Reply to comments by Anonymous Referee #4 (RC2)

Comment #1: The article by Zhao et al., present an interesting global dataset for some soil parameters, linking these properties with climate and biota. Nevertheless, there are several issues that should be clarified and discussed in much more details. The mentioned databases report row data for soil profiles, while the authors use also some parameters which are derived from these data (e.g. SOC and SON stocks). How these data were derived and harmonized should be better explained, since in the paper they are used to derive the linkages between soil, climate and biota. For the soil profiles in the different databases, were used only the soil layers having all the necessary parameters useful to calculate the stocks of C and N? I am referring in particular to Bulk density and rock fragments content. If not, how the authors were dealing with this fact? They were using pedotransfer functions to derive bulk density? And if rock fragments content was missing? Since these two parameters are affecting very much the stock the authors should make an effort in explaining how the database were harmonized. The discussion is sometimes weak. For instance the authors found a correlation between bulk density, MAT and MAP. Similarly the all variation in relation to MAT and MAP? The discussion on the observed differences between ecosystems is quite poor. Not so many recent references are considered for the discussion. The effect of the vegetation on the selected soil parameters should be better considered and discussed.

Response: Thanks for your helpful comments. We have revised the manuscript according to your suggestions:

First, we have included more details on the method to compile our global soil database (also see our reply to comment #2). Specially, SOC/SON stocks were calculated based on bulk density and concentrations of SOC/SON. We directly calculated the stocks of SOC and SON when all the necessary parameters were available. In the case that bulk density was not measured and SOC content was reported, we made estimates of bulk density based on regional-specific pedotransfer functions (Yang et al. 2007; Abdelbaki, 2018) and further estimated SOC/SON stocks. We first established empirical relationship between bulk density and SOC content in each regions (Table R1) and further estimated bulk density based on measured SOC for the soil profiles with missing data for bulk density. Overall, there were 42% profiles with measured data on bulk density and 58% profiles with estimated data on bulk density. We agree that correction for rock fragment is important to estimate soil C stocks, but it remains a global challenge because existing databases usually contain limited information on gravel fractions than bulk density and SOC concentrations (Jandl et al., 2014). Nevertheless, the inclusion of gravel and roots > 2 mm has been evidenced to exert a relatively low impact on the calculation of SOC stocks in the surface soil layer (0-30 cm), mainly due to the fact that surface soil usually contains a low proportion of gravels (Saiz et al., 2012). Currently, we assumed no rock fragment or rock issue had been handled if it was not reported, but we might use the mean gravel fractions of each vegetation type or soil orders as a potential correction factor. Nevertheless, this approach might also result in new uncertainty if used at the global scale. We may conduct such an analysis to deal with the gravel issue if the reviewer support this idea. We have also discussed the uncertainty due to missing gravel information in the revised manuscript. Thanks for your understanding!

Second, we have improved the discussion section by 1) discussing the potential causes for the correlations between soil physical properties (bulk density and soil texture) and climate (MAT and MAP), 2) discussing the shifts of soil properties across biomes and the interactions between soil and vegetation, and 3) including more recent references. Please find more details in our reply to comments #6, 7, 8, 10 and associated references.

Table R1 Empirical regression models for relationship between bulk density (BD, g cm^{-3}) and soil organic carbon content (SOC, %) for each region.

Region	Model	R^2	Num
Tropical Asia	$BD = 1.336e^{-0.054\ SOC}$	0.26	765
Mexico	$BD = 1.380e^{-0.061\ SOC}$	0.63	1243
Africa	$BD = 1.480e^{-0.073\ SOC}$	0.30	3770
Continental US	BD = -0.173ln(SOC) + 1.382	0.45	1239
Canada	$BD = 1.507e^{-0.027\ SOC}$	0.20	163
Russia	BD = -0.222ln(SOC) + 1.287	0.59	777
South America	BD = -0.07ln(SOC) + 1.233	0.15	2105
Europe	$BD = 1.4661e^{-0.041\ SOC}$	0.60	2391
East Asia	$BD = 1.4719e^{-0.08\ SOC}$	0.35	634
Australia	$BD = 1.3319e^{-0.062\ SOC}$	0.74	167

Comment #2: Specific comment: Page 3 Line 5-10: “Compiled”. And what about harmonization of the data?

