Global convergence in correlations among soil properties

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Abstract: The correlations among major soil properties at a global scale are essential for explaining the global convergence of ecological processes in terrestrial ecosystems but have never been assessed. In this study, a global soil database was analyzed to determine whether correlations among soil properties were consistent and how such correlations varied among continents and land use types. Across the entire dataset, the electrical conductivity of soils increased significantly with increasing pH; additionally, the total nitrogen and cation exchange capacity increased significantly with increasing organic carbon content, while the organic carbon content and cation exchange capacity decreased significantly with increasing sand content in soil. The correlations between paired soil properties were consistent among continents and land use types. The slopes of the relationships, however, varied significantly by continent and land use type. The results indicated a global convergence of correlations among soil properties and variation in the slopes of specific relationships between paired soil properties among continents and land use types. Such consistent global correlations and different slopes of specific correlations can have important implications in explaining the global patterns of biogeochemical processes and can provide some basis for linking soil resources with ecological processes on a global scale.

Keywords: continent, land use, organic carbon, electricity, pH, CEC
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1 Introduction

The distribution of soil resources and their availability to soil biota and plants determine the evolution and functioning of terrestrial ecosystems at different spatial scales and ecosystem levels[1,2]. For example, soil biota and microbial processes depend on the availability and stoichiometry (C:N:P) of soil nutrients[3,4]. The decomposition of soil organic material and the emission of greenhouse gases driven by microbial processes are often affected by the soil environment and the availability of nutrients[5,6]. Foliar and root traits[7,8], plant stoichiometry[9-11], plant functions[12] and the response of plants to environmental changes are often correlated with soil resources[13-15]. Thus, a precise prediction of the availability of soil resources could help us understand some important ecological processes in terrestrial ecosystems.

The correlations among soil properties can predicate the availability of soil resources, and most of these correlations have been assessed. For example, the scaling of soil organic carbon (OC) to nitrogen (N) (C:N ratio) can effectively indicate the mineralization of soil OC and N and, thus, their availabilities to soil microbes and plants in different ecosystems[16,17]. The C:N ratios are generally higher in forest soil than in cultivated soil[18]. The cation exchange capacity (CEC) of soil can describe the availability of nutrients for plant growth, and soil OC is often used to predicate soil CEC due to the high dependence of soil CEC on soil OC[19,20]. Although the relationships between soil properties have been reported at the slope[21], site[22] and regional scales[23], studies are relatively limited at the global scale. Furthermore, whether and how these relationships depend on different continents and land uses remain less studied, hindering a precise understanding of the availability of soil resources and ecological processes.

Global convergences have been observed for many plant traits and ecological processes. For example, Reich et al.[12] found a global convergence in the functioning of plants across biomes. Xu et al.[24] established convergence in the relationship of exchanges of CO_2 and N_2O between the soil and atmosphere within terrestrial ecosystems. Mahecha et al.[25] reported a global convergence in the temperature sensitivity of respiration at the ecosystem level. Therefore, a global convergence in the correlations was hypothesized to exist among major soil properties, because the traits and functioning of plants, emissions of CO_2 and N_2O from the soil and ecosystem respiration are closely related to soil resources.

To test the hypothesis, the correlations among major soil properties were examined, including OC, total N (TN) and sand content, pH, electrical conductivity (ECE) and CEC at a global scale by analyzing a global soil dataset. The effects of continent and land use type on these correlations were also tested. The objective of this study was to determine whether the correlations among soil properties were convergent and whether such correlations varied among continents and land use types.

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2 Materials and methods

2.1 Description of the dataset

The dataset analyzed in this study was derived from a global soil database (ISRIC-WISE-Global Soil Profile Data (ver. 3.1)) (Figure 1)[26]. This database contains 10253 soil profiles from 149 countries. Only 10 profiles were sampled from Antarctica; thus, this continent was excluded from the dataset. Soil depth varied with soil profile in the database; therefore, we used averaged values of soil properties in the upper 35 cm. The soils in this layer are important for most biogeochemical processes and plant growth. It excluded an additional 355 profiles in which the top sampling depths were deeper than 35 cm. In total, 9888 profiles in the dataset were used in this study. Of these, 3822 provided accurate descriptions of land use.

These soil profiles were classified into four land use types: cultivated land, forest, grassland and preserved land. Soil OC, TN and sand content, pH, ECE and CEC were selected as the major properties for the current analysis because these variables can indicate the physicochemical properties and fertility of soils. The soil OC content and CEC are assumed to depend on the clay content[19,20], but the analysis showed that they depended more on the sand content; as a result, sand content rather than clay content was chosen in this study. The global distributions of the profiles are shown in Figure 1. The basic conditions of the dataset used in this study are shown in Table 1.

