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Pattern and variation of C:N:P ratios in China's soils: a synthesis of observational data

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Abstract Inspired by previous studies that have indicated consistent or even well-constrained (relatively low variability) relations among carbon (C), nitrogen (N) and phosphorus (P) in soils, we have endeavored to explore general soil C:N:P ratios in China on a national scale, as well as the changing patterns of these ratios with soil depth, developmental stages and climate; we also attempted to determine if well-constrained C:N:P stoichiometrical ratios exist in China's soil. Based on an inventory data set of 2,384 soil profiles, our analysis indicated that the mean C:N, C:P and N:P ratios for the entire soil depth (as deep as 250 cm for some soil profiles) in China were 11.9, 61 and 5.2, respectively, showing a C:N:P ratio of ~60:5:1. C:N ratios showed relatively small variation among different climatic zones, soil orders, soil depth and weathering stages, while C:P and N:P ratios showed a high spatial heterogeneity and large variations in different climatic zones, soil orders, soil depth and weathering stages. No well-constrained C:N:P ratios were found for the entire soil depth in China. However, for the 0–10 cm organic-rich soil, which has the most active organism–environment interaction, we found a well-constrained C:N ratio (14.4, molar ratio) and relatively consistent C:P (136) and N:P (9.3) ratios, with a general C:N:P ratio of 134:9:1. Finally, we suggested that soil C:N, C:P and N:P ratios in organic-rich topsoil could be a good indicator of soil nutrient status during soil development.

Keywords Carbon · Nitrogen · Phosphorus · Stoichiometry · China

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Introduction

All substances on earth are composed of chemical elements, and elemental composition is the most fundamental in biology and ecology (Michaels 2003; Schimel 2003). Thus a cell, an organism, an ecosystem, and even the biosphere can be reduced to its elemental composition in some simple elemental ratios. Although soil is influenced by complex factors such as climate, soil parent materials, topography and development stages, and is often characterized by high biological diversity, structural complexity and spatial heterogeneity (Chadwick et al. 1999; Cleveland and

Liptzin 2007), many previous studies (e.g. Melillo et al. 2003; Vitousek et al. 2002, 2004; Brady and Weil 2002; Post et al. 1982; Walker and Adams 1958) have indicated that soil carbon (C), nitrogen (N) and phosphorus (P) are often closely related. Walker (1956) suggested that C, N, and P are associated in fairly definite proportions in soil organic matter (SOM). Based on the analysis of 22 grassland soil profiles, Walker and Adams (1958) found a constrained correlation among organic C (SOC) and organic P (SOP) in the soil. Through a literature review of 48 published resources, Cleveland and Liptzin (2007) found a well constrained C:N:P ratio in global soil microbial biomass and 0–10 cm organic-rich soil. All these findings reported relatively constrained elemental ratios, or homeostasis, in plants and soil organisms. It is suggested that the feedbacks from living organisms can modify soil nutrient content and result in "Redfield-like" correlations between the elemental ratio of the biota and soil in terrestrial ecosystems (Neff et al. 2000; Sterner and Elser 2002; Cleveland and Liptzin 2007).

Redfield (1958) found that planktonic biomass contains C, N and P in an atomic ratio of 106:16:1, similar to the ratio of C, N and P in marine water. This C:N:P ratio, known as "Redfield Ratio", has stimulated a large number of subsequent studies on the C:N:P stoichiometry of multiple biota in aquatic and terrestrial ecosystems (e.g., Sterner 1995; Elser et al. 1996; Sterner and Elser 2002; Cleveland and Liptzin 2007; McGroddy et al. 2004). Compared to marine ecosystems, terrestrial ecosystems vary greatly due to varied and complex habitats, biota and environmental factors. Furthermore, soil is far more complex than other terrestrial systems. The relative immobility of the soil tends to promote and maintain spatial heterogeneity in nutrient cycles. This heterogeneity is caused by both local-scale disturbances, such as land use change and human interferences, and regional-scale differences in glacial history, climate, geologic parent material, topography, and biotic diversity (Jenny 1941). Nutrients are continuously redistributed in terrestrial ecosystems by a number of ways including plant litterfall, soil water flow and plant-atmosphere exchange, none of which appears within marine environments (McGroddy et al. 2004). Unlike the homogeneous aquatic environment, soil is highly heterogeneous both horizontally and vertically. The soil P supply depends on the total P content and the weathering stage of the parent material, both of which are characterized by spatial heterogeneities. Furthermore, the infiltration and diffusion rate of nutrients in soil is much slower than that in the aquatic ecosystem. As a result, the feedbacks from terrestrial organisms are limited to the top-soil, while the supply of P comes from the parent materials that are located at the bottom of the soil. This mechanism results in a complex and highly variable vertical pattern of total P (TP) content through the soil profile (Brady and Weil 2002). Based on vertical soil analysis to a depth of 53 cm, Walker and Adams (1958) concluded that the total soil P content was related to the P content of parent material, and decreased down through the soil profile at a rate much slower than the rate of C and N. This finding indicates that soil has inconsistent vertical patterns of N:P ratio. Although Cleveland and Liptzin (2007) stated that a remarkably constrained soil C:N:P ratio of 186:13:1 exists on the global scale, their analysis was mainly based on samples from surface soils (0–10 cm mineral soil). The constrained C:N:P ratio in the topsoil found by Cleveland and Liptzin (2007) may not be applicable to the entire depth of soil profiles.

Considering the high spatial heterogeneity of soil nutrients and the dependence of P supply on weathering conditions of parent material, large-scale soil datasets of soil C, N, and P that cover a range of ecosystem types and soil weathering stages are necessary to examine the patterns of elemental ratio in the soil. However, even the most frequently cited global soil database today, the World Inventory of Soil Emission (WISE) database (Batjes 2002), contains less than 900 soil profiles that record soil P content. While several previous studies tried to compile soil observations through published reports, inconsistent soil sampling and measuring approaches, as well as incomplete site descriptions from various literature resources has usually limited the quantity and quality of available data sources.

Since China has various soil types that developed under different bioclimatic conditions and are derived from various parent materials in diversified topographical environments, the study of the relationships among C, N, and P in China's soil is likely to make great contributions to the establishment of a global C, N, and P relationship. Based on soil chemical data from the Second Chinese Soil Survey, which provided C:N:P for over 2,473 typical soil profiles across China that were sampled and measured in standard approaches (Wang et al. 2003; Tian et al. 2006; Zhang et al. 2005; Wu et al. 2003; Yang et al. 2007), our objectives in this study are to: (1) explore the general C:N, C:P and N:P ratios in China's soil at a national scale; and (2) find how these ratios change with climate, soil orders, soil depth and weathering status. Based on these two objectives, we have also tried to verify whether or not well-constrained C:N:P ratios exist in the top and deeper soils.