Response: Thanks for your reminder! We have included more details on the methods of data screening and compiling in the revised manuscript and supplement. Along with ground-truth soil profile data (Table S1), we have also derived general information of soil sampling (site location, sampling time, source of data), pedologic information on soil orders and the horizons of the sampled soil profiles, mean annual temperature (MAT), mean annual precipitation (MAP), seasonality of air temperature (TS, calculated as $100\times SD_{monthly}/Mean_{monthly}$), seasonality of precipitation (PS), mean annual normalized difference vegetation index (NDVI), elevation (global digital elevation map [DEM]), slope, and land use type for each recorded site (Table R1). Specifically for each profile, we recorded data on the number of horizon, top and bottom depth, and values of soil physical properties (sand/silt/clay fraction [%], gravel content [>2mm, %], bulk density [g/cm^3]), and chemical properties (pH, organic carbon content [%]; and total nitrogen content [%]) (Table R2). Data harmonization was conducted by four steps:

First, we screened sampling and measurement approaches of each soil property and excluded data those were not comparable to others in methodology. For instance, geographic coordinate data were included only when WGS84 or a geographic coordinate system that could be converted to WGS84 projection was used; Soil texture data were included only when the internationally accepted particle size class were used (clay < 2 µm < silt < 50 µm < sand < 2000 µm). This allows us to construct a database of soil properties with comparable methodology.

Second, we excluded records with no measured data on the target soil depth (0-30cm). In case that soil organic matter was measured instead of soil organic C, we used a Bemmelen index (0.58) to convert organic matter into organic C. If data of bulk density were not measured, we made estimates based on regional-specific pedotransfer functions. We first established empirical relationship between bulk density and SOC content and further estimated bulk density based on measured SOC in case data were missing for bulk density.

Third, we extracted data on soil properties of the 0-30cm soil depth based on their depth of occurrence in a profile. SOC (STN) density was calculated based on bulk density and contents of SOC (STN).

Finally, we excluded values of each soil property departure from the median at the 95% level-of-confidence according to Pleijsier (1989). The remaining data were used for statistical analyses in order to reduce the influence of outliers.

We have also revised the section on data set in the revised manuscript (Page 3&4, 2.1 Data set).

Table R2 Information recorded in GSD.

Site Data	Horizon Data
Profile ID[a]	***Profile ID & Horizon Id***[b]
General:	***General:***
Source of data	Horizon number
Description of year	depth, top
Soil classification	depth, bottom
Site location and information:	***Physical attributes:***
Location (description, region/ country)	Sand/Silt/Clay fraction (%)
Latitude & Longitude	Gravel content (>2mm, %)
Climate (MAT & MAP)	Bulk density (g/cm^3)
Elevation/ slope/ aspect	
Parent material	***Chemical attributes:***
Land use	Organic carbon (%)
	Total Nitrogen (%)
	pH-H_2O

a. unique indentifier for profile in GSD. b. Unique reference number for horizon within a profile. c. sand, 2.0-0.05mm; silt, 0.05-0.002mm, and clay, <0.002mm.

Comment #3: Page 3 Line 20-30: Since most of the soil profiles were collected a very different range of years, how the climate was related to the properties? What you mean with pedological information? The fact the soil profiles data are presented by horizons?

Response: Thanks for your comments. First, we know that soil profile data were measured across a very different range of years, but we used multiple-year mean values of climate variables in our analysis because soil properties were formed by subjecting to a climate for a long term. As 96% of soil profiles in GSD were sampled during 1950 to 2000, we used multiple-year (1950-2010) averages of climatic variables from WorldClim database. Second, our database includes pedological information on soil orders and soil horizons of sampled soil profiles. We calculated surface soil properties (0-30 cm) based on data for each horizon. We have extended the discussion accordingly in the revised manuscript (Page 4, Line 15-18).

