

Pattern and Variation of C:N:P Ratios in China's Soils: A Synthesis of Observational Data

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

19

20 **Keywords** Carbon · Nitrogen · Phosphorus · Stoichiometry · China

21

22 **Introduction**

23

24 All substances on earth are composed of chemical elements, and elemental
25 composition is the most fundamental in biology and ecology (Michaels 2003; Schimel
26 2003). Thus a cell, an organism, an ecosystem, and even the biosphere can be reduced
27 to its elemental composition in some simple elemental ratios. Although soil is
28 influenced by complex factors such as climate, soil parent materials, topography and
29 development stages, and is often characterized by high biological diversity, structural
30 complexity and spatial heterogeneity (Chadwick et al. 1999; Cleveland and Liptzin
31 2007), many previous studies (e.g. Melillo et al. 2003; Vitousek et al. 2002, 2004;
32 Brady and Weil 2002; Post et al. 1982; Walker and Adams 1958) have indicated that
33 soil carbon (C), nitrogen (N) and phosphorus (P) are often closely related. Walker
34 (1956) suggested that C, N, and P are associated in fairly definite proportions in soil
35 organic matter (SOM). Based on the analysis of 22 grassland soil profiles, Walker and
36 Adams (1958) found a constrained correlation among organic C (SOC) and organic P
37 (SOP) in the soil. Through a literature review of 48 published resources, Cleveland and
38 Liptzin (2007) found a well constrained C:N:P ratio in global soil microbial biomass
39 and 0-10cm organic-rich soil. All these findings reported relatively constrained
40 elemental ratios, or homeostasis, in plants and soil organisms. It is suggested that the
41 feedbacks from living organisms can modify soil nutrient content and result in
42 “Redfield-like” correlations between the elemental ratio of the biota and soil in
43 terrestrial ecosystems (Neff et al. 2000; Stener and Elser 2002; Cleveland and Liptzin

44 2007).

45 Redfield (1958) found that planktonic biomass contains C, N and P in an
46 atomic ratio of 106:16:1, similar to the ratio of C, N and P in marine water. This C:N:P
47 ratio, known as “Redfield Ratio”, has stimulated a large number of subsequent studies
48 on the C:N:P stoichiometry of multiple biota in aquatic and terrestrial ecosystems (e.g.,
49 Sterner 1995; Elser et al. 1996; Stener and Elser 2002; Cleveland and Liptzin 2007;
50 McGroddy et al. 2004). Compared to marine ecosystems, terrestrial ecosystems vary
51 greatly due to varied and complex habitats, biota and environmental factors.

52 Furthermore, soil is far more complex than other terrestrial systems. The relative
53 immobility of the soil tends to promote and maintain spatial heterogeneity in nutrient
54 cycles. This heterogeneity is caused by both local-scale disturbances, such as land
55 use change and human interferences, and regional-scale differences in glacial history,
56 climate, geologic parent material, topography, and biotic diversity (Jenny 1941).

57 Nutrients are continuously redistributed in terrestrial ecosystems by a number of ways
58 including plant litterfall, soil water flow and plant-atmosphere exchange, none of
59 which appears within marine environments (McGroddy et al. 2004). Unlike the
60 homogeneous aquatic environment, soil is highly heterogeneous both horizontally and
61 vertically. The soil P supply depends on the total P content and the weathering stage of
62 the parent material, both of which are characterized by spatial heterogeneities.

63 Furthermore, the infiltration and diffusion rate of nutrients in soil is much slower than
64 in the aquatic ecosystem. As the result, the feedbacks from terrestrial organisms are
65 limited to the top-soil, while the supply of P comes from the parent materials that are

66 located at the bottom of the soil. This mechanism results in a complex and highly
67 variable vertical pattern of total P (TP) content through the soil profile (Brady and Weil
68 2002). Based on vertical soil analysis to a depth of 53 cm, Walker and Adams (1958)
69 concluded that the total soil P content was related to the P content of parent material,
70 and decreased down through the soil profile at a rate much slower than the rate of C
71 and N. This finding indicates that soil has inconsistent vertical patterns of N:P ratio.
72 Although Cleveland and Liptzin (2007) stated that a remarkably constrained soil C:N:P
73 ratio of 186:13:1 exists on the global scale, their analysis was mainly based on samples
74 from surface soils (0~10 cm mineral soil). The constrained C:N:P ratio in the topsoil
75 found by Cleveland and Liptzin (2007) may not be applicable to the entire depth of soil
76 profiles.

