SOC require an appropriate~~ sampling ~~design, based on~~ designs must consider the controlling factors at the scale of interest~~,~~ in order to elucidate ~~these~~their effects on SOC against the ~~background~~ variability within and between plots.

Author contributions

Conceived and designed the study: Marleen de Blécourt, Rhett Harrison and Rainer Brumme. Performed the study: Marleen de Blécourt and Ekananda Paudel. Analyzed the data: Marleen de Blécourt, Marife D. Corre and Edzo Veldkamp. Wrote the paper: Marleen de Blécourt. All co-authors read and contributed to revisions of the manuscript.

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Table 1: Means (± SE)[a] of ~~litter layer~~vegetation characteristics~~, tree basal area~~ and topographical attributes of four different land-use types in a tropical montane landscape in SW China.

Characteristics	Mature forest (n=10)	Regenerating or highly disturbed forest (n=11)	Grassland (n=3)	Tea plantation (n=3)	P value
Litter layer C concentration (%)	40.0 (1.1)	40.1 (1.1)	42.8 (0.2)	39.7 (2.3)	0.38
Litter layer C:N ratio	29.7 (1.5) b	36.4 (2.1) ab	43.2 (6) a	35 (3.4) ab	0.02
Litter layer carbon stock (Mg C ha^{-1})	5.6 (0.6) a	4.2 (0.5) a	1.7 (0.2) b	1.5 (0.2) b	<0.01
Tree basal area (m^2 ha^{-1})	29 (2.5) a	18.2 (1.9) b	3 (0.7) c	0.8 (0.2) c	<0.01
Slope (%)	29.7 (1.6) a	26.7 (1.1) ab	31 (3.8) a	12.9 (1.3) b	0.05
Elevation (m)	1664 (66)	1559 (67)	1719 (59)	1573 (119)	0.54
Compound topographic index[b]	9.9 (0.4)	8.9 (0.2)	8.4 (0.2)	9.8 (0.8)	0.29

[a]Within a row, means followed by different letters indicate significant differences among land-use types, and means without letters indicate no significant difference among land-use types (linear mixed effects model, one-way ANOVA or Kruskal-Wallis ANOVA at $P \leq 0.05$).

[b]Compound topographic index (Gessler et al., 1995; Moore et al., 1993) quantifies landscape positions based on slope and upstream contributing area orthogonal to flow direction. High CTI values refer to valleys with large catchments and low CTI values denotes to ridges or steep slopes.

Table 2: Means (± SE)[a] of soil ~~characteristics~~properties of four different land-use types in a tropical montane landscape in SW China.

Characteristic	Depth (m)	Mature forest (n=10)	Regenerating or highly disturbed forest (n=11)	Grassland (n=3)	Tea plantation (n=3)	P value
Sand (%)	0-0.15	39.8 (3.9)	36.3 (3.1)	47.4 (3.7)	37.6 (10.6)	0.55
	0.6-0.9	40.9 (4.4)	31.5 (4.3)	47.5 (3.9)	33.6 (9.3)	0.24
Silt plus clay (%)	0-0.15	60.2 (3.9)	63.7 (3.1)	52.6 (3.7)	62.4 (10.7)	0.54
	0.6-0.9	59.1 (4.4)	68.5 (4.3)	52.5 (3.9)	66.4 (9.3)	0.24
Bulk density (g cm^{-3})	0-0.15	0.8 (0.05)	0.8 (0.02)	0.8 (0.03)	0.7 (0.1)	0.59
	0.6-0.9	1.1 (0.05)	1.1 (0.03)	1.0 (0.03)	1.1 (0.0)	0.5
Soil C:N ratio	0-0.15	15.1 (0.6)	14.3 (0.4)	16.3 (1.1)	14.2 (0.8)	0.21
	0.6-0.9	10.7 (0.5)	10.4 (0.3)	12.5 (0.9)	10.4 (0.7)	0.18
pH (H_2O)	0-0.15	4.5 (0.1) b	4.8 (0.1) a	5.0 (0.2) a	5.0 (0.1) a	<0.01
	0.6-0.9	5.0 (0.1)	5.0 (0.1)	5.0 (0.2)	4.9 (0.3)	0.82
pH (KCl)	0-0.15	3.6 (0.1) b	3.8 (0.1) ab	3.9 (0.1) ab	4.1 (0.1) a	0.02
	0.6-0.9	3.8 (0.1)	3.9 (0.1)	3.9 (0.2)	4.1 (0.1)	0.30
ECEC[b] ($cmol_c$ kg^{-1} clay)	0-0.15	47.3 (7.6) ab	32.5 (3.6) ab	53.6 (4.4) a	24.1 (3.3) b	0.04
	0.6-0.9	23.6 (4.3)	16.2 (3.2)	17.5 (1.6)	7.7 (1.5)	0.10
Al saturation (%)	0-0.15	72.4 (3.1)	64.2 (6.1)	60.5 (12.2)	49.3 (12.4)	0.27
	0.6-0.9	86.3 (1.4)	80.5 (6.1)	87.8 (1.4)	62.8 (14.8)	0.22
Base saturation (%)	0-0.15	20.5 (3.1)	29.3 (6.0)	35.6 (11.8)	43.5 (11.3)	0.12
	0.6-0.9	8.5 (1.5)	12.0 (5.3)	7.9 (1.5)	29.1 (13.3)	0.11