Comment #4: Page 5 line 20-25: What is the meaning of providing a mean global value for SOC and SON?
Response: We realized that this sentence doesn't belong here because this paragraph presents results on spatial patterns of soil properties. In the revised manuscript, we have moved this sentence to the end paragraph of section 3.2, which demonstrated results of the density and stocks of SOC and STN at global scale.

Comment #5: Page 6 line 5: In brackets (MAT < 400 mm) is probably MAP rather than MAT?
Response: Typo corrected.

Comment #6: Page 6 line 20-30: the fact that bulk density is affected by precipitation and temperature should be better discussed. Similarly the increases in clay content in relation to MAT and MAP. How soil erosion affect the clay fraction? Is soil erosion selective for the clay? And Silt and Sand? An effect of the actual land use on bulk density should also be pointed out in the discussion.
Response: Thanks for your comments and suggestions. In the revised manuscript, we have discussed the effects of climate, soil erosion and land use on soil physical properties (e.g., bulk density and soil texture).

First, the increase of bulk density with higher MAT and lower MAP is likely due to an accompanying decrease of SOCD (Ruehlmann and Körschens, 2009), which is jointly regulated MAT and MAP (Fig. R1; see more discussion on the effect of climate on SOCD in section 4.3; Wiesmeier et al., 2019). Higher MAT and MAP can accelerate the rate of weathering (Jenny, 1941; Lal, 2018), thus resulting in lower sand fraction and higher soil clay fraction.

Second, previous studies indicate that silt is most sensitive to soil erosion, while sand is less mobile due to high weight and clay is protected by soil aggregates (Wischmeier and Mannering, 1969; Torry et al., 1997; Wang et al., 2013).

Third, the effect of land use is important at a local scale. For instance, a change of forest or grassland to croplands can significantly decrease SOCD and thus decrease soil bulk density, while reforestation generally increases SOCD and thus decreases soil bulk density (Don et al., 2011). However, our static mapping of global soil properties are not able to account for the effect of temporal land use change.

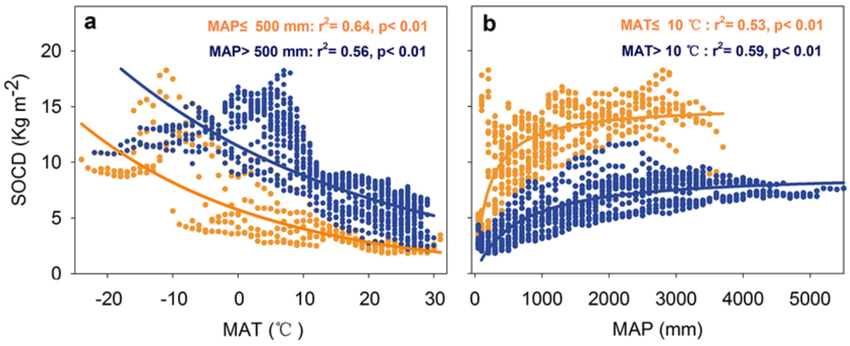

Figure R1. Changes in SOCD with MAT and MAP.

Comment #7: Page 7 line 5-10: The fact that in the tropical area Clay and bulk density decrease with altitude how can be explained? Which is the meaning of this decrease?

Response: Thanks for your suggestion. We have discussed the possible causes for the altitudinal trends of bulk density and clay, which is similar to the trends across latitudes. First, the decrease of clay fraction with higher altitude is likely due to 1) a younger soil age (Waite and Sack, 2011), 2) lower weathering rate under lower temperature (Grieve et al., 1990; Kramer and Chadwick, 2016), and 3) a downslope translocation of surface soil to lower altitude. Second, the decrease of bulk density with altitude is likely due to an increase in SOC retention (Fig. R2f), which mainly results from low rate of decomposition along with lower temperature (Grieve et al., 1990 ; Kramer and Chadwick, 2016).