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

87 Since China has various soil types that developed under different bioclimatic

88 conditions and are derived from various parent materials in diversified topographical
89 environments, the study of the relationships among C, N, and P in China's soil is likely
90 to make great contributions to the establishment of a global C, N, and P relationship.
91 Based on soil chemical data from the Second Chinese Soil Survey, which provided
92 C:N:P for over 2,473 typical soil profiles across China that were sampled and
93 measured in standard approaches (Wang, et al. 2003; Tian, et al. 2006; Zhang, et al.
94 2005; Wu et al. 2003; Yang et al. 2007), our objectives in this study are to: 1) explore
95 the general C:N, C:P and N:P ratios in China's soil at a national scale; and 2) find how
96 these ratios change with climate, soil orders, soil depth and weathering status. Based
97 on these two objectives, we have also tried to verify whether or not well-constrained
98 C:N:P ratios exist in the top and deeper soils.

99

100 **Materials and methods**

101

102 **Data sources**

103

104 We examined geo-referenced soil profiles collected in the second Chinese soil survey
105 and developed mean values for various soil groups (National Soil Survey Office 1993,
106 1994a, b, 1995a, b, 1996). This database includes 2,473 soil profiles, each of which
107 represents a soil type in the Chinese Soil Taxonomy system (Li and Zhao 2001; Wang
108 et al 2003). Each soil profile is divided into A, B, C and other horizons, according to
109 actual soil conditions. The properties investigated include the thickness of horizons,

110 total soil organic matter (SOM) (determined by the $K_2Cr_2O_7$ - H_2SO_4 digestion method),
111 total P content (measured by Perchloric acid digestion followed by the molybdate
112 colorimetric test), total soil N (analyzed with the Kjeldahl procedure), soil bulk density
113 (measured according to the core sampling method), soil available P (The Olsen method
114 (Olsen et al., 1954) was used for available P analysis) and geographic location
115 information. SOC content was calculated as a portion of SOM which has been
116 described by Wang et al. (2003). Of all the 2,473 soil profiles, 2,405 have total P
117 content records, 2,462 have SOM data and 2,445 have total N records, 1,760 have
118 available P records, and 1,535 profiles have geographic location information. We
119 excluded soil profiles that did not have any of the total C, N or P data. The final dataset
120 used in this analysis includes 2,384 soil profiles. We integrated the soil data for the
121 1,535 profiles for which we had geographical information into a Geographical
122 Information System (GIS) database to show their geographic distribution (Fig. 1).

123 The Chinese Soil Taxonomy system (National Soil Survey Office 1998) was
124 used in this soil survey. This system has a hierarchical structure, with 12 orders, 61
125 great groups, 235 sub-great groups, 909 families and more than 2,473 soil types (soil
126 profiles, each with its distribution area in China). Using the transformation procedure
127 of Zhang et al. (2005), we were able to compare these results with the United Nation
128 Food and Agriculture Organization/UNESCO (1988) soil classification system, and
129 also the equivalent USDA soil taxonomy system (Soil Survey Staff 1975).

130 Calculation of soil C, N and P ratios: The soil total C, N and P concentrations
131 (mg/kg) were transformed to a unit of mmol/kg, and C: N, C: P and N: P ratios for each

132 type soil were calculated as molar ratios (atomic ratio), rather than mass ratios. To
 133 reflect China's soil C, N and P ratios more accurately, we used both area-weighted and
 134 number-weighted average methods to calculate the mean ratios. The formula for
 135 area-weighted mean soil C, N and P ratios is:

$$136 \quad \bar{R}_{CNP} = \frac{\sum_{i=1}^n (AREA_i \times R_{CNP_i})}{\sum_{i=1}^n AREA_i}, \quad (1)$$

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

$$145 \quad \bar{R}_{CNP} = \frac{\sum_{i=1}^n (R_{CNP_i})}{n} \quad (2)$$

146 Because the classification systems of soil horizons are different for different soil
 147 samples, we divided each soil profile into four layers with a range of soil depths (0-10
 148 cm, 20-50 cm, 50-100 cm, and >100 cm, respectively), rather than into the horizontal
 149 or subhorizontal types (such as O, A, E, B and C horizons). The patterns of soil C, N
 150 and P concentrations and their ratios for these four layers were compared in all soil
 151 types and orders. We calculated the C: N, C: P and N: P ratios of each soil layer using

152 the soil C, N and P concentration data of the corresponding soil type and layer. The
153 mean C, N and P concentrations and C: N, C: P and N: P ratios of each soil layer were
154 based on number-weighted averages (Formula 2). The mean C: N, C: P and N: P
155 ratios for all Chinese soil types (entire depth) were based on the number-averaged
156 values of all the soil types (Formula 2) rather than on soil sub-great groups or soil
157 orders.