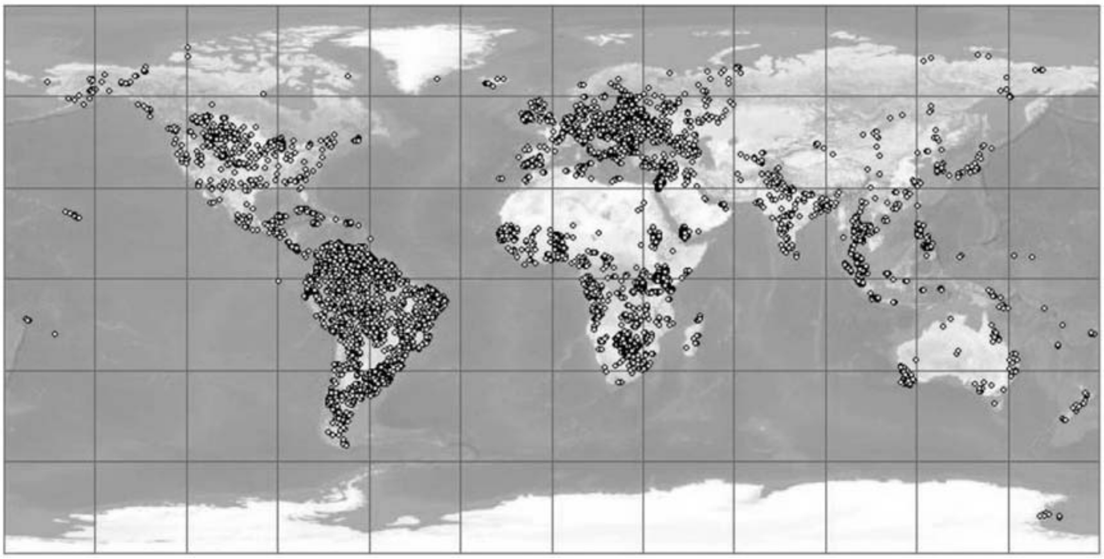


Figure 1 Global distribution of geo-referenced soil profiles in WISE3[26]

Table 1 Basic conditions of the dataset

	Total profile numbers	Number of paired soil properties				
		OC-TN	OC-CEC	pH-ECE	SAND-OC	SAND-CEC
Across the whole dataset						
	9888	6724	9030	7145	9212	8943
Within continents						
AF	4063	2535	3719	3012	3736	3721
AS	1795	1014	1644	1248	1738	1663
AU	208	159	176	184	177	180
EU	1231	977	1070	721	1127	1020
NA	834	599	737	519	765	714
SA	1757	1440	1684	1461	1669	1645
Within land use types						
C	1780	1191	1648	1296	1708	1642
F	342	257	312	295	319	304
G	1135	554	1044	881	1030	1050
PN	565	460	536	469	542	523

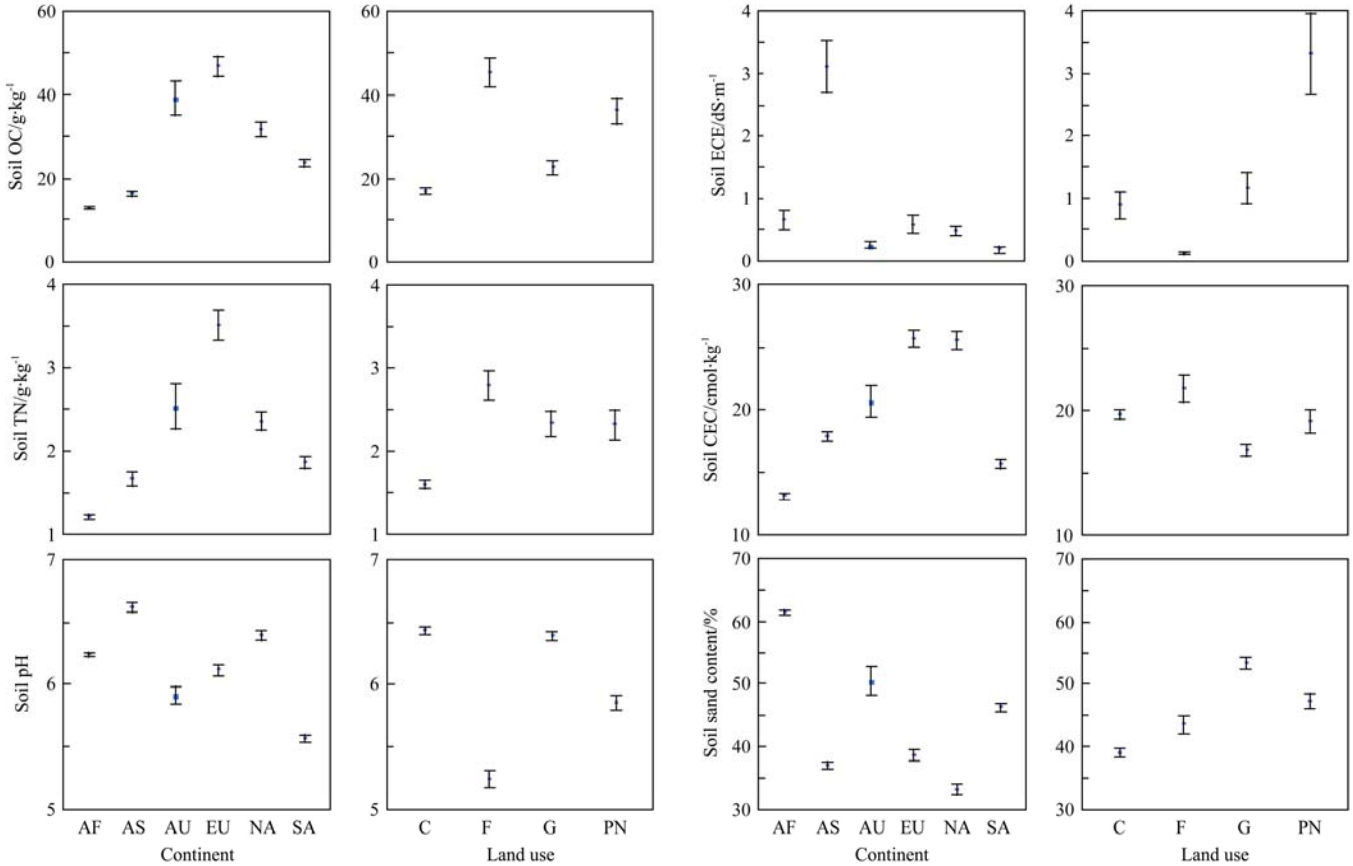
Note: OC: organic carbon; TN: total nitrogen; SAND: sand content; CEC: cation exchange capacity; ECE: electrical conductivity; AF: Africa; AS: Asia; AU: Oceania; EU: Europe; NA: North America; SA: South America; C: cultivated land; F: forest; G: grassland; PN: preserved land.