Materials and methods

Data sources

We examined geo-referenced soil profiles collected in the second Chinese soil survey and developed mean values for various soil groups (National Soil Survey Office 1993, 1994a, b, 1995a, b, 1996). This database includes 2,473 soil profiles, each of which represents a soil type in the Chinese Soil Taxonomy system (Li and Zhao 2001; Wang et al. 2003). Each soil profile is divided into A, B, C and other horizons, according to actual soil conditions. The properties investigated include the thickness of horizons, total soil organic matter (SOM) (determined by the $K_2Cr_2O_7$–H_2SO_4 digestion method), total P content (measured by Perchloric acid digestion followed by the molybdate colorimetric test), total soil N (analyzed with the Kjeldahl procedure), soil bulk density (measured according to the core sampling method), soil available P (The Olsen method (Olsen et al. 1954) was used for available P analysis) and geographic location information. SOC content was calculated as a portion of SOM which has been described by Wang et al. (2003). Of all the 2,473 soil profiles, 2,405 have total P content records, 2,462 have SOM data and 2,445 have total N records, 1,760 have available P records, and 1,535 profiles have geographic location information. We excluded soil profiles that did not have any of the total C, N or P data. The final dataset used in this analysis includes 2,384 soil profiles. We integrated the soil data for the 1,535 profiles for which we had geographical information into a Geographical Information System (GIS) database to show their geographic distribution (Fig. 1).

The Chinese Soil Taxonomy system (National Soil Survey Office 1998) was used in this soil survey. This system has a hierarchical structure, with 12 orders, 61 great groups, 235 sub-great groups, 909 families and more than 2,473 soil types (soil profiles, each with its distribution area in China). Using the transformation

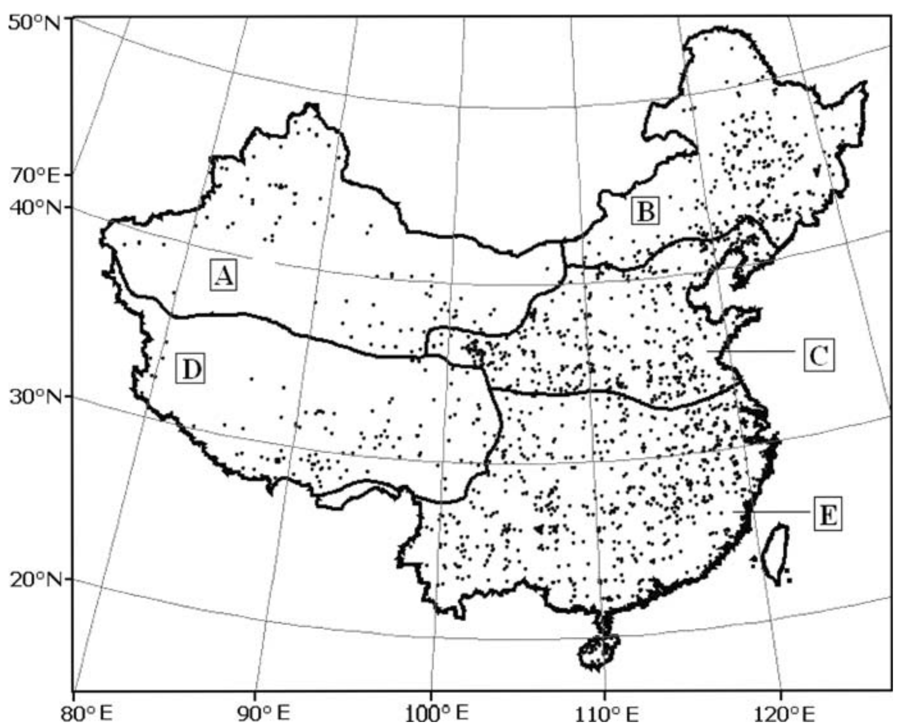

Fig. 1 Distribution of soil sampling points in China. Five zones were defined based on climate differences: **a** temperate desert; **b** cool temperate zone, **c** warm temperate zone, **d** frigid highland, **e** tropical & subtropical zone

procedure of Zhang et al. (2005), we were able to compare these results with the United Nation Food and Agriculture Organization/UNESCO (1988) soil classification system, and also the equivalent USDA soil taxonomy system (Soil Survey Staff 1975).

Calculation of weighted soil C, N and P ratios: The soil total C, N and P concentrations (mg/kg) were transformed to a unit of mmol/kg, and C:N, C:P and N:P ratios for each type soil were calculated as molar ratios (atomic ratio), rather than mass ratios. To reflect China's soil C, N and P ratios more accurately, we used both area-weighted and number-weighted average methods to calculate the mean ratios. The formula for area-weighted mean soil C, N and P ratios is:

$$\bar{R}_{CNP} = \frac{\sum_{i=1}^{n} (AREA_i \times R_{CNP_i})}{\sum_{i=1}^{n} AREA_i}, \quad (1)$$

where $\bar{R}_{CNP}$ is the area-averaged C:N, C:P or N:P ratio, i refers to the ith soil type; n is the total number of soil, $AREA_i$ is the area of the ith soil type, and R_{CNPi} is the corresponding C:N, C:P or N:P ratio of the ith soil type. The number-weighted average also has its own advantages as the impacts of soil area on soil C, N and P ratio patterns can be discerned and results from different research studies can be compared. Therefore, we calculated mean C, N and P ratios for different soil orders, soil depth and climate zones using number-weighted average. The formula for a number-weighted average is:

$$\bar{R}_{CNP} = \frac{\sum_{i=1}^{n} (R_{CNP_i})}{n} \quad (2)$$

Because the classification systems of soil horizons are different for different soil samples, we divided each soil profile into four layers with a range of soil depths (0–10 cm, 20–50 cm, 50–100 cm, and >100 cm, respectively), rather than into the horizontal or sub-horizontal types (such as O, A, E, B and C horizons). The patterns of soil C, N and P concentrations and their ratios for these four layers were compared in all soil types and orders. We calculated the C:N, C:P and N:P ratios of each soil layer using the soil C, N and P concentration data of the corresponding soil type and layer. The mean C, N and P concentrations and C:N, C:P and N:P ratios of each soil layer were based on number-weighted averages (Formula 2). The mean C:N, C:P and N:P ratios for all Chinese soil types (entire depth) were based on the number-averaged values of all the soil types (Formula 2) rather than on soil sub-great groups or soil orders.