158 We changed the Chinese soil taxonomic classification system to produce 12 soil
159 orders (Entisols, Gelisols, Histosols, Inceptisols, Andisols, Aridisols, Vertisols, Alfisols,
160 Mollisols, Ultisols, Spodosol, and Oxisols) which correspond to the USDA soil
161 taxonomic system (Zhang et al. 2005). We then compared the C, N and P
162 concentrations and ratios of different soil orders. The C, N and P concentrations and
163 ratios of each soil sub-great group were averaged based on Formula 2. We
164 reclassified these 12 soil orders into three soil weathering status groups: slightly
165 weathered soils (Entisols, Gelisols, Inceptisols,), moderately weathered soils (Aridisols,
166 Vertisols, Alfisols, Mollisols), and strongly weathered soils (Ultisols, Spodosol,
167 Oxisols) according to the soil developmental time series described by Brady and Weil
168 (2002) and Zhang et al. (2005). We compared the C, N and P ratios of these three
169 weathering status groups based on data that considered entire soil depth.

170

171 Division of climate zones

172

173 Precipitation and temperature are known to influence vegetative cover, plant litter
174 quality and soil biota, which in turn influence the physical and chemical properties of
175 soil, and soil development. Thus, climate can leave a distinct imprint on soil C, N,
176 and P concentrations and ratios. China is characterized by great spatial variability in
177 climate, ranging from tropical to cool temperate zones (Tian et al., 2003; Wu et al.,
178 2003). The tropical & subtropical zone is extremely humid due to the influence of
179 Asian monsoon circulations (Tian et al., 2003), while in frigid highland areas annual
180 precipitation and temperature are very low due to the northern location and higher
181 elevation (See Table 1). Considering the obvious differences in climate and parent
182 soil types, and applying the Holdridge life-zone classification system, we divided
183 China into five zones: frigid highland, cool temperate, warm temperate, temperate
184 desert, and tropical & subtropical, based on the 1: 1,000,000 Land-use Map of China
185 (Wu 1988). These five zones reflect only climate differences among these zones,
186 rather than any specific land covers. For example, Temperate Desert includes
187 woodlands, grasslands, desert, wetlands, and other types of land cover. We obtained
188 the mean soil C, N and P concentrations and ratios in each climate zone by averaging
189 the corresponding values of all soil types within the climate zone (Formula 2).

190 Statistical Analysis

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

195 95% confidence intervals.

196

197 **Results and analysis**

198

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

200

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

210 The C:N, C:P and N:P ratios of the organic-rich soil layer were significantly
211 higher than corresponding values for total soil depth (Table 2). The C:N:P ratio
212 (134:9:1) of this layer was also different from that of the total soil depth (60:5:1).
213 However, the C: available P (15,810) and N: available P (1114) ratios of the
214 organic-rich layer were significantly lower than that of the total soil depth (64,233 and
215 5,725, respectively).

216 The C:N ratio showed no significant difference among different soil depths

217 where the deeper soil was greater than 50cm (Table 3). The C: P ratio of the
218 organic-rich soil layer was over four times higher than that of the >100 cm soil layer
219 and showed significant decrease as soil depth increased; this can be attributed to soil C
220 concentration decreasing faster than soil P concentration as soil depth increases. The
221 vertical pattern of the N:P ratio was similar to that of the C:P ratio, showing a peak
222 value in 0-10 cm organic-rich soil (Table 3).