2.2 Statistical analysis

A two-way analysis of variance was used to test the variations in soil properties among continents and land use types. A simple regression analysis was conducted to establish the correlation of soil OC content and CEC with soil sand content, of soil TN content and CEC with soil OC content and of soil ECE with soil pH. These correlations were tested both among and within continents and land use types. The slopes of these correlations among continents and land use types were examined using SMATR version 2. The variance and regression analyses were conducted using SAS 9.0.

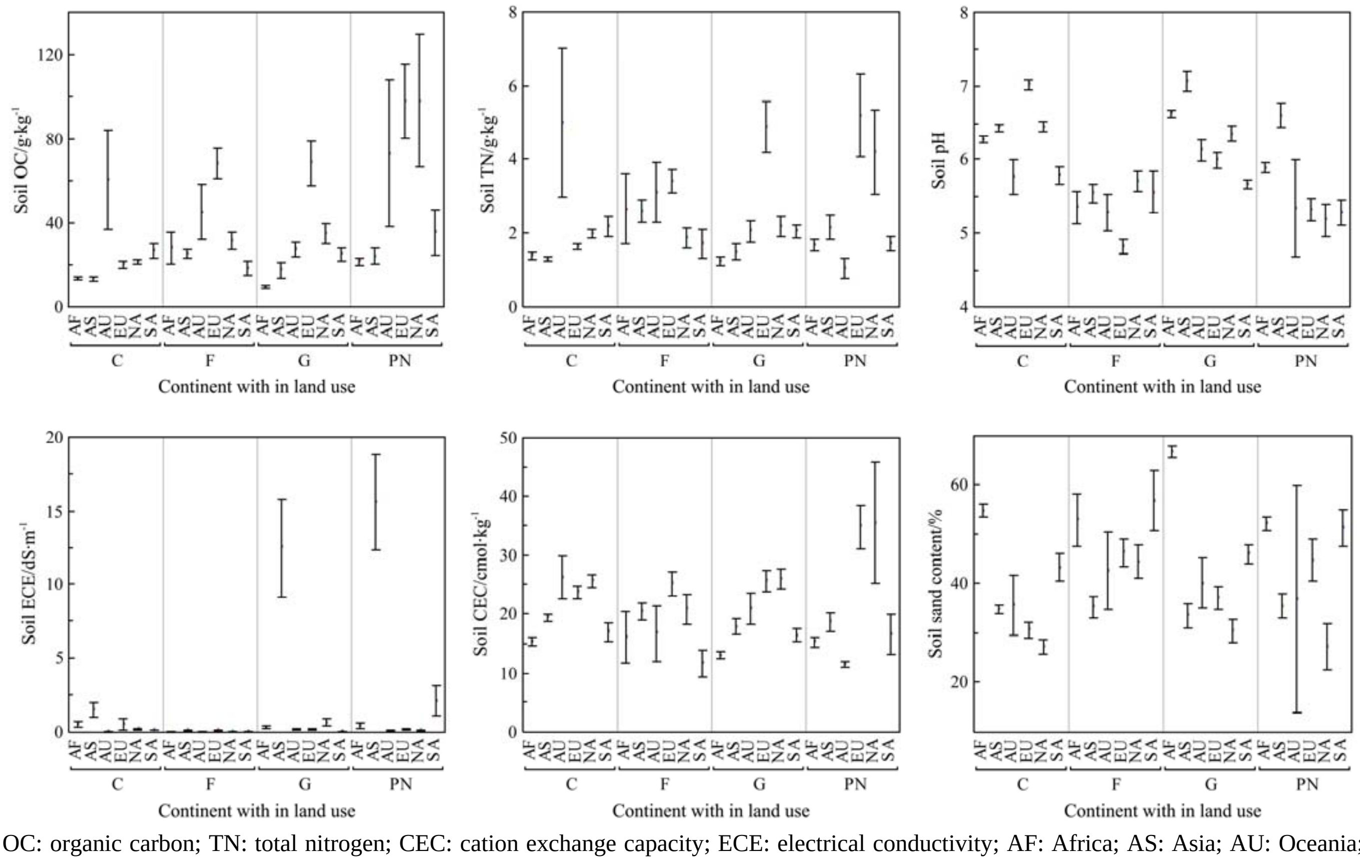
3 Results

The global analysis indicated that soil properties varied significantly among continents and land use types (Figure 2). Within continents, soils from Europe (EU), Oceania (AU) and North America (NA) had higher OC and TN contents and CECs (p<0.01), while soils from NA and Asia (AS) had higher pH values (p<0.01). Soils from Africa (AF) and AU had higher sand contents (p<0.01), while the soils from AS had higher ECEs (p<0.01). Within land use types, the soil OC and TN contents were higher in forests but lower in cultivated land. Conversely, soil pH was higher in cultivated land but lower in forests. Forests, cultivated land and grassland had higher soil CECs than did preserved land. Unlike the observation that pH and soil OC, TN and sand content in forests were similar to those of preserved land, ECE was significantly higher in forests and significantly lower in preserved land. Additionally, the variations in soil properties among land use types depended on the continent (Figure 3). For example, higher OC and TN contents were observed in cultivated soils from AU but in forest and grassland soils from EU. Higher pH values were observed in cultivated soils from EU, in forests from NA and in grassland from AS. These results suggest that differences among continents and land use types play important roles in influencing the global patterns of soil properties.