[a]Within a row, means followed by different letters indicate significant differences among land-use types, and means without letters indicate no significant difference among land-use types (linear mixed effects model, one-way ANOVA or Kruskal-Wallis ANOVA at $P \leq 0.05$).

[b]ECEC, effective cation exchange capacity.

Table 3: Means (± SE)[a] of soil organic carbon stocks (Mg C ha^{-1}) of four different land-use types in a tropical montane landscape in SW China.

Depth (m)	Mature forest (n = 10)	Regenerating or highly disturbed forest (n = 11)	Tea plantation (n = 3)	Grassland (n = 3)	P value
0-0.15	65.5 (6.8)	58.4 (4)	44.3 (7)	66 (2.6)	0.15
0.15-0.3	51.7 (4.5)	47.5 (3.7)	40.3 (3.6)	55.1 (5)	0.32
0.3-0.6	73.4 (8)	58.9 (4.8)	59.1 (7.6)	67.7 (2.6)	0.37
0.6-0.9	38 (3.2)	34.6 (3.5)	34 (5.3)	47.4 (4)	0.40
0.9-1.2[b]	18 (3.1)	23.2 (6)	20.8 (7.7)	38.5 (14.9)	0.35
Sum 0-0.9	228.6 (19.7)	199.5 (14.8)	177.6 (19.6)	236.2 (13.7)	0.34
Sum 0-1.2[b]	252.1 (25.4)	230.5 (24.6)	216.2 (32.1)	274.6 (28.2)	0.71

[a]Within a row, means followed by different letters indicate significant differences among land-use types, and means without letters indicate no significant difference among land-use types (linear mixed effects model and one-way ANOVA at $P \leq 0.05$).

[b]The number of replicates per land-use type deviates from the original number of replicate plots because the soil depth of some sampling plots did not reach down to 1.2 m. For the 0.9-1.2-m depth and total SOC stocks to 1.2 m, the number of replication is as follows: mature forest (n = 8), regenerating or highly disturbed forest (n=8), tea plantation (n=3), grassland (n=3).

Table 4: Coefficient estimates[a] (± SE) of effects of soil texture, effective cation exchange capacity (ECEC), vegetation characteristics and topographical attributes on soil organic carbon (SOC) concentrations and total SOC stocks in forests (regenerating or highly disturbed forest and mature forest combined) and open land (tea plantation and grassland combined) in a tropical montane landscape in SW China.