In order to compare our results with other such analyses, we transformed the Chinese soil taxonomic classification system to produce 12 soil orders (Entisols, Gelisols, Histosols, Inceptisols, Andisols, Aridisols, Vertisols, Alfisols, Mollisols, Ultisols, Spodosol, and Oxisols) which correspond to the USDA soil taxonomic system (Zhang et al. 2005). We then compared the C, N and P concentrations and ratios of different soil orders. The C, N and P concentrations and ratios of each soil sub-great group were averaged based on Formula 2. We reclassified these 12 soil orders into three soil weathering status groups: slightly weathered soils (Entisols, Gelisols, Inceptisols,), moderately weathered soils (Aridisols, Vertisols, Alfisols, Mollisols), and strongly weathered soils (Ultisols, Spodosol, Oxisols) according to the soil developmental time series described by Brady and Weil (2002) and Zhang et al. (2005). We compared the C, N and P ratios of these three weathering status groups based on data that considered entire soil depth.

Division of climate zones

Precipitation and temperature are known to influence vegetative cover, plant litter quality and soil biota, which in turn influence the physical and chemical properties of soil, and soil development. Thus, climate can leave a distinct imprint on soil C, N, and P concentrations and ratios. China is characterized by great spatial variability in climate, ranging from tropical to cool temperate zones (Tian et al. 2003; Wu et al. 2003). The tropical & subtropical zone is extremely humid due to the influence of Asian monsoon circulations (Tian et al. 2003), while in frigid highland areas annual precipitation and temperature are very low due to the northern location and higher elevation (See Table 1). Considering the obvious differences in climate and parent soil types, and applying the Holdridge life-zone classification system, we divided China into five zones: frigid highland, cool temperate, warm temperate, temperate desert, and tropical & subtropical, based on the 1:1,000,000 Land-use Map of China (Wu 1988). These five zones reflect only climate differences among these zones, rather than any specific land

Table 1 Climate zones in China and their corresponding annual average climate data

Climate zones	Minimum temperature (°C)	Maximum temperature (°C)	Mean annual temperature (°C)*	Mean annual precipitation (mm)
Frigid highland	−7.3	0.7	−3.4	348.5
Temperate desert	−1.1	11.0	4.5	252.1
Cool temperate zone	−3.7	7.9	1.7	418.2
Warm temperate zone	3.9	14.2	8.4	511.9
Tropical & subtropical zone	11.8	19.5	15.0	1226.3

* Data were calculated from the 30-year (1961–1990) average climate data in China

covers. For example, Temperate Desert includes woodlands, grasslands, desert, wetlands, and other types of land cover. We obtained the mean soil C, N and P concentrations and ratios in each climate zone by averaging the corresponding values of all soil types within the climate zone (Formula 2).

Statistical analysis

We performed all the statistic analyses using SPSS v11.5 software (SPSS Inc., Chicago, Illinois). We used variance of analysis (ANOVA) with LSD (Least Square Difference) post hoc test of significance to compare C, N and P concentrations, densities, and ratios within and across groups. The mean values were reported with 95% confidence intervals.

Results and analysis

General patterns of soil C, N and P ratios in China

Although soil C, N and P content varied significantly due to the differences in climate, parent material, biota, topography and disturbance history, we found a general pattern of soil C, N and P ratios in China (Table 2). The number-weighted mean soil C:N, C:P and N:P ratios were 11.9, 61 and 5.2, respectively, which was not vastly different from area-weighted means (12.1, 61, and 5.0, respectively, Table 2). The C:N, C:P and N:P ratios of the surface organic-rich layer (0–10 cm of A horizon) were 14.4, 136, and 9.3, respectively. From the frequency distribution of soil C, N and P ratios (Fig. 2), we found that all the soil elemental ratios followed a normal distribution pattern, with most C:N, C:P and N:P ratios in the range of 6–12, 24–48, and 3–6, respectively.

The C:N, C:P and N:P ratios of the organic-rich soil layer were significantly higher than corresponding values for total soil depth (Table 2). The C:N:P ratio (134:9:1) of this layer was also different from that of the total soil depth (60:5:1). However, the C: available P (15,810) and N: available P (1114) ratios of the organic-rich layer were significantly lower than that of the total soil depth (64,233 and 5,725, respectively): due to significant lower available P in the deeper soil.

Table 2 Soil C, N and P ratios in China

	Sample number	C:N	C: P	N: P	C: Av_P[®]	N:Av_P	C:N:P
Organic-rich layer (0–10 cm)	133[§]	14.4 ± 0.4a[ξ]	136 ± 11a	9.3 ± 0.7a	15810 ± 1832a	1114 ± 115a	134:9:1
All soil layers (Number-weighted)	8125*	11.9 ± 0.1b	61 ± 0.9b	5.2 ± 0.1b	64233 ± 20414b	5725 ± 1564b	60:5:1
All soil layers (Area-weighted)	7731[#]	12.1	61	5.0	–	–	60:5:1

[®] Av_P: available P

[ξ] Values were geometric means ± 1 SE; Different letters between two items in a column meant significantly different between them ($P < 0.05$), while the same letters indicated no significant difference