OC: organic carbon; TN: total nitrogen; CEC: cation exchange capacity; ECE: electrical conductivity. AF: Africa; AS: Asia; AU: Oceania; EU: Europe; NA: North America; SA: South America; C: cultivated land; F: forest; G: grassland; PN: preserved land.

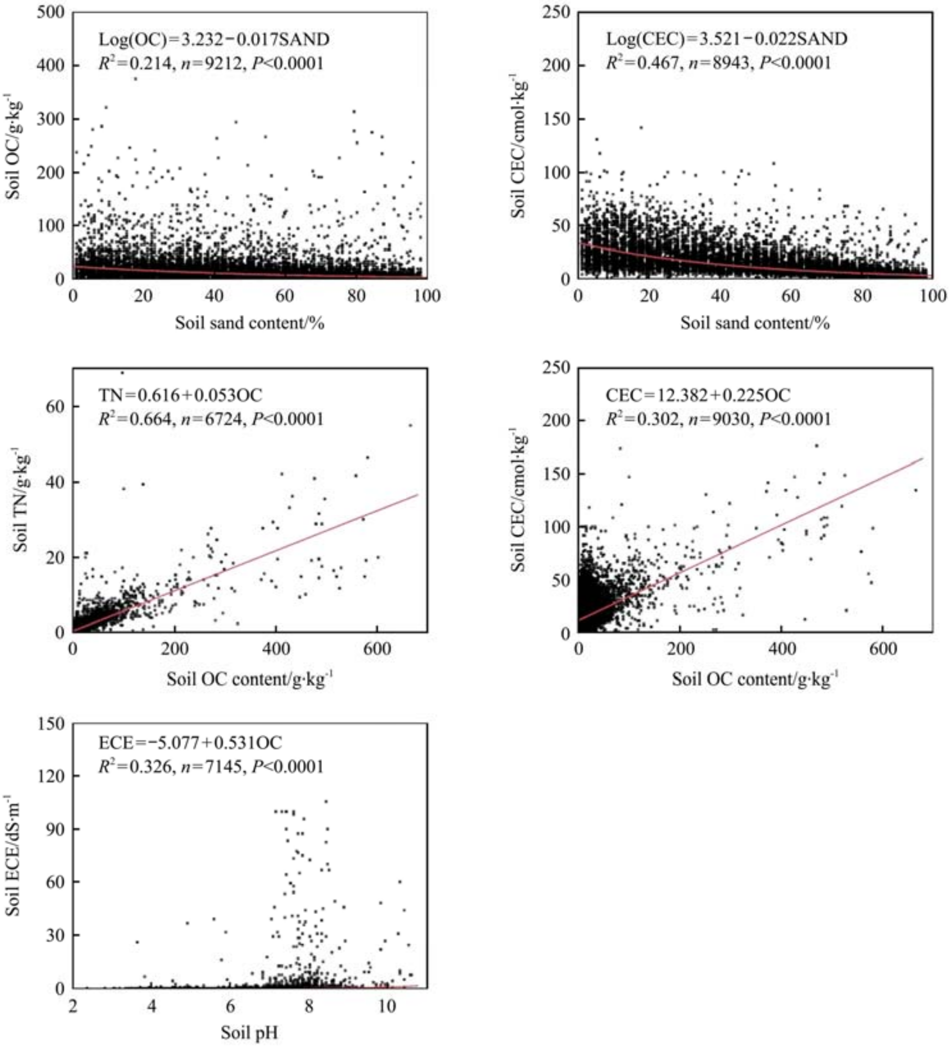
Figure 2 Variations in soil properties with continents and land use types



OC: organic carbon; TN: total nitrogen; CEC: cation exchange capacity; ECE: electrical conductivity; AF: Africa; AS: Asia; AU: Oceania; EU: Europe; NA: North America; SA: South America; C: cultivated land; F: forest; G: grassland; PN: preserved land.

Figure 3 Effects of continents on soil properties within land use types

Soil properties were significantly correlated among the continents and land use types (Figure 4). ECE increased significantly with increasing pH; TN content and CEC increased significantly with increasing OC content; OC content and CEC decreased significantly with increasing sand content. The correlations between paired soil properties were consistent among continents and land use types (Tables 2 and 3), indicating global convergences in the correlations. These global convergences suggest that, at the global scale, ECE was mainly determined by pH, CEC was influenced by both OC and sand content, and TN content was determined by OC content, which in turn depended on sand content.



OC: organic carbon; CEC: soil cation exchange capacity; TN: total nitrogen; ECE: soil electrical conductivity.