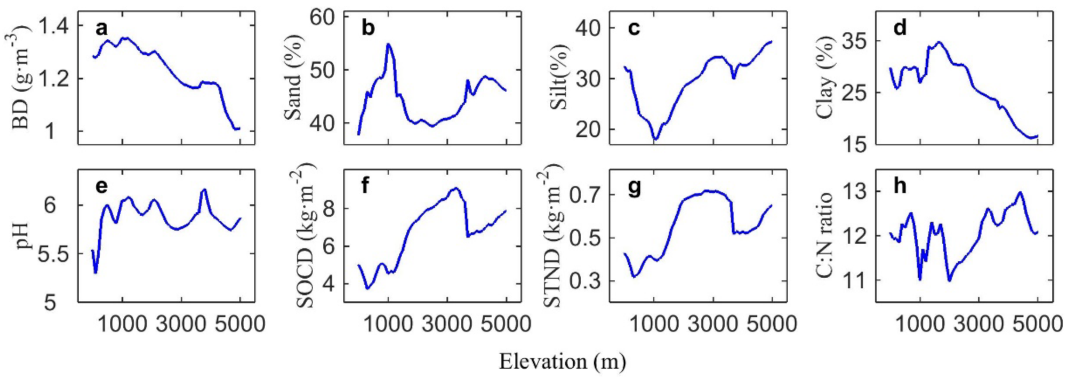

Figure R2. Changes in surface soil properties with elevation in tropical regions. a: Bulk density (g·cm^{-3}); b: Sand (%); c: Silt (%); d: Clay (%); e:Ph; f: SOCD (kg C·m^{-2}); g: STND (kg N·m^{-2}); h: C:N ratio.

Comment #8: Figure 2: SOC density box Looking at the SOC density it appear that there is quite a lot of C in the North Mediterranean area, which is usually quite poor in SOC due to the continuous use of the land for agricultrue since millennia. On the other side also the area covered by tropical primary forests in Africa (e.g. Congo basis) seems to be relatively poor? How they authors can explain these facts?

Response: Thanks for your comments. We have mapped the original records of SOCD on the map in North Mediterranean croplands and found similar results as the mapped values (Fig.

R3). As indicated by a meta-analysis, croplands have significantly lower SOCD as compared with local plantation, forest and grassland (Don et al., 2011). In the North Mediterranean region, an increase in the area of olive plantation and vineyard in last decades might have contributed to the relatively high values of SOCD (Parras-Alcántara et al., 2013). We have separately mapped SOCD for global croplands (Fig. R3) and the values of SOCD in North Mediterranean area were not as high as the impression by Figure 2 in the manuscript. This is likely visual illusion due to a mix of croplands with natural vegetation.

Due to fast turnover with rapid decomposition of organic matter, SOC content has been evidenced to be relatively poor in tropical forests (e.g., Congo and Amazon tropical forests) (Wang et al., 2018). Accordingly, previous mappings of SOCD have also shown relatively low values in tropical forests (Köchy et al., 2015; Jackson et al., 2017).