[§] The sample number for available P is only 85

*T he sample number for available P is 1,760

[#] No area information for 394 soil samples

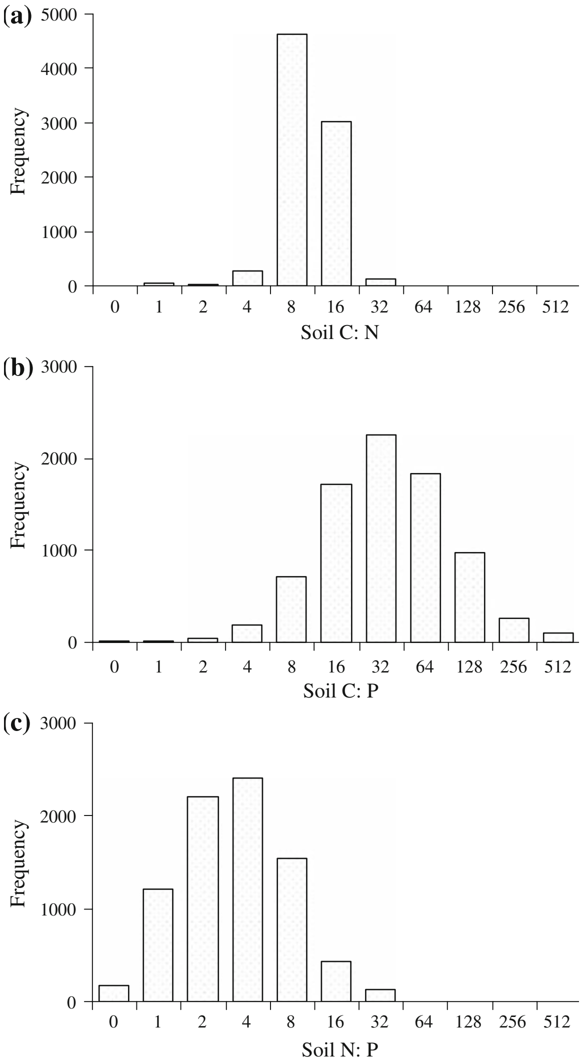

Fig. 2 Frequency distribution of soil C:N (**a**), C:P (**b**) and N:P (**c**) ratios in China. The x-axis of the histogram is presented using a log2 scale to highlight the lognormal distribution

The C:N ratio showed no significant difference among different soil depths that are deeper than 50 cm (Table 3). The C:P ratio of the organic-rich soil layer was over four times higher than that of the >100 cm soil layer and had a significant decrease as soil depth increased; this can be attributed to soil C concentration decreasing faster than soil P concentration as soil depth increases. The vertical pattern of the N:P ratio was similar to that of the C:P ratio, showing a peak value in 0–10 cm organic-rich soil (Table 3).

The highest C:N ratios were found in Northeast China, the eastern Tibet Plateau and sandy areas of Northwest China (Fig. 3a). The C:P and N:P ratios showed almost the same distribution patterns across China. The highest C:P and N:P ratios were found in Northeast China and the eastern Tibet Plateau (Figs. 3b, 2c), which might be due to C and N having a higher rate of accumulation than P's weathering rate.

Soil C, N and P ratios among different climate zones and soil orders

The highest C:N ratio (13.6) was in the frigid highland zone where there is soil with higher C content and lower N, while the lowest one (10.7) was in the warm temperate zone which has the lowest C and N contents compared to other climate zones. Soil C:P and N:P ratios varied considerably among different climate zones (Table 4). The highest C:P (78) and N:P (6.4) ratios occurred in the tropical & subtropical zone which had the lowest P content, while the lowest C:P (32) and N:P (2.6) ratios were in the temperate desert zone where N content was lower and P content was the greatest.

Soil orders are assigned largely on the basis of soil properties that reflect the course of major soil developments; thus, C, N and P ratios of a specific soil order can reflect the accumulated impact of climate, organisms, relief, parent material, and time on soil chemical properties (Jenny 1941). In China,

Table 3 Total soil C, N and P concentrations and ratios along a gradient of soil depth

Depth (cm)	C:N	C:P	N:P	Total C (mmol/kg)	Total N (mmol/kg)	Total P (mmol/kg)
0–10	14.4 ± 0.4a[ξ]	136 ± 11a	9.3 ± 0.7a	2047 ± 154a	134 ± 8.5a	25 ± 2.8ab
10–50	12.3 ± 0.1b	74 ± 1.3b	6.1 ± 0.2b	1174 ± 22b	96 ± 2.5b	23 ± 1.0a
50–100	11.2 ± 0.1c	46 ± 1.4c	4.2 ± 0.1c	617 ± 26c	53 ± 1.5c	19 ± 0.5b
>100	11.5 ± 1.0c	29 ± 2.3d	2.7 ± 0.1d	439 ± 45d	38 ± 1.8d	19 ± 1.1ab

* Values were means ± 1 SE; different letters between two items in a column meant significantly different between them ($P < 0.05$), while the same letters indicated no significant difference

Fig. 3 Distribution of soil C:N, C:P and N:P ratios in China represented by C:N, C:P and N:P ratios of each soil sub-great group (**a**: C:N ratio; **b**: C:P ratio; **c**: N:P ratio)