Figure 4 Correlations among soil properties across continents and land use types

Even though consistent relationships between paired soil properties occurred in all continents and land use types, the slopes of specific relationships varied significantly with the continent (Table 2) and land use type (Table 3). Within continents, significantly higher regression slopes of the relationships of OC content and CEC to sand content were observed in EU, lower slopes were observed for these two relationships in AF, and the slopes for the other continents (–0.011 to –0.016 and –0.019 to –0.021, respectively) were similar to the slopes observed on the global scale (–0.017 and –0.022, respectively), suggesting that OC content and CEC were highly dependent on sand content in EU but less dependent in AF. The TN content and CEC depended strongly on the OC content in AF and SA, while the ECE depended strongly on the pH in NA and AS.

Higher regression slopes were found for the relationships of OC content and CEC to sand content were observed in forests, while lower slopes for these two correlations were observed in grassland. ECE depended strongly on pH in preserved land but weakly in forests. The TN content and CEC depended more strongly on OC content in cultivated land than in forest and grassland.

The sampling profiles in South America (SA), AF and AS accounted for 77% of the total global dataset; thus, the correlations among soil properties within land use types for these three continents were examined further. The correlations within land use types varied significantly with the continent (Table 4). Most relationships of OC content and CEC to sand content had higher regression slopes in AS but lower slopes in AF for the four land use types. The regression slope of the relationship of the TN content to OC content was higher in AF than in AS for cultivated land and forest but higher in AS than in AF for grassland. The dependence of the CEC on the OC content was higher in SA for cultivated land, forest and preserved land and was higher in AF for grassland. These results suggest nonconvergence in the regression slope of the relationship between paired soil properties within continents and land use types, indicating variation in the dependence of certain soil properties on other properties within continents and land use types.

Table 2 Correlations among soil properties within continents

Continent	Intercept		Slope		R^2	*n*	*p*
	Estimate	Std Err	Estimate	Std Err			
Log(OC) = *a* + *b* × SAND							
Africa	3.36	0.03	–0.022 c	0.001	0.32	3736	<0.001
Asia	2.70	0.04	–0.011 b	0.001	0.08	1738	<0.001
Oceania	3.84	0.11	–0.014 b	0.002	0.22	177	<0.001
Europe	3.18	0.05	–0.002 a	0.001	0.01	1127	0.010
North America	3.33	0.05	–0.012 b	0.001	0.12	765	<0.001
South America	3.36	0.04	–0.016 bc	0.001	0.21	1669	<0.001
Log(CEC) = *a* + *b* × SAND							
Africa	3.84	0.03	–0.027 c	0.000	0.57	3721	<0.001
Asia	3.33	0.03	–0.021 b	0.001	0.38	1663	<0.001
Oceania	3.67	0.10	–0.021 b	0.002	0.43	180	<0.001
Europe	3.40	0.04	–0.012 a	0.001	0.21	1020	<0.001
North America	3.58	0.04	–0.019 b	0.001	0.35	714	<0.001
South America	3.28	0.04	–0.020 b	0.001	0.35	1645	<0.001
Log(ECE) = *a* – *b* × pH							
Africa	–5.29	0.10	0.533 b	0.015	0.34	2350	<0.001
Asia	–5.12	0.22	0.582 b	0.031	0.25	1040	<0.001
Oceania	–3.34	0.60	0.202 d	0.099	0.03	151	0.043
Europe	–4.44	0.15	0.450 c	0.026	0.29	702	<0.001
North America	–5.73	0.24	0.650 a	0.037	0.41	449	<0.001
South America	–3.51	0.10	0.240 d	0.018	0.15	1018	<0.001
TN = *a* + *b* × *OC*							
Africa	0.29	0.03	0.063 a	0.001	0.59	2535	<0.001
Asia	0.77	0.08	0.050 b	0.003	0.29	1014	<0.001
Oceania	0.68	0.18	0.048 b	0.002	0.71	159	<0.001
Europe	0.95	0.10	0.051 b	0.001	0.74	977	<0.001
North America	0.95	0.07	0.043 c	0.001	0.72	599	<0.001
South America	0.42	0.05	0.068 a	0.001	0.71	1440	<0.001
CEC = *a* + *b* × OC							
Africa	9.21	0.26	0.309 a	0.012	0.16	3719	<0.001
Asia	14.41	0.42	0.208 c	0.015	0.11	1644	<0.001
Oceania	14.42	1.45	0.191 c	0.025	0.25	176	<0.001
Europe	18.08	0.57	0.171 c	0.006	0.42	1070	<0.001
North America	17.77	0.68	0.245 bc	0.011	0.40	737	<0.001
South America	9.49	0.32	0.265 b	0.007	0.44	1684	<0.001

Note: OC: organic carbon; TN: total nitrogen; SAND: sand content; CEC: cation exchange capacity; ECE: electrical conductivity. Slopes with different lower case letters within the same relationship were significant at $p<0.01$.