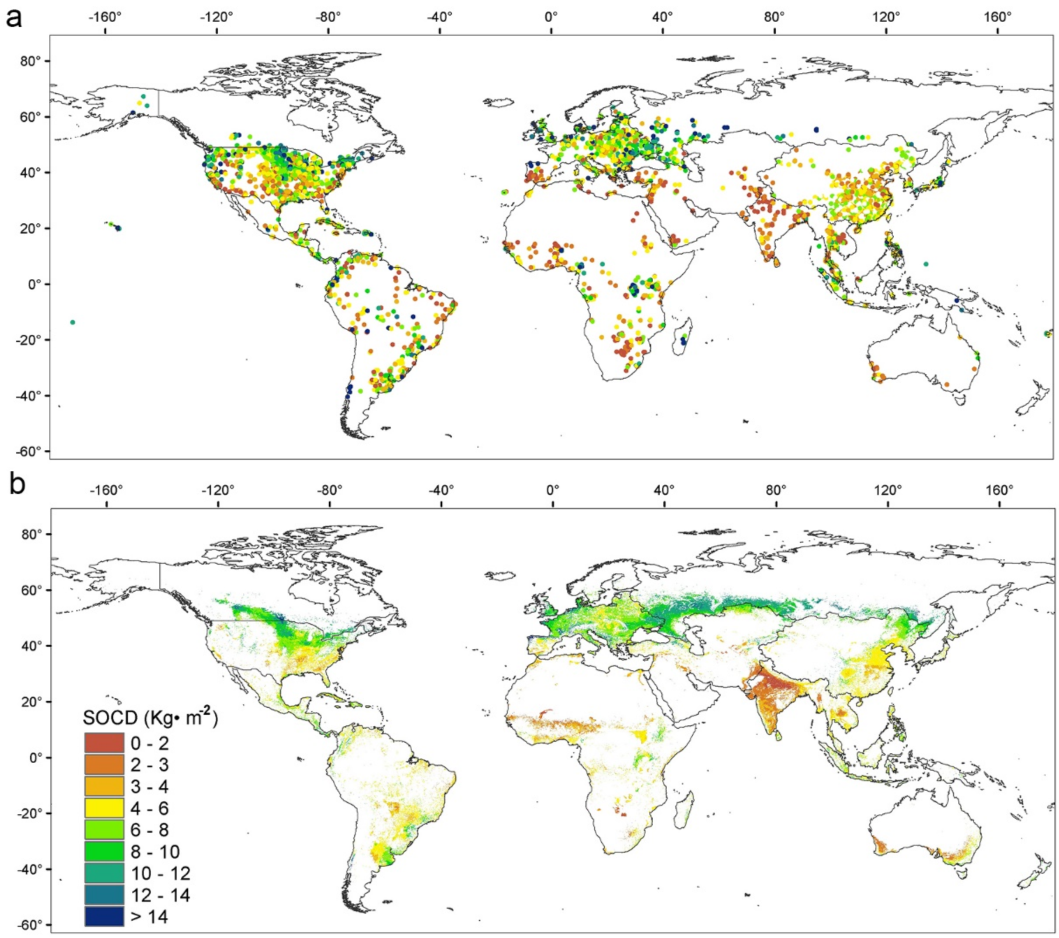

Figure. R3. Site records (a) and spatial variations (b) of SOCD in croplands.

Comment #9: Bulk density box How the authors explain the very high values of BD for the United states? Why they are so high compared to other regions. Apparently in the USA there are not so many differences in BD in relation to the different ecosystems (e.g. Forests vs. grassland vs cropland)

Response: Thanks for the comments. We have summarized the original records of bulk density for each 11 regions (Table R3). The results showed that mean regional bulk density was also relatively high in the continental United States. We have further summarized the original records of bulk density for forests, grassland and cropland in the US. We also found that bulk density of forests, grassland and cropland didn't show much difference (Table R4). Overall, our mapping of bulk density is in consistent with the pattern based on raw data and is similar to previous mapping on global bulk density (Hengl et al., 2014; Shangguan et al., 2014).

Table R3 Mean values of sampled bulk density data for each region in the GSD.

	Bulk density (g·cm^{-3})		
Region	Mean	SD	Number
Tropical Asia	1.33	0.23	860
Mexico	1.22	0.26	316
Africa	1.37	0.16	3740
Continental US	1.57	0.22	9322
Canada	1.25	0.32	790
Russia	1.12	0.28	386
South America	1.21	0.19	1764
Europe	1.27	0.30	1527
East Asia	1.29	0.20	2762
Australia	1.12	0.27	162
West Asia	1.48	0.20	333
Alaska	1.07	0.35	79
Total	1.33	0.23	860

Table R4 Mean values of sampled bulk density data for each biomes in the Continental US.