Response	Effect	Forest (n = 21)		Open land (n = 6)	
		Estimate	P value	Estimate	P value
SOC concentration (%) at 0-0.15 m	Intercept	2.22 (0.66)	<0.001	6.47 (0.48)	<0.001
	Land-use type[b]		ns	-2.01 (0.30)	<0.01
	Silt-plus-clay percentage (%)		ns		ns
	ECEC[c] at 0.6-0.9 m ($cmol_c$ kg^{-1} clay)		ns		ns
	Litter layer carbon stock (Mg C ha^{-1})	0.16 (0.04)	<0.001	0.29 (0.1)	<0.01
	Litter layer C:N ratio		ns		ns
	Tree basal area (m^2 ha^{-1})	0.03 (0.01)	<0.001		ns
	Slope (%)		ns	-0.04 (0.01)	<0.01
	Relative elevation[d] (m)	0.01 (0.001)	<0.01		ns
	Compound ~~topographic~~Topographic Index		ns		ns
SOC concentration (%) at 0.15-0.30 m	Intercept	0.94 (0.86)	0.28	4.79 (0.54)	<0.001
	Land-use type[b]		ns	-1.64	0.05
	Silt-plus-clay percentage (%)	0.02 (0.01)	0.16		ns
	ECEC[c] at 0.6-0.9 m ($cmol_c$ kg^{-1} clay)		ns		ns
	Litter layer carbon stock (Mg C ha^{-1})	0.17 (0.03)	<0.001	0.34 (0.14)	0.03
	Litter layer C:N ratio		ns	-0.02 (0.01)	0.10
	Tree basal area (m^2 ha^{-1})	0.01 (0.006)	0.13	-0.17 (0.08)	0.06
	Slope (%)		ns		ns
	Relative elevation[d] (m)	0.01 (0.001)	0.13		ns
	Compound ~~topographic~~Topographic Index		ns		ns
Total SOC stock (Mg C ha^{-1}) at 0-0.9 m	Intercept	109.8 (24.1)	<0.001	247.4 (27.1)	<0.001
	Land-use type[b]		ns	-63.22 (16.3)	0.06
	Silt-plus-clay percentage at 0.15-0.3 m (%)		ns		ns
	ECEC[c] at 0.6-0.9 m ($cmol_c$ kg^{-1} clay)		ns		ns
	Litter layer carbon stock (Mg C ha^{-1})	5.3 (1.53)	<0.001	14.27 (6.05)	0.03
	Litter layer C:N ratio		ns		ns
	Tree basal area (m^2 ha^{-1})	0.89 (0.35)	0.01	-3.53 (3.71)	0.36
	Slope (%)		ns	-2.54 (0.87)	0.01
	Relative elevation[d] (m)	0.08 (0.05)	0.09		ns
	Compound ~~topographic~~Topographic Index		ns		ns

[a]Linear mixed effects models with sampling plot as random intercept. All effects were included in the full model, and model simplification resulted in the minimum adequate model. ns - not significant (i.e., the effects excluded by model simplifications)

[b]The land-use effect in open land is calculated as SOC in tea plantation minus SOC in grassland.

[c]ECEC, Effective Cation Exchange Capacity.

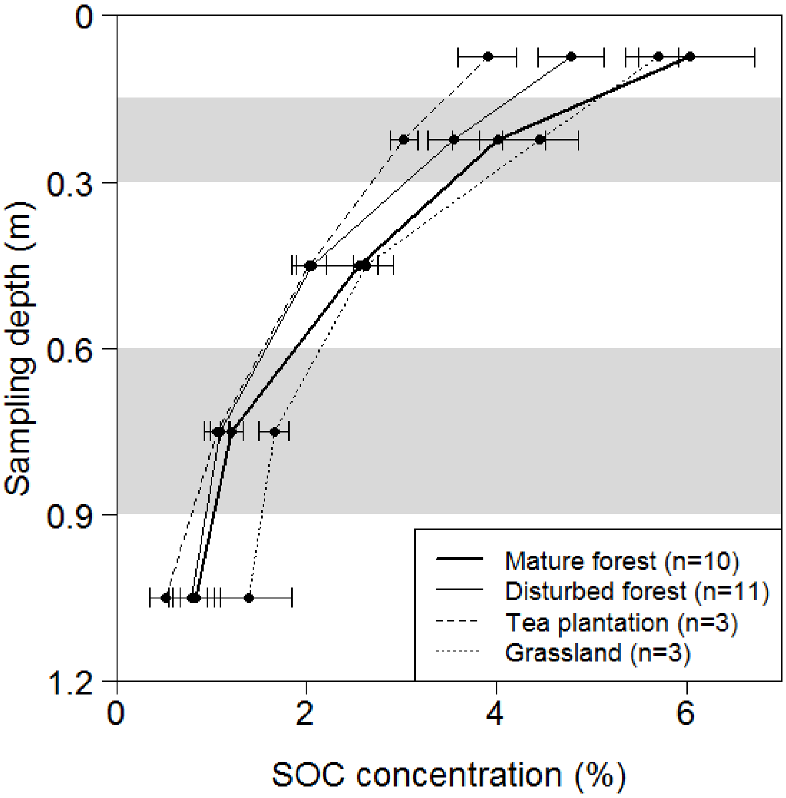
[d]Relative elevation is the change in elevation compared to the lowest situated sampling plot.