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

228

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

230

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

238 Soil orders are assigned largely on the basis of soil properties that reflect the

239 course of major soil developments; thus, C, N and P ratios of a specific soil order can
240 reflect the accumulated impact of climate, organisms, relief, parent material, and time
241 on soil chemical properties (Jenny, 1941). In China, only nine soil orders were found,
242 with Histosols and Andisols being the least frequent (Table 5). We found that
243 Histosols had the highest C: N ratio, while Vertisols and Entisols had the lowest.
244 With the exception of Histosols, the differences between C: N ratios and the eight
245 remaining soil orders in China were small (variance range from 10.73 to 13.38).
246 Histosols had the highest C: P (340) and N:P ratios (17.77), while Aridisols had the
247 lowest C:P (29.0) and N:P (2.60) ratios.

248

249 **Discussions**

250

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

252

253 Well-constrained C:N:P ratios in planktonic biomass were found to have important
254 impacts on nutrient cycles and biological processes in marine ecosystems. The
255 “Redfield-like” ratios were found in plants (e.g. Reich and Oleksyn 2004; McGroddy
256 et al. 2004) and soil microbial communities (e.g. Cleveland and Liptzin 2007). Could
257 the relatively fixed elemental ratios in terrestrial organisms (such as plant leaves, litters,
258 and microbes) result in consistent nutrient ratios in the soil just like that found by
259 Redfield (1958) in the marine ecosystem? Could the analysis of soil element ratios
260 provide insight into the nature of nutrient limitation in terrestrial ecosystems?

261 Cleveland and Liptzin (2007) studied the C:N:P stoichiometry in soil and stated that
262 similar to marine ecosystems, the atomic C:N:P ratios in the top soil were
263 well-constrained due to the interactions between the environment and soil organisms.
264 Their study, however, only focused on surface soils (typically 0-10 cm), which
265 represent organic-rich horizons, and their data were obtained from discrete publications.
266 The limited sample size (< 150) of their study also indicates that it is necessary for
267 further studies to verify the well-constrained relationships at the top soil.

268 Based on more than 2,437 soil profiles and over 8,000 soil layers across China,
269 we carried out the correlation analyses among soil total C, N and P and among total C,
270 total N and available P (Table 9), the results revealed that the C:N ratio of the
271 organic-rich soil layer was well-constrained considering the relatively high correlation
272 coefficient (0.93) among C and N concentrations. There were also relatively
273 constrained C:P and N:P ratios in the organic-rich soil layer (Correlation coefficients
274 were 0.62 and 0.51, respectively). This might imply that there has a relatively
275 constrained C:N:P ratio in the organic-rich soil layer as reported by Cleveland and
276 Liptzin (2007). In this sense, we agree with Cleveland and Liptzin (2007) on their
277 statement that “Redfield-like” interactions between C, N and P may exist in soil. We
278 found a similar C:N ratio (14.4) to that found by Cleveland and Liptzin (2007) in the
279 organic-rich soil layer, but we found lower C:P (136) and N:P (9.3) ratios; that the
280 C:N:P ratio (134:9:1) from this study is different from theirs (186:13:1) implies that
281 C:N:P ratios might change with environmental factors although C, N and P are
282 relatively well-constrained at the organic-rich topsoil. When came to the total soil

283 depth, there was no relatively constrained C:N:P stoichiometric ratios for deeper soil
284 (correlation coefficients are very low except that between total C and N, Table 9).
285 However, a well-constrained C:N ratio was found for the deeper soil considering its
286 higher correlation coefficient (0.88). Many previous studies (e.g. Vitousek 2004;
287 Melillo et al. 2003; Post et al. 1985) also found strong correlations between total C and
288 total N in the soil. As in the marine ecosystem where most of the soil N is fixed by
289 microorganisms, the relatively constrained C:N:P ratios in the topsoil reflect the ability
290 of terrestrial organisms to modify their abiotic environment to meet their nutrient
291 requirements.

292

293 Unlike the soil C and N, the weathering of the parent material, which is located
294 at the bottom of the soil profile, provides the major sources of available soil P (Walker
295 and Adams 1958). Soil P is further translocated by plants and accumulated in the
296 surface soil in the form of SOP resulting in a complex vertical distribution pattern in
297 the soil profile (Smeck 1985; Mellilo et al. 2003; Vitousek 2004). We found that the
298 C:P ratio decreased dramatically with the soil depth (Table 3). Walker and Adams
299 (1958) also found that as the soil depth increased, the C:P ratio declined much faster
300 than the C:N ratio. This is mainly because of the relatively stable soil P content
301 throughout the soil profile when compared to the rapid decline in SOC with soil depth
302 (Table 3). Through analyses of C: P and N: P ratios, we found that despite large
303 variations of C and N content, low soil P content always led to high C: P and N: P
304 ratios. This pattern indicates, as suggested by Walker and Adams (1958), that the