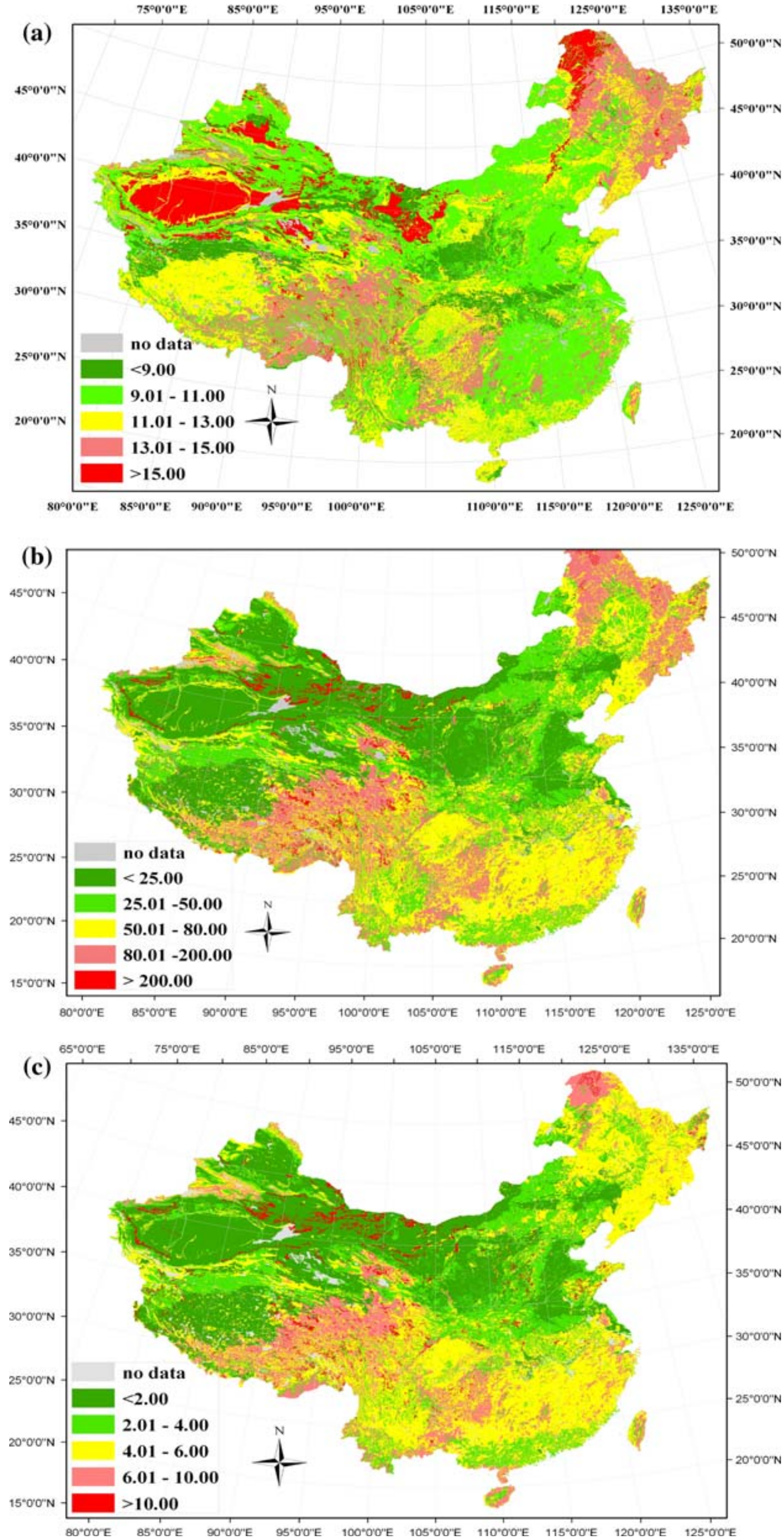

Table 4 Soil C, N and P concentrations and ratios in different climate zones in China

Climate zone	Number	C:N	C:P	N:P	C content (mmol/kg)	N content (mmol/kg)	P content (mmol/kg)
Frigid highland	749	13.6 ± 1.1a*	62 ± 3.0a	5.9 ± 0.7ac	1120 ± 69a	97 ± 12a	20.6 ± 1.3ab
Temperate desert	319	12.2 ± 0.2abc	32 ± 2.1b	2.6 ± 0.1b	775 ± 63b	60 ± 4b	26.0 ± 2.6b
Cool temperate zone	378	12.4 ± 0.2ab	74 ± 6.0c	5.4 ± 0.3a	1826 ± 158c	128 ± 8c	26.3 ± 1.1b
Warm temperate zone	1676	10.7 ± 0.1c	38 ± 1.1bd	3.6 ± 0.1b	581 ± 21b	53 ± 2b	21.1 ± 1.0ab
Tropical & subtropical zone	2071	12.1 ± 0.1b	78 ± 2.1c	6.4 ± 0.2c	997 ± 25d	79 ± 2d	19.0 ± 1.3a
Average	5193	11.9 ± 0.2	60 ± 1.1	5.1 ± 0.1	927 ± 20	76 ± 2	20.9 ± 0.7

* Values were means ± 1 SE; different letters between two items in a column meant significantly different between them ($P < 0.05$), while the same letters indicated no significant difference

Table 5 The C, N and P ratios for different soil orders

Soil order	No. of samples	C:N ratio	C:P ratio	N:P ratio
Entisols	2150	11.35 ± 0.13a*	56.4 ± 1.6ab	5.11 ± 0.26ab
Histosols	16	17.41 ± 1.03c	340 ± 82e	17.77 ± 3.46c
Inceptisols	727	11.41 ± 0.19a	57.6 ± 3.2ab	4.88 ± 0.23ab
Andisols	22	13.38 ± 0.67ac	42.2 ± 7.9acb	2.96 ± 0.51abde
Aridisols	300	11.24 ± 0.22a	29.0 ± 1.8c	2.60 ± 0.15d
Vertisols	77	10.73 ± 0.36ab	41.7 ± 4.4ac	4.63 ± 0.68abde
Alfisols	614	12.1 ± 0.24abc	63.5 ± 2.6b	5.46 ± 0.29abe
Mollisols	785	13.05 ± 1.07bc	59.8 ± 2.9ab	4.97 ± 0.19ab
Ultisols	502	13.32 ± 0.26bc	86.4 ± 4.4d	6.43 ± 0.28e

* Values were means ± 1 SE; different letters between two items in a column meant significantly different between them ($P < 0.05$), while the same letters indicated no significant difference

only nine soil orders were found, with Histosols and Andisols being the least frequent (Table 5). We found that Histosols had the highest C:N ratio, while Vertisols and Entisols had the lowest. With the exception of Histosols, the differences between C:N ratios and the eight remaining soil orders in China were small (variance range from 10.73 to 13.38). Histosols had the highest C:P (340) and N:P ratios (17.77), while Aridisols had the lowest C:P (29.0) and N:P (2.60) ratios.

Discussions

Do well-constrained soil C:N:P stoichiometric ratios exist?

Well-constrained C:N:P ratios in planktonic biomass were found to have important impacts on nutrient cycles and biological processes in marine ecosystems. The "Redfield-like" ratios were found in plants (e.g. Reich and Oleksyn 2004; McGroddy et al. 2004) and soil microbial communities (e.g. Cleveland and Liptzin 2007). Could the relatively fixed elemental ratios in terrestrial organisms (such as plant leaves, litters, and microbes) result in consistent nutrient ratios in the soil just like that found by Redfield (1958) in the marine ecosystem? Could the analysis of soil element ratios provide insight into the nature of nutrient limitation in terrestrial ecosystems? Cleveland and Liptzin (2007) studied the C:N:P stoichiometry in soil and stated that similar to marine ecosystems, the atomic C:N:P ratios in the top soil were well-constrained due to the interactions between the environment and soil organisms. Their study, however, only focused on surface soils (typically 0–10 cm), which represent organic-rich horizons, and their data were obtained from discrete publications. The limited sample size (<150) of their study also indicates that it is necessary for further studies to

Table 6 Correlations among soil organic C (mmol/kg), total N (mmol/kg) and total P (mmol/kg) and among soil organic C, total N and available P (mmol/kg) for the organic-rich soil layer (0–10 cm) and the entire soil depth in China

Independent variables	Dependent variables	Sample number	Correlation coefficient (R)
Soil C at surface layer	Soil N at surface layer	133	0.93
Soil C at surface layer	Soil P at surface layer	133	0.62
Soil C at surface layer	Soil available P at surface layer	85	0.69
Soil N at surface layer	Soil P at surface layer	133	0.51
Soil N at surface layer	Soil available P at surface layer	85	0.60
Soil C for all layers	Soil N for all layers	8125	0.88
Soil C for all layers	Soil P for all layers	8125	0.14
Soil C for all layers	Soil available P for all layers	1760	0.17
Soil N for all layers	Soil P for all layers	8125	0.14
Soil N for all layers	Soil available P for all layers	1760	0.17

Note: The relationships between variables were significant at $P < 0.001$.

verify the well-constrained relationships at the top soil.