Table 3 Correlations among soil properties within land use types

Land use	Intercept		Slope		R^2	*n*	*p*
	Estimate	Std Err	Estimate	Std Err			
Log(OC) = *a* + *b* × SAND							
Cultivated land	2.93	0.03	–0.013 b	0.001	0.18	1708	<0.001
Forest	3.47	0.11	–0.006 a	0.002	0.03	319	0.007
Grassland	3.64	0.05	–0.026 c	0.001	0.45	1030	<0.001
Preserved land	3.29	0.09	–0.013 b	0.002	0.10	532	<0.001
Log(CEC) = *a* + *b* × SAND							
Cultivated land	3.52	0.03	–0.023 b	0.001	0.49	1642	<0.001
Forest	3.29	0.09	–0.014 a	0.002	0.16	304	<0.001
Grassland	3.72	0.04	–0.025 b	0.001	0.61	1050	<0.001
Preserved land	3.44	0.06	–0.021 b	0.001	0.40	515	<0.001
Log(ECE) = *a* – *b* × pH							
Cultivated land	–5.34	0.16	0.570 b	0.024	0.35	1043	<0.001
Forest	–3.22	0.16	0.208 c	0.031	0.16	241	<0.001
Grassland	–5.55	0.19	0.591 b	0.030	0.32	792	<0.001
Preserved land	–6.81	0.34	0.911 a	0.055	0.47	311	<0.001
TN = *a* + *b* × OC							
Cultivated land	0.58	0.03	0.055 a	0.001	0.71	1191	<0.001
Forest	1.01	0.11	0.038 b	0.001	0.72	257	<0.001
Grassland	0.67	0.07	0.052 a	0.001	0.84	554	<0.001
Preserved land	0.61	0.10	0.045 b	0.001	0.76	450	<0.001
CEC = *a* + *b* × OC							
Cultivated land	14.40	0.47	0.315 a	0.018	0.16	1648	<0.001
Forest	11.75	1.01	0.234 b	0.014	0.47	312	<0.001
Grassland	12.88	0.49	0.199 c	0.009	0.30	1044	<0.001
Preserved land	11.38	0.70	0.211 bc	0.008	0.55	528	<0.001

Note: OC: organic carbon; TN: total nitrogen; SAND: sand content; CEC: cation exchange capacity; ECE: electrical conductivity. Slopes with different lower case letters within the same relationship were significant at $p<0.01$.

Table 4 Correlations among soil properties within continents and land use types

Land use	Continent	Intercept		Slope		R^2	*n*	*p*
		Estimate	Std Err	Estimate	Std Err			
Log(OC) = *a* + *b* × SAND								
Cultivated land	Africa	3.25	0.08	–0.019 b	0.001	0.31	441	<0.001
Cultivated land	Asia	2.57	0.05	–0.010 a	0.001	0.11	718	<0.001
Cultivated land	South America	3.72	0.17	–0.020 b	0.003	0.29	84	<0.001
Forest	Africa	5.08	0.43	–0.041 d	0.008	0.70	15	0.001
Forest	Asia	3.32	0.18	–0.012 a	0.004	0.08	94	0.006
Forest	South America	3.51	0.48	–0.016 ab	0.008	0.20	17	0.074
Grassland	Africa	3.53	0.08	–0.028 c	0.001	0.54	532	<0.001
Grassland	Asia	2.65	0.19	–0.008 a	0.005	0.04	75	0.094
Grassland	South America	3.55	0.11	–0.017 ab	0.002	0.30	181	<0.001
Preserved land	Africa	3.24	0.11	–0.014 ab	0.002	0.14	309	<0.001
Preserved land	Asia	2.93	0.24	–0.013 a	0.006	0.058	91	<0.001
Preserved land	South America	3.81	0.27	–0.021 b	0.005	0.30	51	<0.001

Land use	Continent	Intercept		Slope		R^2	*n*	*p*
		Estimate	Std Err	Estimate	Std Err			
Log(CEC) = *a* + *b* × SAND								
Cultivated land	Africa	3.67	0.07	–0.024 b	0.001	0.52	438	<0.001
Cultivated land	Asia	3.46	0.04	–0.026 b	0.001	0.51	683	<0.001
Cultivated land	South America	3.52	0.16	–0.026 b	0.003	0.46	82	<0.001
Forest	Africa	4.37	0.52	–0.040 c	0.009	0.59	14	0.001
Forest	Asia	3.05	0.17	–0.010 a	0.004	0.05	95	0.025
Forest	South America	4.29	0.35	–0.041 c	0.006	0.77	17	<0.001
Grassland	Africa	4.21	0.06	–0.032 bc	0.001	0.76	555	<0.001
Grassland	Asia	3.23	0.14	–0.017 ab	0.003	0.25	81	<0.001
Grassland	South America	3.49	0.10	–0.024 b	0.002	0.46	179	<0.001
Preserved land	Africa	3.64	0.08	–0.026 b	0.001	0.55	298	<0.001
Preserved land	Asia	3.18	0.13	–0.015 ab	0.003	0.22	92	<0.001
Preserved land	South America	3.46	0.23	–0.025 b	0.004	0.45	49	<0.001
Log(ECE) = *a* – *b* × pH								
Cultivated land	Africa	–5.48	0.30	0.563 bc	0.046	0.35	285	<0.001
Cultivated land	Asia	–5.16	0.28	0.574 bc	0.039	0.34	427	<0.001
Cultivated land	South America	–3.86	0.45	0.330 c	0.074	0.23	68	<0.001
Forest	Africa			Not significant			6	
Forest	Asia	–4.97	0.35	0.539 bc	0.059	0.60	58	<0.001
Forest	South America			Not significant			13	
Grassland	Africa	–4.76	0.22	0.424 c	0.032	0.30	400	<0.001
Grassland	Asia	–7.54	1.72	1.077 a	0.229	0.29	57	<0.001
Grassland	South America	–4.46	0.28	0.398 c	0.049	0.31	148	<0.001
Preserved land	Africa	–6.11	0.38	0.707 b	0.060	0.49	152	<0.001
Preserved land	Asia	–7.78	1.08	1.173 a	0.153	0.46	71	<0.001
Preserved land	South America	–7.27	1.01	1.079 a	0.173	0.58	30	<0.001
TN = *a* + *b* × OC								
Cultivated land	Africa	0.11	0.05	0.077 b	0.002	0.85	254	<0.001
Cultivated land	Asia	0.82	0.05	0.033 e	0.001	0.53	465	<0.001
Cultivated land	South America	0.47	0.22	0.062 c	0.005	0.65	78	<0.001
Forest	Africa	–0.34	0.43	0.095 a	0.010	0.91	12	<0.001
Forest	Asia	0.00	0.17	0.085 ab	0.005	0.81	73	<0.001
Forest	South America	–0.19	0.12	0.097 a	0.005	0.97	16	<0.001
Grassland	Africa	0.53	0.07	0.040 d	0.002	0.76	148	<0.001
Grassland	Asia	0.10	0.13	0.089 a	0.006	0.84	43	<0.001
Grassland	South America	0.75	0.08	0.050 d	0.002	0.84	167	<0.001
Preserved land	Africa	0.26	0.08	0.061 c	0.002	0.82	260	<0.001
Preserved land	Asia	0.19	0.11	0.064 c	0.002	0.93	66	<0.001
Preserved land	South America	0.41	0.19	0.068 bc	0.008	0.64	45	<0.001
CEC = *a* + *b* × OC								
Cultivated land	Africa	11.99	0.93	0.240 bc	0.042	0.07	424	<0.001
Cultivated land	Asia	16.20	0.78	0.236 c	0.035	0.06	683	<0.001
Cultivated land	South America	7.37	1.22	0.360 ab	0.029	0.63	92	<0.001
Forest	Africa	1.61	2.50	0.488 a	0.060	0.85	14	<0.001
Forest	Asia	12.94	2.25	0.306 b	0.070	0.17	96	<0.001
Forest	South America	3.20	2.37	0.499 a	0.101	0.62	17	<0.001
Grassland	Africa	9.86	0.69	0.371 ab	0.032	0.20	543	<0.001
Grassland	Asia	13.84	1.23	0.208	0.033	0.35	73	<0.001
Grassland	South America	8.47	0.80	0.316 b	0.017	0.65	184	<0.001
Preserved land	Africa	10.83	0.89	0.206 c	0.022	0.22	303	<0.001
Preserved land	Asia	13.60	1.73	0.193 c	0.040	0.21	89	<0.001
Preserved land	South America	6.59	1.56	0.272 bc	0.018	0.82	51	<0.001