Table 5: Overview of published soil organic carbon (SOC) stocks in four different land-use types from montane areas of mainland SE Asia.

Land use	Country, site	Soil type	Elevation (m)	Climate MAP (mm)	Climate MAT (°C)	Depth (m)	SOC stock (Mg C ha^{-1})	Reference
Forest	Laos, total country	-	-	-	-	0-0.3	112	Chaplot et al. (2010)
Forest	China, Xishuangbanna	Haplic Acrisol	600	1539	21.7	0-1	84-102	~~Lü et al. (2010)~~Lü et al. (2010)
Forest	China, Menglong, Xishuangbanna	Ferralsols and (hyper) ferralic Cambisols	700-830	1377	22.7	0-0.9	170	de Blécourt et al. (2013)
Forest	Thailand, Nam Hean watershed	Red Yellow Podzolic soils and Reddish Brown Lateritic soils	215-1674	1405	16.9 (DS[a])-32.5 (WS[a])	0-1	196.24	Pibumrung et al. (2008)
Forest	Thailand, Khun Samun Watershed	Hyperalic Alisols (Humic) and Endogleyic Luvisol (Chromic)	300-800	1400	22-29	0-1.2	~170	Aumtong et al. (2009)
Forest	China, Subtropical zone	-	-	-	-	0-1	104.4-111.2	Yu et al. (2011)
Tea	China, Southwest	Haplic Acrisol	-	1000-1700	15-19	0-0.6	132.3-158.7	Li et al. (2011)
Fallow	Thailand, Khun Samun Watershed	Hyperalic Alisols (Humic) and Endogleyic Luvisol (Chromic)	300-800	1400	22-29	0-1.2	~210	Aumtong et al.(2009)

~ an approximate value, deciphered from a figure.

[a] DS - dry season, WS - wet season.