Based on more than 2,384 soil profiles and over 8,000 soil layers across China, we carried out the correlation analyses among soil total C, N and P and among total C, total N and available P (Table 6), the results revealed that the C:N ratio of the organic-rich soil layer was well-constrained considering the relatively high correlation coefficient (0.93) among C and N concentrations. There were also relatively constrained C:P and N:P ratios in the organic-rich soil layer (Correlation coefficients were 0.62 and 0.51, respectively). This might imply that there has a relatively constrained C:N:P ratio in the organic-rich soil layer as reported by Cleveland and Liptzin (2007). In this sense, we agree with Cleveland and Liptzin (2007) on their statement that "Redfield-like" interactions among C, N and P may exist in soil. We found a similar C:N ratio (14.4) to that found by Clevaland and Liptzin (2007) in the organic-rich soil layer, but we found lower C:P (136) and N:P (9.3) ratios; that the C:N:P ratio (134:9:1) from this study is different from theirs (186:13:1) implies that C:N:P ratios might change with environmental factors although C, N and P are relatively well-constrained at the organic-rich topsoil. There was, however, no relatively constrained C:N:P stoichiometric ratios for deeper soil except that a well-constrained C:N ratio was found for the deeper soil considering its higher correlation coefficient (0.88, Table 6). Many previous studies (e.g. Vitousek 2004; Melillo et al. 2003; Post et al. 1985) also found strong correlations between total C and total N in the soil. As in the marine ecosystem where most of the available N is fixed by microorganisms, the relatively constrained C:N:P ratios in the topsoil reflect the ability of terrestrial organisms to modify their abiotic environment to meet their nutrient requirements.

Unlike the soil C and N, the weathering of the parent material, which is located at the bottom of the soil profile, provides the major sources of available soil P (Walker and Adams 1958). Soil P is further translocated by plants and accumulated in the surface soil in the form of SOP resulting in a complex vertical distribution pattern in the soil profile (Smeck 1985; Mellilo et al. 2003; Vitousek 2004). We found that the C:P ratio decreased dramatically with the soil depth (Table 3). Walker and Adams (1958) also found that as the soil depth increased, the C:P ratio declined much faster than the C:N ratio. This is mainly because of the relatively stable soil P content throughout the soil profile when compared to the rapid decline in SOC with soil depth (Table 3). Through analyses of C:P and N:P ratios, we found that despite large variations of C and N content, low soil P content always led to high C:P and N:P ratios. This pattern indicates, as suggested by Walker and Adams (1958), that the C:N:P ratio in the soil is mainly controlled by the P supply.

Although there is no constrained C:N:P ratio in the deeper soil, the vertical distribution of P in the soil still provided strong evidence of biotic regulation of soil nutrients. Despite the location of the parent material and the downward movement of P leaching, the terrestrial organisms seem to be able to reduce P gradient along the soil profile by uptake and translocating P from the P-rich deep soil to the surface layer to meet their nutrient requirements (Zhang et al. 2005).

Controlling factors in the C:N:P ratio in China's soil

Climate imposes important controls both on soil development and on the biota and its interaction with the soil nutrients (Chadwick et al. 1999; Vitousek 2004; Oleksyn 2003). Spatial distribution of soil C, N and P density across China has seen substantial variation (Wang et al. 2003; Zhang et al. 2005; Tian et al. 2006). Despite the spatial variations of C and N contents, the C:N ratio was relatively stable among climate zones (Table 4), indicating the feedbacks of a similar biota on the chemical composition of the soil. The C:P and N:P ratios, however, varied significantly among different climate zones in China (Table 4). The element ratio highlights the impacts of extreme climate regimes on soil nutrient balance. The high temperature and precipitation in tropical-subtropical regions can result in high P leaching rate and P occlusion in highly weathered soils (Vitousek et al. 1987; Neufeldt et al. 2000; Zhang et al. 2005). At the same time, the high productivity of tropical-subtropical ecosystems maintains relatively high soil C and N content, which gave these regions the highest C:P and N:P ratios. In contrast, the dry and cool climate regime in the temperate desert resulted in low productivity, lower soil C and N contents and low P loss through leaching, and higher soil P content, which gave it the lowest soil C:P and N:P ratios among all the climate zones. The spatial and vertical distribution pattern of C:N:P ratios suggests that the relatively constrained requirements of nutrients from plants exert a large impact on C:N:P ratios in soil except for climate. However, due to land cover information has not been recorded simultaneously with the Chinese soil survey data, we are unable to analyze direct impacts of plants on soil C:N:P ratios.

Site-level chronosequence studies have suggested that soil C:N:P ratios may change during soil development, indicating a shift in soil limitation nutrients (Crews et al. 1995; Chadwick et al. 1999; Frizano et al. 2002; Vitousek 2004). To capture the pattern of elemental ratios of different soil developmental stages, we further grouped the nine soil orders into three soil weathering classes: slight, moderate and strong weathering soil (Brady and Weil 2002; Zhang et al. 2005). The soil C:N ratios increased significantly ($P < 0.05$) with increasing soil weathering time (11.37, 12.32, and 13.32, respectively) (Table 7). We also found that the strongly weathered soil had the highest C:P ratio (99.0), while the C:P ratio of the moderately weathered soil (63.1) was similar to that of the slight weathering soil (64.9). The N:P ratio showed the same trend, with the highest N:P ratio in strong weathering soil (7.37), indicating P deficiency in highly weathered soils. The N:P ratio was found to be the lowest in the moderate weathering soil (5.41), which was not significantly lower than that of the slight weathering soil (5.78). This result was similar to that reported by Crews et al. (1995) and Vitousek (2004). Walker and Syers (1976) proposed that soil total P decreases with increasing soil developmental time. We found the same pattern in this study.