Note: OC: organic carbon; TN: total nitrogen; SAND: sand content; CEC: cation exchange capacity; ECE: electrical conductivity. Slopes with different lower case letters within same relationship were significantly at p<0.01.

4 Discussions

As expected, the global analysis found similar correlations between paired soil properties in all continents and land use types, demonstrating global convergences in correlations among soil properties. The correlations among soil sand, OC and TN contents and CEC have been well established on relatively small scales[16,17,19,20]. Correlations between pH and ECE, however, are variable but have been less commonly reported in the literature. For example, Johnson et al.[27] and Corwin et al.[28] observed positive correlations between pH and ECE in the pasture, forest and cultivated soils, while Shi et al.[29] and Akahane et al.[30] suggested a negative correlation in cultivated soils. A consistent positive correlation was found among six continents and four land use types, suggesting a fundamental positive scaling of pH to ECE. A possible explanation for this positive correlation might be the high salinities (and thus high ECEs) found in soils with high pH.

The analysis suggests a global generality of relationships among soil properties. This global convergence is mainly due to the concurrence of soil properties regardless of location or land use type. High sand content often leads to high soil permeability and mineralization rates of soil organic matter[31,32], low stability of soil aggregates[33] and fewer cation-exchange sites on soil particles [32], which decrease the OC and CEC. Most N in soils is found in organic matter, explaining the significant positive correlation between the OC and N contents in various ecosystems[34]. More organic matter in the soil (thus a higher OC content) provides more surface area and exchange sites for cations in soil particles, resulting in higher CECs [35].

Although the analysis found universal specific correlations between paired soil properties among continents and land use types, the regression slopes of the specific correlations varied significantly with the continent and land use type. These variations may be due to the significant differences in soil properties within continents and land use types. On a global scale, the OC and N contents were significantly higher in soils from temperate regions than in soils from tropical regions[36]. Thus, the OC and TN contents were thus higher in EU, AU and NA than in AS, AF and SA (p<0.05). Land in AF and AU was highly desertified relative to other continents[37]. The sand contents were therefore higher in the soils from AF and AU. As predicted by the correlations that CEC significantly increased with increasing OC and decreasing sand content, the CEC values were larger in NA and EU than in AF and SA. Soil pH is largely controlled by precipitation because high rainfall leaches the base/primary nutrients and cations from the soil and thereby decreases pH. Under these global patterns of soil properties among continents, the higher sand and lower OC contents and lower CEC values in AF soils corresponded to the lower dependence of OC content and CEC on sand content (lower regression slopes of the relationships between sand content and OC content and between sand content and CEC), while the lower sand content and higher OC content and CEC in EU soils resulted in the higher dependence of OC content and CEC on sand content (higher regression slopes). The significantly lower OC content in AF resulted in the higher scaling of OC to TN and CEC, while the higher OC content in EU resulted in lower scaling. ECE was significantly higher in AS than in other continents, resulting in a significantly higher regression slope for the relationship of ECE to pH.