~~Figure 1: Soil organic carbon~~

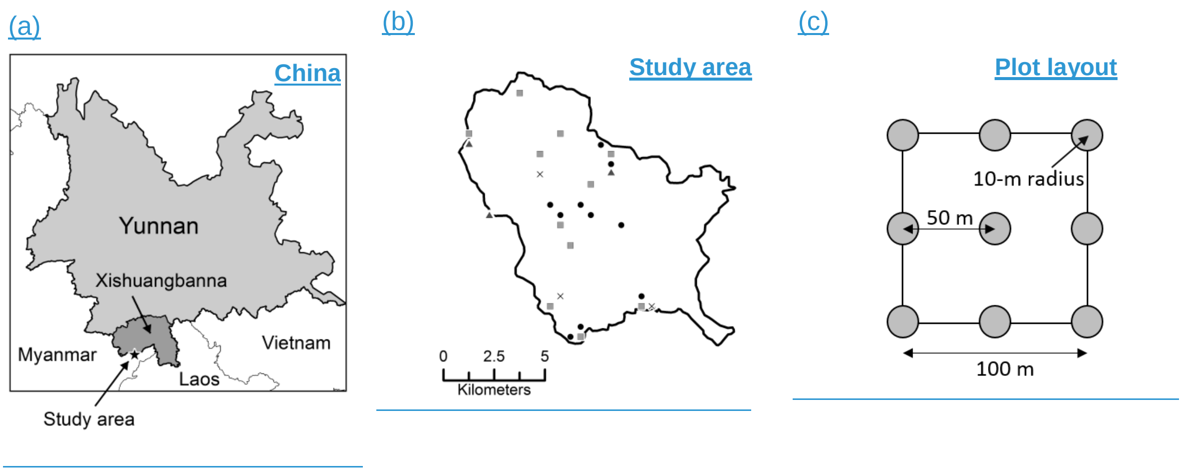


Figure 1: Sampling design: (a) The location of the study area in Xishuangbanna prefecture, Yunnan province, China, is depicted by the black star. (b) Location of the 27 sampling plots in the study area (10,000 ha), black circles were classified as mature forests (n=10), grey