Chinese versus global soil C:N:P ratios

Several studies have explored the patterns of soil C:N ratios though soil C:N ratios were not their primary focus. For example, based on the global World Inventory of Soil Emission Potential (WISE) dataset

Table 7 The C, N and P contents and C, N and P ratios for different soil weathering stages

Weathering stage	No. of samples	C:N ratio	C:P ratio	N:P ratio	C content (mmol/kg)	N content (mmol/kg)	P content (mmol/kg)
Slight	2915	11.37 ± 0.11a*	64.9 ± 1.7a	5.78 ± 0.23a	803 ± 19a	71.0 ± 3.2a	18.7 ± 1.0a
Moderate	1776	12.32 ± 0.48b	63.1 ± 1.9a	5.41 ± 0.16a	1004 ± 36b	79.4 ± 2.2a	18.4 ± 0.5a
Strong	502	13.32 ± 0.26c	99.0 ± 5.0b	7.37 ± 0.32c	994 ± 46ab	70.7 ± 2.6a	13.5 ± 0.6b

* Values were means ± 1 SE; different letters between two items in a column meant significantly different between them ($P < 0.05$), while the same letters indicated no significant difference

Table 8 Comparisons of soil C:N ratios of different depths and soil orders around the world (Batjes 1996) and in China (this study)

Soil order	Soil depth							
	0–30 cm		30–50 cm		50–100 cm		0–100 cm	
	Batjes	This study	Batjes	This study	Batjes	This study	Batjes	This study
Entisols	14.21	12.05 ± 0.42*	13.04	11.20 ± 0.42	12.03	10.87 ± 0.43	12.89	11.50 ± 0.19
Histosols	30.10	16.33 ± 4.17	34.77	16.53 ± 5.80	26.02	18.81 ± 2.84	28.99	17.61 ± 2.44
Inceptisols	13.42	12.36 ± 0.48	11.32	11.41 ± 0.61	10.50	10.66 ± 0.85	11.54	11.36 ± 0.49
Andisols	15.52	13.10 ± 2.00	16.10	13.00 ± 2.08	16.68	12.79 ± 2.74	16.22	13.11 ± 1.62
Aridisols	13.10	11.19 ± 0.59	11.46	10.89 ± 0.90	10.13	11.49 ± 0.73	11.28	11.56 ± 0.46
Vertisols	15.52	10.54 ± 1.54	14.58	10.52 ± 1.07	14.58	11.54 ± 1.23	14.86	11.19 ± 1.14
Alfisols	13.57	14.13 ± 1.06	11.56	12.57 ± 0.72	10.68	11.13 ± 0.57	11.73	12.39 ± 0.60
Mollisols	13.01	12.10 ± 0.37	11.73	12.69 ± 1.45	10.47	11.69 ± 0.48	11.48	11.85 ± 0.33
Ultisols	15.32	15.53 ± 0.89	11.74	12.71 ± 0.84	10.33	11.43 ± 0.66	12.11	12.83 ± 0.86
Average[§]	15.84	12.65	14.93	11.69	13.36	11.19	14.42	11.80

* Mean value ± 1.96 SE (95% confidence interval)

[§] This average is calculated from the number-weighted average (by soil profile numbers) of C:N ratios of all the soil orders

(http://www.daac.ornl.gov), Batjes (1996) studied the changing patterns of C:N ratios in relation to soil depth (Table 8). The average C:N ratios of all the soil orders reported by Batjes for 0–30, 30–50, and 50–100 cm depths (15.84, 14.93, and 13.36, respectively) were higher than our corresponding values (12.65, 11.69, and 11.19, respectively). Additionally, based on the WISE dataset, Batjes (1996, 2002) explored the concentrations of soil C and N as well as C:N ratios of eleven soil orders around the world (Table 8). The average C:N ratio reported by Batjes for all soil orders at 0–100 cm depth (14.42) was higher than our corresponding values. Both studies found Histosols had the highest C:N ratio. Based on global soil C and N data of 2,700 soil profiles from Oak Ridge National Laboratory (http://www.dacc.ornl.gov, Zinke et al. 1984), Post et al. (1982; 1985) reported global patterns of soil C and N storage and C:N ratios in terms of the Holdridge life zones. We summarized the mass-based C:N ratios and transformed them into mole-based ratios for climate zones: tundra/frigid highland (20.3), cool temperate zone (20.2), warm temperate zone (20.6), and tropical and subtropical zone (15.4), respectively. We found that all the C:N ratios reported by Post et al. were higher than our results for each corresponding climate zone. These differences might be due to some of the soil samples used in Post et al. (1985) having a humified litter layer (i.e., 0 cm soil depth in the Zinke et al. 1984 dataset) which has a higher C:N ratio than soil. For regional climate patterns, Post et al. (1985) indicated that relatively large amounts of soil N in tropical and subtropical regions was associated with both recalcitrant humic materials in an advanced state

Table 9 The C, N densities and C:N ratios summarized from Post et al. (1985)*

Climate zones	No. of samples	C density (kg/m^3)	N density (kg/m^3)	C:N ratio
Tundra/Frigid highland	53	22.73	1.37	20.3
Cool temperate zone	1613	14.60	0.92	20.2
Warm temperate zone	546	13.00	1.16	20.6
Tropical and subtropical zone	547	11.07	1.08	15.4

* All the data were summarized from the published results rather than calculated from original dataset. Each climate zone included all the land cover types showing in this zone, and the values of C and N density and C:N ratios were averaged by these land cover types

of decay and the lowest C:N ratios, while slow decomposition in boreal regions resulted in higher C:N ratios than in other regions. Since Post et al.'s research included no soil samples from China, our dataset and analysis can provide valuable supplementary information for the study of global soil C:N ratios. The reports for large-scale soil C:P and N:P ratio patterns are limited. Recently, Cleveland and Liptzin (2007) estimated the global soil C:P and N:P ratios of the surface soil (0–10 cm) to be 186 and 13.1, respectively. Our analysis reveals relatively lower C:P (136) and N:P 9.3 ratios at the 0–10 cm soil in China (Table 9).

Conclusions

We found that the number-weighted average soil C:N, C:P, and N:P ratios in China were 12, 61, and 5, respectively, with a C:N:P ratio of 60:5:1 for all soil layers. The C:N ratio variation range among samples from different climate zones and different soil depth was relatively small, while large spatial heterogeneity (both horizontal and vertical) was found in C:P and N:P ratios. C:P and N:P ratios decreased dramatically with increased soil depth. However, a highly constrained C:N:P ratio of 134:9:1 was found at the 0–10 cm organic-rich soil, which indicated reciprocal interactions between terrestrial organisms and the abiotic soil environment in the biologically active soil layer. The C:P and N:P ratios in the soil were primarily determined by soil P content, which was controlled by the soil (parent material) type, soil weathering stage, and climate factors that affect soil weathering rate. Certainly, the C:N:P ratios derived from this analysis based on China's soil database are very different from those derived from other studies based on global soil datasets. Consequently, our dataset and analysis provides valuable supplementary information for the study of global soil elemental ratios, especially C:P and N:P ratios.