Within types of land use, the OC and N accumulated in soils of forests and preserved land but were lost in cultivated soil[38,39], resulting in higher OC and TN contents in forests and preserved land but lower contents in cultivated land. The accumulation of organic matter in soil often decreases soil pH[40]. The analysis of the global dataset showed significant decreases in pH with increasing OC content (Figure 5). Thus, the soil pH in forests and preserved land is significantly lower than that in other types of land use. The soil of cultivated land was globally well developed compared to the soil of undisturbed land, and the sand content was significantly lower. The lower sand content in cultivated soil and higher OC content in forest soil led to significantly higher CECs in cultivated land and forests. Based on the global pattern of soil properties with land use types, the lower sand and higher OC contents and the higher CECs in forest soil led to the relatively higher dependence of soil OC content and CEC on sand content. The accumulation of OC is generally greater than the accumulation of N in forest soil[38,41], explaining the relatively lower dependence of TN content on OC content. The lower OC content and higher CEC in cultivated soil led to the highest regression slope for the relationship of CEC to OC content. Similarly, the higher ECE and lower pH in the soil of preserved land led to the highest slope for the relationship of ECE to pH. Taken together, the convergence in the correlation between paired soil properties among continents and land use types, and the different regression slope for specific correlations within continents and land use types, demonstrate a global dependence of OC content and CEC on sand content, of TN content and CEC on OC content and of ECE on pH.

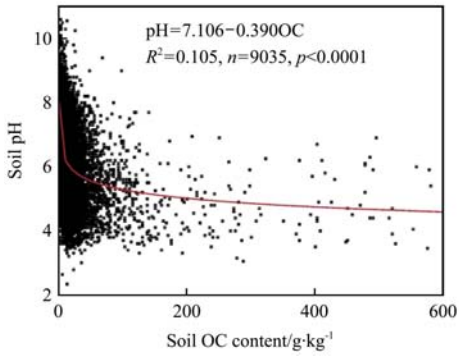


Figure 5 Correlation between soil OC and soil pH across continents and land use types. Soil pH decreased significantly with soil OC content

Sand, OC and TN contents, pH, CEC and ECE directly affect the availability of soil water and nutrients to plants and soil microbes[42,43] and the tolerance of plants and soil microbes to soil contamination and degradation[44,45]. Thus, these properties affect the responses of plant growth, functional traits and biogeochemical processes to the availability of soil resources and to changes in soil quality. The evidence presented in this study for the global convergence of correlations among soil properties imply a general scaling of soil resources to some ecosystem traits, such as plant function and biogeochemical cycles. The consistent dependence of TN content on OC content indicates a global convergence in the availability of soil N to plants, which supports the global convergences in foliar N content and foliar traits[8,9] and thus in plant function[12]. The consistent correlations between sand and OC contents and between OC and TN contents indicate a convergence in the availability of soil OC, which partly contributes to the global convergence in the temperature sensitivity of ecosystem respiration[25]. The universal correlation between OC and TN contents may be related to the convergence in the correlation between the emissions of soil CO_2 and N_2O observed by

Xu et al.[24]. Additionally, the convergence in the dependence of ECE on pH has implications for agricultural production. ECE is a useful index for estimating crop yield[46,47]. An increase in ECE will decrease crop yield[46]. The application of fertilizer, though, often decreases soil pH[48], which would decrease ECE according to the correlation that ECE increases with pH. The effects of fertilization on crop yield would thus be higher than expected on a global scale.

The current results demonstrate that the dependence of certain soil properties on other properties varied significantly among continents and land use types, which can partly explain the variations in ecosystem traits and biogeochemical properties within continents and land use types. The higher scaling of OC to TN contents in AF and SA, but the lower scaling in NA, indicates a higher availability of soil N in AF and SA but a lower availability in NA. Therefore, it is predicted that foliar N should be higher in AS and SA than in NA because foliar N is positively correlated with the availability of soil N and with the N:C ratio[8,9,49]. This prediction is supported by the global patterns of foliar litter N in woody plants[50]. Kang et al.[50] reported higher foliar litter N in woody plants in AF and SA but lower foliar litter N in AS, which is consistent with the observation that the scaling of OC to N contents in forest soil was higher in AF and SA than in AS. The higher scaling of OC to TN contents (lower C:N ratio) in AF and SA can also lead to the rapid turnover of soil OC and thus to the loss of soil OC because the lower C:N ratio accelerates the mineralization of soil organic matter[51]. It is therefore predicted that a higher level of soil respiration in AF and SA than in the other continents, which is consistent with the previous estimate that AF and SA had higher levels of total and heterotrophic soil respiration but lower Q_{10} values than other continents[52].

The global analysis of this study showed that the dependence of soil TN to OC contents (higher C:N ratio) is significantly lower in soils of forests than in soils of cultivated land and grassland, indicating a faster turnover of OC and a higher level of soil respiration in forest soil than in soils of cultivated land and grassland. This result is consistent with the finding that, on a global scale, the turnover time of soil OC and soil respiration are higher in forests than in cultivated land and grassland[53], and the Q_{10} is higher in cultivated land and grassland than in forests[52].

5 Conclusions

In this study, the relationships among major soil properties on a global scale were examined, as well as the variation of these relationships with different continents and land uses. Consistent positive relationships were found between OC and TN, between OC and CEC, and between pH and ECE, and negative relationships were found between sand and OC and between sand and CEC. However, the slope of these relationships differed between continents and land uses. Therefore, it is concluded that there was global convergence in the correlations among soil properties and the variations in the regression slopes of the relationships among continents and land use types. These results can have important implications for explaining the global patterns of biogeochemical processes and can provide some basis for linking soil resources and ecological processes on a global scale.

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