squares as regenerating or highly disturbed forests (n=11), black stars as rough grasslands (n=3), and black crosses as tea plantations (n=3). (c) Sampling plots of 100 m x 100 m with nine 10-m radius subplots (grey cycles) arranged on a square grid with 50-m spacing.

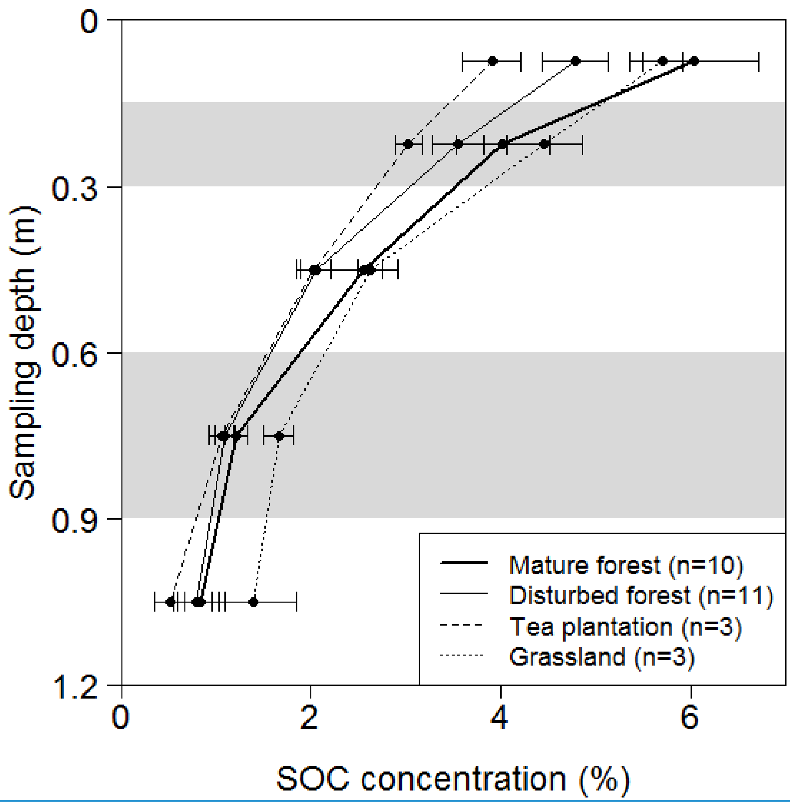
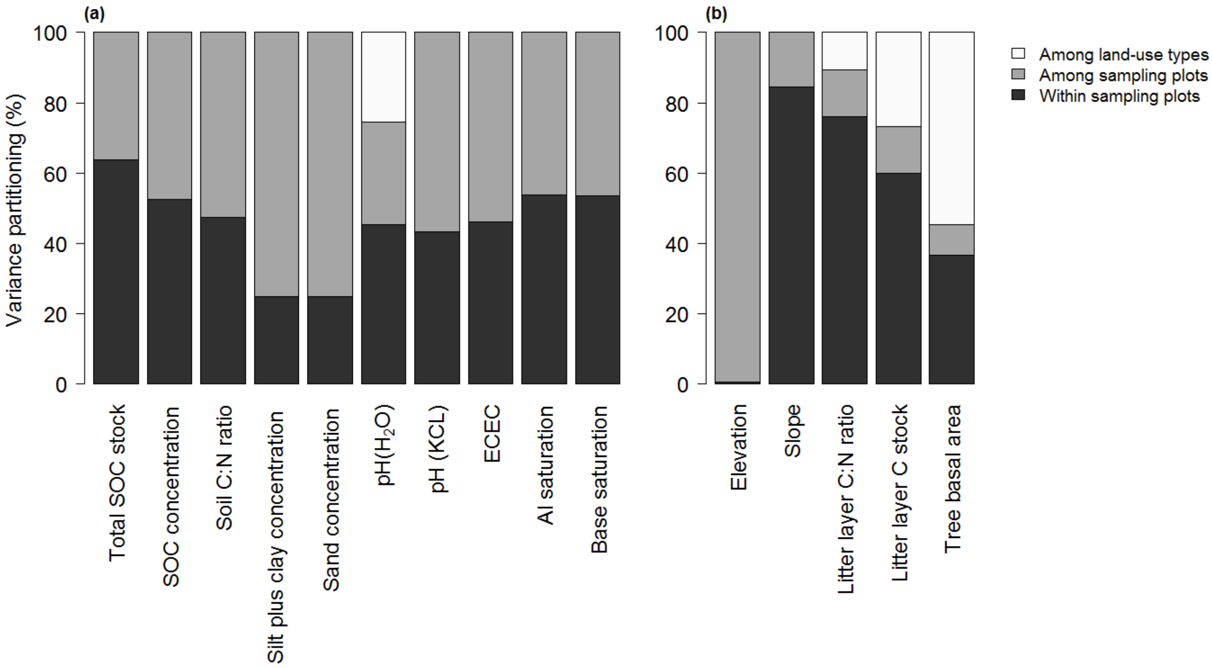