305 C:N:P ratio in the soil is mainly controlled by the P supply.

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

312

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

314

315 Climate imposes important controls both on soil development and on the biota and its
316 interaction with the soil nutrients (Chadwick et al. 1999; Vitousek 2004; Oleksyn
317 2004). Spatial distribution of soil C, N and P density across China has seen substantial
318 variation (Wang et al. 2003; Zhang et al. 2005; Tian et al. 2005). Despite the spatial
319 variations of C and N contents, the C:N ratio was relatively stable among climate
320 zones (Table 4), indicating the feedbacks of a similar biota on the chemical
321 composition of the soil. The C:P and N:P ratios, however, varied significantly among
322 different climate zones in China (Table 4). The element ratio highlights the impacts of
323 extreme climate regimes on soil nutrient balance. The high temperature and
324 precipitation in tropical-subtropical regions can result in high P leaching rate and P
325 occlusion in highly weathered soils (Vitousek and Walker 1987; Neufeldt et al. 2000;
326 Zhang et al. 2005). At the same time, the high productivity of tropical-subtropical

327 ecosystems maintains relatively high soil C and N content, which gave these regions
328 the highest C:P and N:P ratios. In contrast, the dry and cool climate regime in the
329 temperate desert resulted in low productivity, lower soil C and N contents and low P
330 loss through leaching, and higher soil P content, which gave it the lowest soil C:P and
331 N:P ratios among all the climate zones.

332 Site-level chronosequence studies have suggested that soil C:N:P ratios may
333 change during soil development, indicating a shift in soil limitation nutrients (Crews et
334 al. 1995; Chadwick et al. 1999; Frizano et al. 2002; Vitousek 2004). To capture the
335 pattern of elemental ratios of different soil developmental stages, we further grouped
336 the nine soil orders into three soil weathering classes: slight, moderate and strong
337 weathering soil (Brady and Weil 2002; Zhang et al. 2005). The soil C: N ratios
338 increased significantly ($P < 0.05$) with increasing soil weathering time (11.37, 12.32,
339 and 13.32, respectively) (Table 6). We also found that the strongly weathered soil
340 had the highest C: P ratio (99.0), while the C: P ratio of the moderately weathered soil
341 (63.1) was similar to that of the slight weathering soil (64.9). The N: P ratio showed
342 the same trend, with the highest N: P ratio in strong weathering soil (7.37), indicating P
343 deficiency in highly weathered soils. The N:P ratio was found to be the lowest in the
344 moderate weathering soil (5.41), which was not significantly lower than that of the
345 slight weathering soil (5.78). This result was similar to that reported by Crews et al.
346 (1995) and Vitousek (2004). Walker and Syers (1976) proposed that soil total P
347 decreases with increasing soil developmental time. We found the same pattern in this
348 study.

349

350 **Chinese vs. global soil C:N:P ratios**

351

352 While several studies have been conducted to explore the patterns among soil C:
353 N ratios, soil C: N ratios were not the primary focus of these studies. For example,
354 based on the global World Inventory of Soil Emission Potential (WISE) dataset
355 (<http://www.daac.ornl.gov>), Batjes (1996) studied the changing patterns of C: N ratios
356 in relation to soil depth (Table 7). The average C: N ratios of all the soil orders
357 reported by Batjes for 0-30, 30-50, and 50-100 cm depths (15.84, 14.93, and 13.36,
358 respectively) were higher than our corresponding values (12.65, 11.69, and 11.19,
359 respectively). Additionally, based on the WISE dataset, Batjes (1996, 2002) explored
360 the concentrations of soil C and N as well as C: N ratios of eleven soil orders around
361 the world (Table 7). The average C: N ratio reported by Batjes for all soil orders at
362 0-100 cm depth (14.42) was higher than our corresponding values. Both studies found
363 Histosols had the highest C: N ratio. Based on global soil C and N data of 2,700 soil
364 profiles from Oak Ridge National Laboratory (<http://www.dacc.ornl.gov>, Zinke et al.
365 1984), Post et al. (1982; 1985) reported global patterns of soil C and N storage and C:
366 N ratios in terms of the Holdridge life zones. We summarized the mass-based C:N
367 ratios and transformed them into mole-based ratios for climate zones: tundra/ Frigid
368 highland (20.3), cool temperate zone (20.2), warm temperate zone (20.6), and tropical
369 and subtropical zone (15.4), respectively. We found that all the C: N ratios reported by
370 Post et al. were higher than our results for each corresponding climate zone. These