	Bulk density (g·cm^{-3})		
Continental US	Mean	SD	Number
Forest	1.57	0.28	1588
Shrub	1.64	0.27	1096
Grassland	1.56	0.20	2560
Cropland	1.54	0.15	3084
All*	1.57	0.22	9322

Note: Mean measured bulk density was not shown for savanna, wetlands and sparse vegetation because of limited sample size (<100). However, these biomes were also used to calculated regional mean of all biomes.

Comment #10: Table 1. The BD of cropland appear to be similar to those of savanna and grassland. How it can be explained? Similarly, concerning the SOC stock how it can be explained that cropland have similar values of tropical forests?

Response: Thanks. Table 1 shows global means of soil property across biomes, while bulk density shows significant spatial variations within savanna and grasslands (Fig. R4a) as well as croplands (Fig. R4b). Generally, bulk density ranged from ~1.0 to ~1.7 g·cm^{-3} in savanna and grasslands (Fig. R4a), and it ranged from ~1.1 to ~1.7 g·cm^{-3} in croplands (Fig. R4b). Considering the large spatial variation in soil properties and limited overlap in spatial distribution, it is difficult to attribute reasons to the difference of global means between croplands and other biomes. This is the same for the comparison of global mean SOCD between croplands and tropical forests (Fig. R5). SOCD in tropical forests generally ranged from 3 to 10 kg·m^{-2}, while it ranged from 2 to 12 kg·m^{-2} in croplands. When comparing values at a same region (e.g., southeast Asia), SOCD is obviously lower in croplands than in tropical forests (compare Fig. 5a and Fig. 5b). This difference has been also evidenced by meta-analysis based on field observations (Don et al., 2011).