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References

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 47:151–163

Batjes NH (2002) A homogenized soil profile data set for global and regional environmental research (WISE, version 1.1), International Soil Reference and Information Centre, Wageningen, Netherlands, 2002/01 (www.isric.org)

Brady NC, Weil RR (2002) The nature and properties of soils. 13th edition Pearson education. Incorporation, New Jersey

Chadwick OA, Derry LA, Vitousek PM, Huebert BJ, Hedin LO (1999) Changing sources of nutrients during four million years of ecosystem development. Nature 397:491–497

Cleveland CC, Liptzin D (2007) C:N:P stoichiometry in soil: is there a "Redfield ratio" for the microbial biomass? Biogeochemistry 85:235–252

Crews TE, Kitayama K, Fownes J, Herbert D, Mueller-Dombois D, Riley RH, Vitousek PM (1995) Changes in soil phosphorus and ecosystem dynamics across a long soil chronosequence in Hawai'i. Ecology 76:1407–1424

Elser JJ, Dobberfuhl D, MacKay NA, Schampel JH (1996) Organism size, life history, and N:P stoichiometry: towards a unified view of cellular and ecosystem processes. Bioscience 46:674–684

FAO (1988) FAO-UNESCO Soil map of the world. Revised ledgend. FAO World Soil Resources Report No. 60. FAO, Rome

Frizano J, Johnson AH, Vann DR, Scatena FN (2002) Soil phosphorus fractionation during forest development on landslide scars in the Luquillo mountains, Puerto Rico. Biotropica 34:17–26

Jenny H (1941) Factors of soil formation. McGraw-Hill, New York, USA

Li Z, Zhao Q (2001) Organic carbon content and distribution in soils under different land uses in tropical and subtropical China. Plant Soil 231:175–185

McGroddy ME, Daufresne T, Hedin LO (2004) Scaling of C:N:P stoichiometry in forests worldwide: implications of terrestrial Redfield-type ratios. Ecology 85:2390–2401

Melillo JM, Field CB, Moldan B (2003) Interactions of the major biogeochemical cycles: global change and human impacts. Scientific committee on problems of the environment (SCOPE) series, vol 61. Island Press, Washington, USA

Michaels AF (2003) The ratios of life. Science 300:906–907

National Soil Survey Office (1993, 1994a, 1994b, 1995a, 1995b, 1996, 1998) Soil species of China, vol I, II, III, IV, V, VI, VII. China Agriculture Press, Beijing

Neff JC, Hobbie SE, Vitousek PM (2000) Nutrient and mineralogical controls on dissolved organic C, N, and P fluxes and stoichiometry in Hawaiian soils. Biogeochemistry 51:283–302

Neufeldt H, da Silva JE, Ayarza MA, Zech W (2000) Land-use effects on phosphorus fractions in Cerrado Oxisols. Biol Fertil Soils 31:30–37

Oleksyn J, Reich PB, Zytkowiak R, Karolewski P, Tjoelker MG (2003) Nutrient conservation increases with latitude of origin in European *Pinus sylvestris* populations. Oecologia 136:220–235

Post WM, Emanuel WR, Zinke PJ, Stangenberger AG (1982) Soil carbon pools & world life zones. Nature 298:156–159

Post WM, Pastor J, Zinke PJ, Stangenberger G (1985) Global patterns of soil nitrogen storage. Nature 317:613–616
Redfield AC (1958) The biological control of chemical factors in the environment. Am Sci 46:205–211
Reich PB, Oleksyn J (2004) Global patterns of plant leaf N and P in relation to temperature and latitude. Proc Nat Acad Sci USA 101:11001–11006
Schimel DS (2003) All life is chemical. Bioscience 53: 521–524
Smeck NE (1985) Phosphorus dynamics in soil and landscapes. Geoderma 36:185–199
Soil Survey Staff (1975) Soil taxonomy. USDA, Washington DC, USA
Sterner RW (1995) Elemental stoichiometry of species in ecosystems. In: Jones CG, Lawton JH (eds) Linking species and ecosystems. Chapman and Hall, New York, USA., pp 240–252
Sterner RW, Elser JJ (2002) Ecological stoichiometry: the biology of elements from molecules to the biosphere. Princeton University Press, Princeton, New Jersey
Tian HQ, Melillo JM, Kicklighter DW, Pan S, Liu J, McGuire AD, Moore B III (2003) Regional carbon dynamics in monsoon Asia and its implications to the global carbon cycle. Glob Planet Chang 37:201–217
Tian HQ, Wang SQ, Liu JY, Pan S, Chen H, Zhang C, Shi XZ (2006) Storage and distribution of soil organic nitrogen in China. Glob Biogeochem Cycles 20:GB1001. doi:10.1029/2005GB002464
Vitousek PM (2004) Nutrient cycling and limitation: Hawai'i as a model system. Princeton University Press, Princeton, New Jersey
Vitousek PM, Walker LR, Whiteaker LD, Muellerdombois D, Matson PA (1987) Biological invasion by Myrica-Faya alters ecosystem development in Hawaii. Science 238: 802–804
Vitousek PM, Hättenschwiler S, Olander L, Allison S (2002) Nitrogen and nature. Ambio 31:97–101
Walker TW (1956) Nitrogen and herbage production. Proceedings, seventh international grassland congress, p 157
Walker TW, Adams AFR (1958) Studies on soil organic matter. I. Soil Sci 85:307–318
Walker TW, Syers JK (1976) The fate of P during pedogenesis. Geoderma 14:1–19
Wang S, Tian HQ, Liu J, Pan S (2003) Pattern and change in soil organic carbon storage in China: 1960s–1980s. Tellus 55B:416–427
Wu C (1988) 1:1000,000 land use map of China. Science Press, Beijing, China
Wu H, Guo Z, Peng C (2003) Distribution and storage of soil organic carbon in China. Glob Biogeochem Cycles 17:1048. doi:10.1029/2001GB001844
Yang YH, Mohammat A, Feng JM, Zhou R, Fang JY (2007) Storage, patterns and environmental controls of soil organic carbon in China. Biogeochemistry 84:131–141
Zhang C, Tian HQ, Liu J, Wang S, Liu M, Pan S, Shi X (2005) Pools and distributions of soil phosphorus in China. Glob Biogeochem Cycles 19:GB1020. doi:10.1029/2004GB002296
Zinke PJ, Stangenberger AG, Post WM, Emanuel WR, Olson JS (1984) Worldwide organic soil carbon and nitrogen data. ORNL/TM-8857. Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A