Figure 2: Soil organic carbon (SOC) concentrations in relation to sampling depth for four different land-use types in a tropical montane landscape in SW China. Alternating white and grey bands show the sampling depths. For each
645 **depth, means (SE bars) did not differ among land-use types (linear mixed effects model with P = 0.22-0.49 at sampling depths < 0.9 m, and one-way ANOVA with P = 0.37 at 0.9-1.2 m).**



(a)
(b)
Variance partitioning (%)
100
80
60
40
20
0
Total SOC stock
SOC concentration
Soil C:N ratio
Silt plus clay concentration
Sand concentration
pH(H2O)
pH (KCL)
ECEC
Al saturation
Base saturation
Elevation
Slope
Litter layer C:N ratio
Litter layer C stock
Tree basal area
Among land-use types
Among sampling plots
Within sampling plots

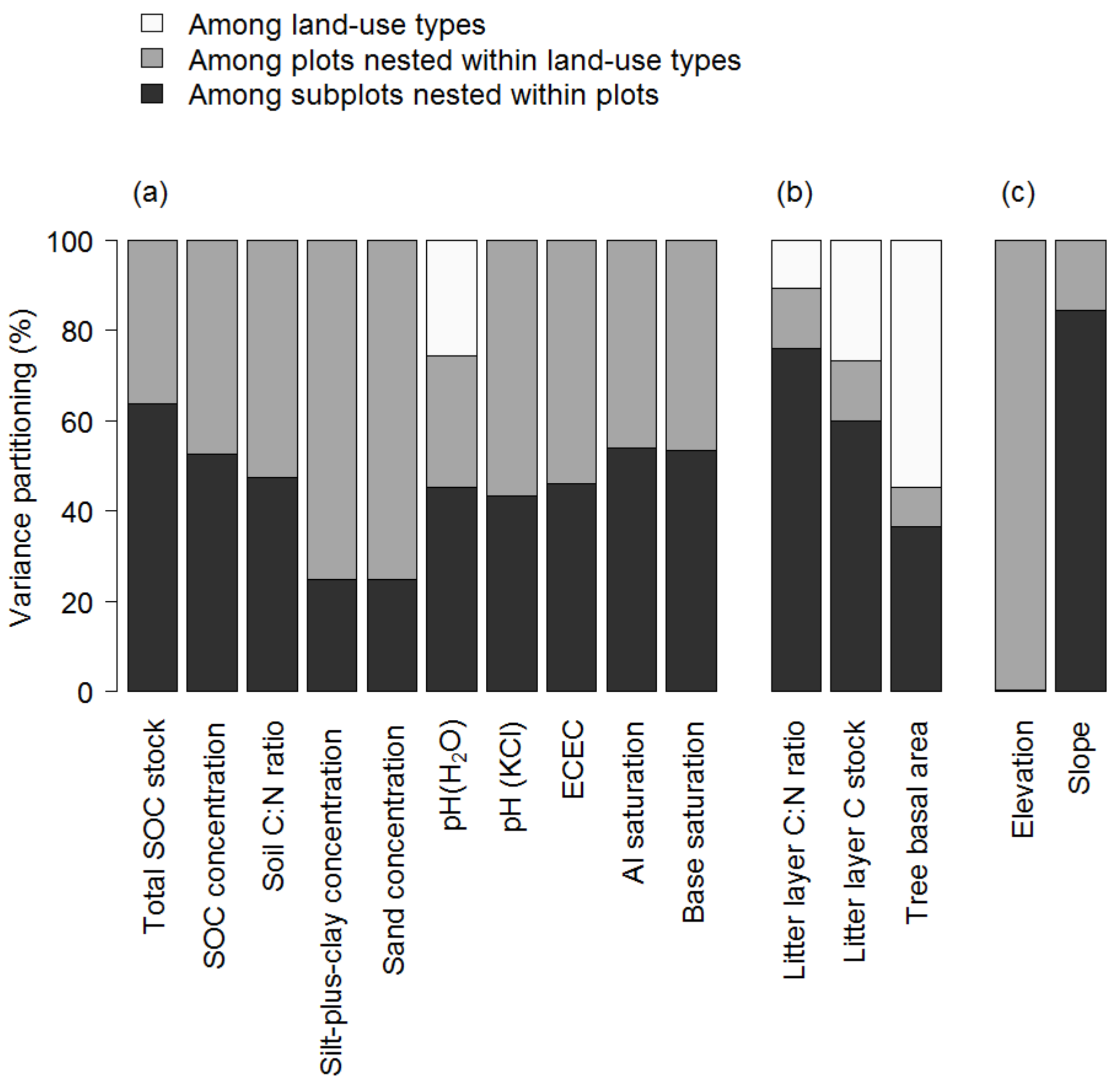


Figure ~~2~~3: Partitioning of the overall variance in (a) ~~SOC and~~total soil ~~characteristics~~organic carbon (SOC) stocks to 0.9-m depth, and SOC concentrations and soil properties at 0-0.15-m depth, ~~and~~ in (b) ~~biophysical~~vegetation characteristics, and in (c) topographical attributes, which can be attributed to the variability among land-use types, sampling plots nested within land-use types, and subplots nested within sampling plots (Linear mixed effects model with likelihood ratio test at $P \leq 0.05$, the variability in litter C:N ratio among land-use types is marginally significant with P = 0.06~~)~~

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Table A1. Direction of effects[a] of soil properties, vegetation~~, and topographic~~ characteristics and topographical attributes on litter layer carbon stock and yearly litterfall[b] in forest in a tropical montane landscape in SW China.

Response	**Effect**	**Direction of effect**	**P value**	**R^2**
Litter layer carbon stock	Elevation	+	0.05	0.19
	Soil pH H_2O (0-0.15-m depth)	-	0.07	
	Yearly litterfall	+	0.03	
Yearly litterfall	Tree basal area	+	<0.01	0.19
	ECEC subsoil	+	0.14	

[a]Linear mixed effects model with sampling plot as random intercept. Fixed effects included in the full models were elevation, slope gradient, compound topographic index, silt-plus-clay percentage, soil pH H_2O, tree basal area, litter C:N ratio, yearly litterfall.

[b]Litterfall was collected every month from 9 of the 21 forest plots. Details on the materials and methods are described by Paudel et al. (2015).