371 differences might be due to some of the soil samples used in Post et al. (1985) having a
372 humified litter layer (i.e., 0 cm soil depth in the Zinke et al. 1984 dataset) which has a
373 higher C:N ratio than soil. For regional climate patterns, Post et al. (1985) indicated
374 that relatively large amounts of soil N in tropical and subtropical regions was
375 associated with both recalcitrant humic materials in an advanced state of decay and the
376 lowest C: N ratios, while slow decomposition in boreal regions resulted in higher C:N
377 ratios than in other regions. Since Post et al.'s research included no soil samples from
378 China, our dataset and analysis can provide valuable supplementary information for the
379 study of global soil C:N ratios. The reports for large-scale soil C:P and N:P ratio
380 patterns are limited. Recently, Cleveland and Liptzin (2007) estimated the global soil
381 C:P and N:P ratios of the surface soil (0-10 cm) to be 186 and 13.1, respectively. Our
382 analysis reveals relatively lower C:P (136) and N:P 9.3 ratios at the 0-10 cm soil in
383 China.

384

385 **Conclusions**

386 We found that the number-weighted average soil C: N, C: P, and N: P ratios in
387 China were 12, 61, and 5, respectively, with a C: N: P ratio of 60:5:1 for all soil layers.
388 The C:N ratio variation range among samples from different climate zones and
389 different soil depth was relatively small, while large spatial heterogeneity (both
390 horizontal and vertical) was found in C:P and N:P ratios. C:P and N:P ratios decreased
391 dramatically with increased soil depth. However, a highly constrained C:N:P ratio of
392 134:9:1 was found at the 0-10 cm organic-rich soil, which indicated reciprocal

393 interactions between terrestrial organisms and the abiotic soil environment in the
394 biologically active soil layer. The C:P and N:P ratios in the soil were primarily
395 determined by soil P content, which was controlled by the soil (parent material) type,
396 soil weathering stage, and climate factors that affect soil weathering rate. Certainly, the
397 C:N:P ratios derived from this analysis based on China's soil database are very
398 different than those derived from other studies based on global soil datasets.
399 Consequently, our dataset and analysis provides valuable supplementary information
400 for the study of global soil elemental ratios, especially C:P and N:P ratios.

401

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407

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- 502

503 **TABLE 1. Climate zones in China and their corresponding annual average**504 **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

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

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 (0-10cm)	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;

*The sample number for available P is 1,760;

[#] No area information for 394 soil samples.

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.

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 \pm 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 6. 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 7. 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.

TABLE 8. 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.

Table 9 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. Relatively well-constrained relationships ($P < 0.01$) were found among soil total C, N, P and available P at the organic-rich soil layer, while no significant correlations were found for C:N:P ratios in the deeper soil.

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 ($P < 0.001$)