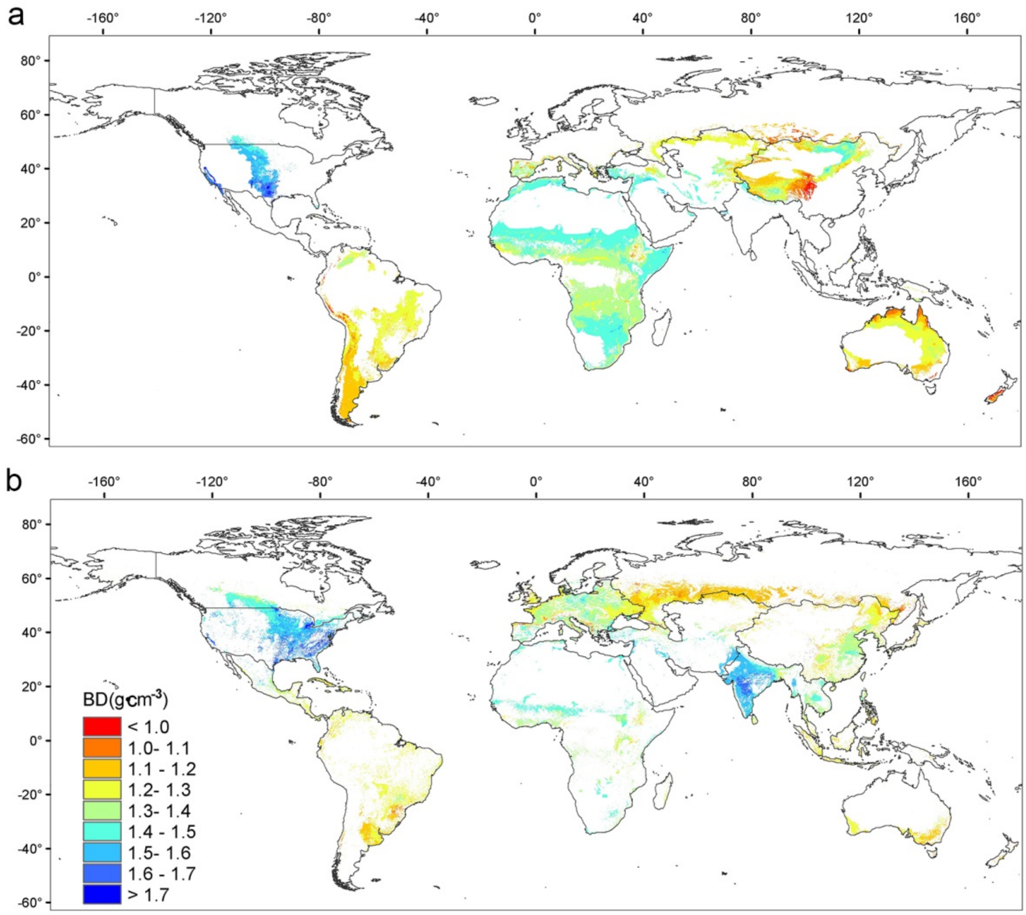

Figure. R4. Spatial variations of bulk density in (a) savanna and grassland, and (b) croplands.

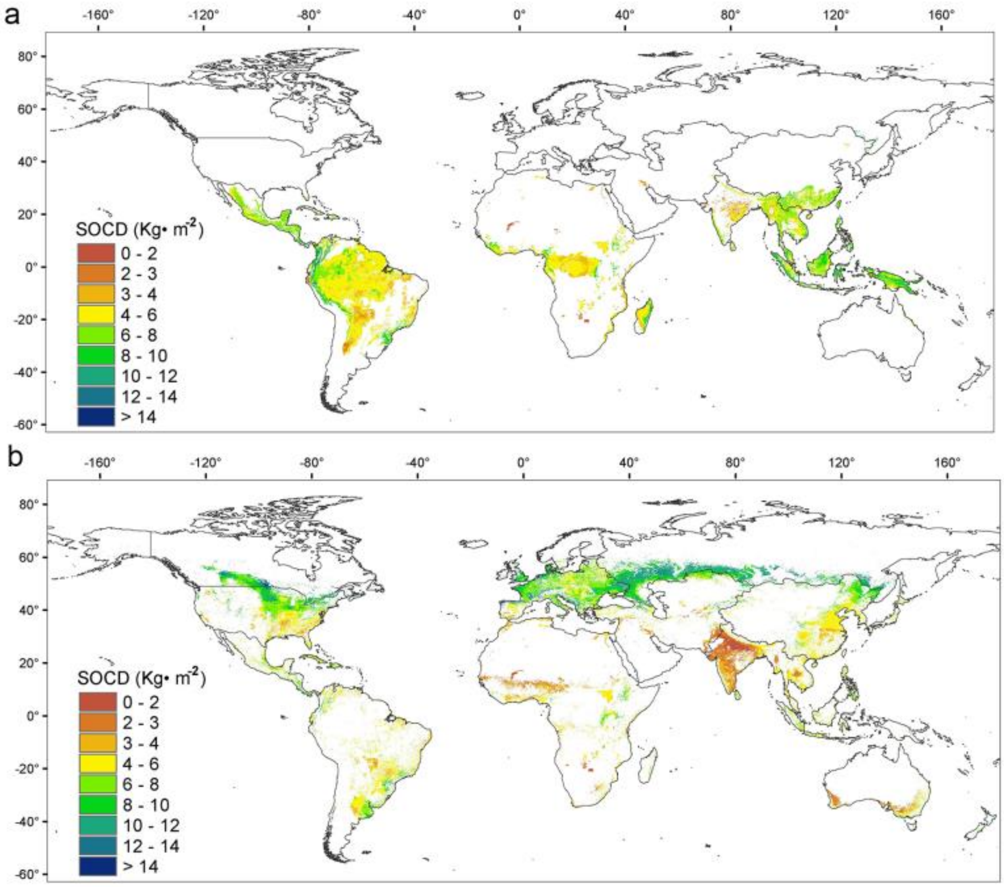

Figure. R5. Spatial variations of SOCD in (a) tropical forests, and (b) croplands.

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