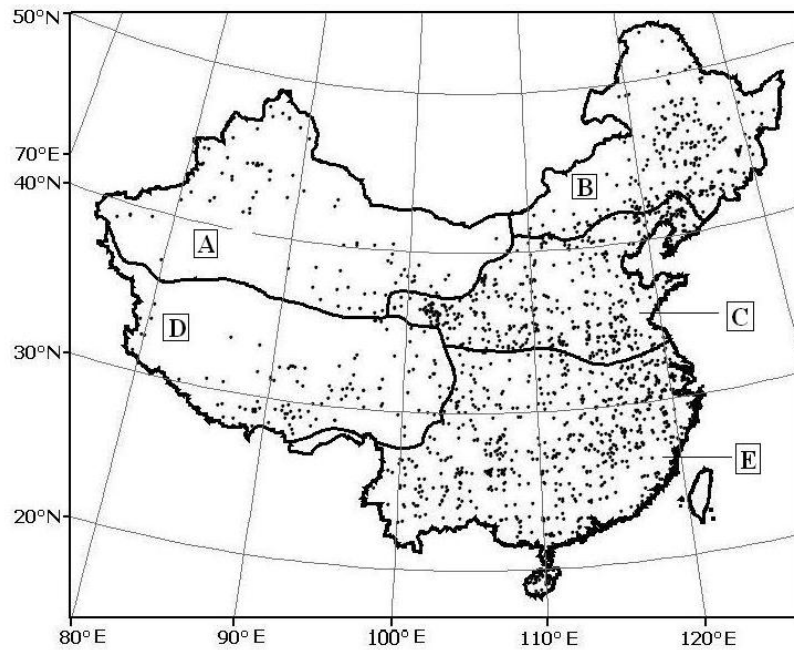


Fig. 1 Distribution of soil sampling points in China. Five zones were defined based on climate differences: (A) temperate desert; (B) cool temperate zone; (C) warm temperate zone; (D) frigid highland; (E) tropical & subtropical zone.

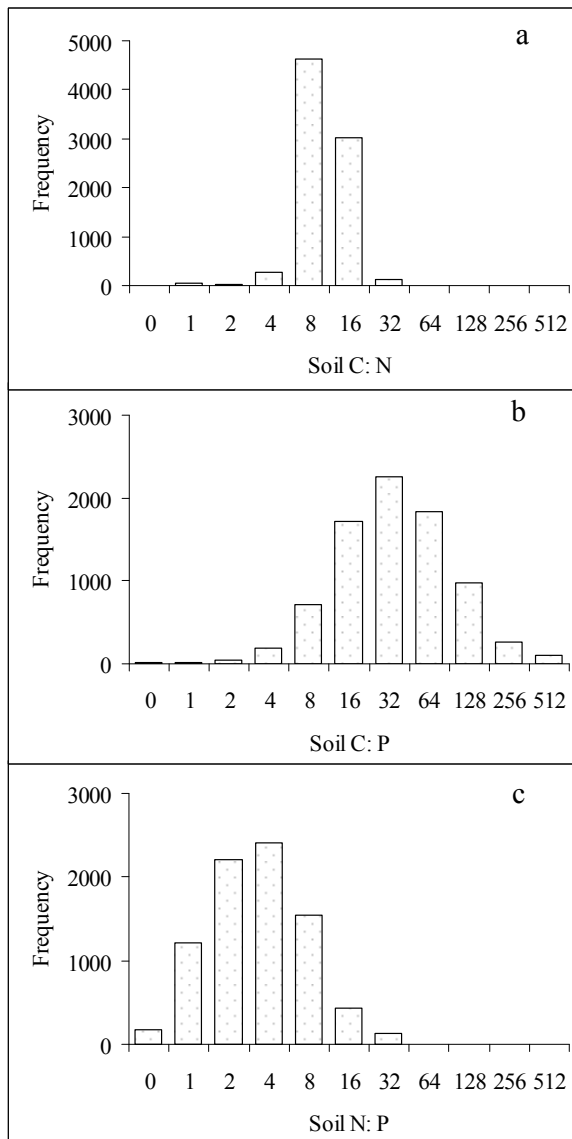
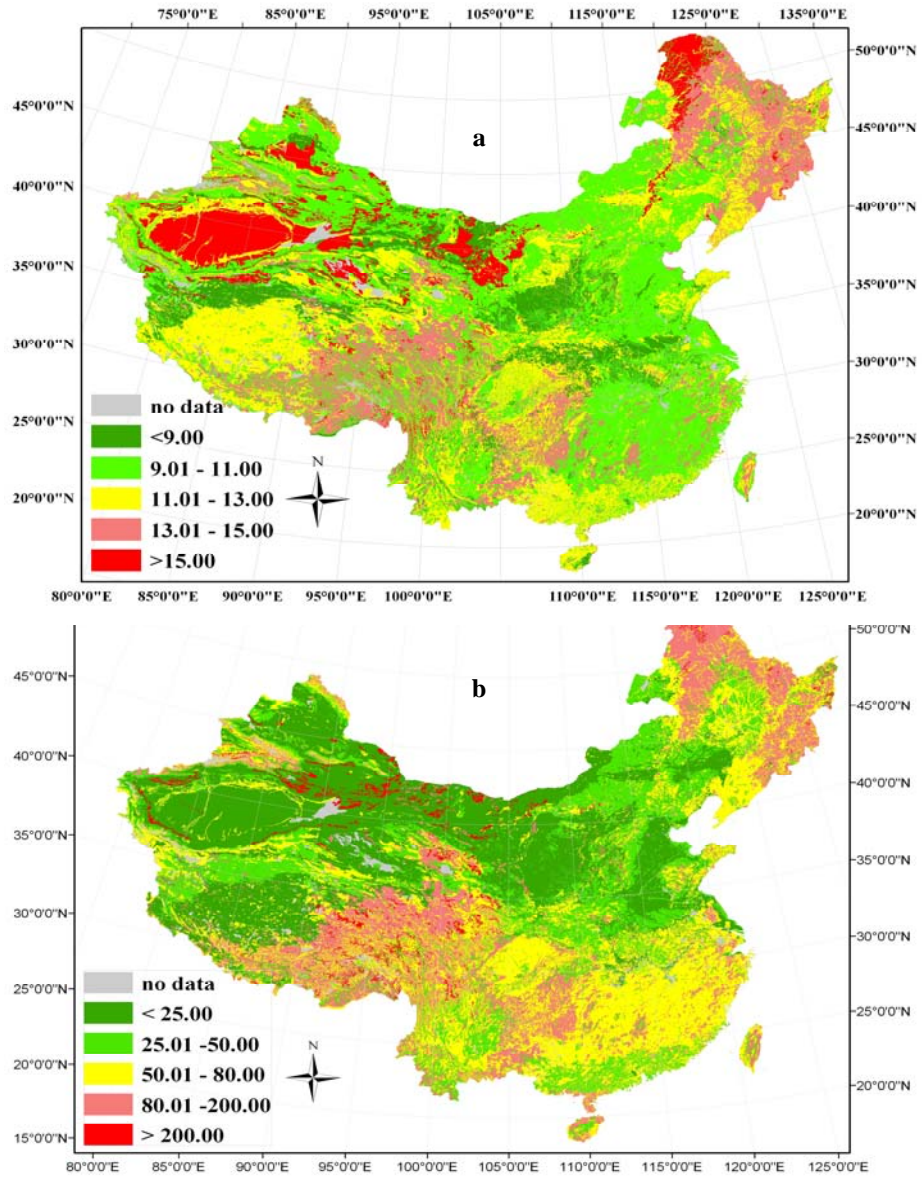


Fig. 2 Frequency distribution of soil C: N (a), C: P (b) and N: P (c) ratios in China. The x-axis of the histogram is presented using a log₂ scale to highlight the lognormal distribution.



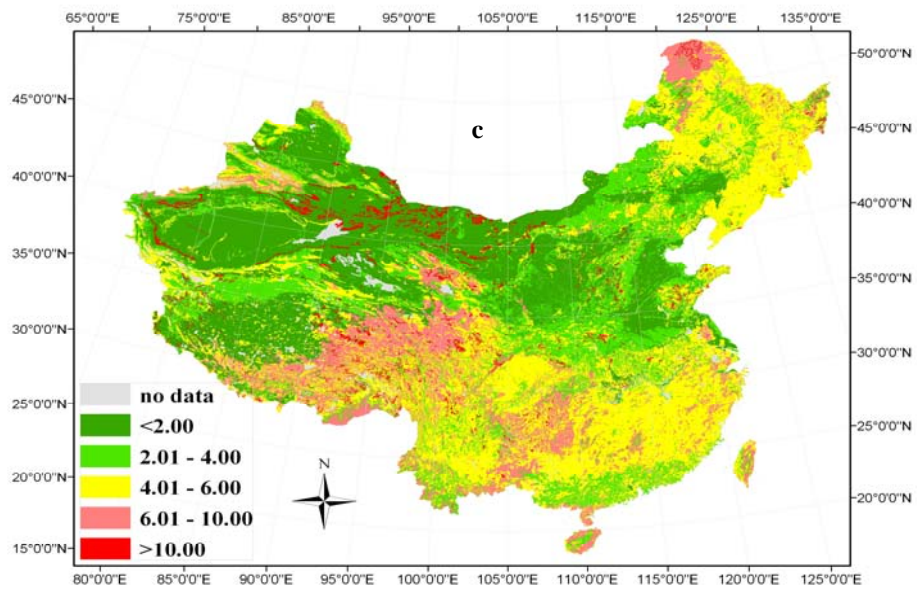


Fig. 3 Distribution of soil C: N, C: P and N: P ratios in China represented by C: N, C: P and N: P ratios of each soil sub-great group (a: C: N ratio; b: C: P ratio; c: N: P ratio).