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# Vertical Distribution of Soil Carbon, Nitrogen, and Phosphorus in Typical Chinese Terrestrial Ecosystems

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**Abstract:** Characterization of the vertical distribution of soil organic carbon (C), nitrogen (N), and phosphorus (P) may improve our ability to accurately estimate soil C, N, and P storage. Based on a database of 21 354 records in 74 long-term monitoring plots from 2004 to 2013 in the Chinese Ecosystem Research Network (CERN), we built fitting functions to quantify the vertical distribution of soil C, N, and P (up to 100 cm depth) in the typical Chinese terrestrial ecosystems. The decrease of soil C, N, and P content with depth can be well fitted with various mathematical functions. The fitting functions differed greatly between artificial (agriculture) and natural (desert, forest, and grassland) ecosystems, and also differed with respect to soil C, N, and P content. In both the artificial and natural ecosystems, the best fitting functions were exponential functions for C, quadratic functions for N, and quadratic functions for P. Furthermore, the stoichiometric ratios of soil C, N, and P were ranked in descending order: grassland > forest > agriculture > desert, and were also associated with climate. This study is the first to build the fitting functions for the profile distribution of soil C, N, and P in China at a national scale. Our findings provide a scientific basis to accurately assess the storage of C, N, and P in soils at a large scale, especially for the integrative analysis of historical data.
**Keywords:** soil profile; storage; stoichiometry; vertical distribution; China

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## 1 Introduction

Soil organic carbon (SOC), nitrogen (N), and phosphorus (P) are important indicators for soil fertility and quality (Andrews *et al*., 2004; Lal, 2004; Schindler, 2006). Soil is the largest SOC pool of terrestrial ecosystems (1500 Pg C) (Jobbagy and Jackson, 2000). Many studies have demonstrated that terrestrial ecosystems have a tremendous capacity to sequester atmospheric $CO_2$; thus, rational management could help partially offset anthropogenic $CO_2$ increase (Conant *et al*., 2001; He *et al*., 2008). N is essential for plant growth, and it is estimated that vegetation adsorbs about 50%–70% N from the soil (Dewes, 1999). Thus, N addition may significantly enhance primary productivity in most terrestrial ecosystems. Similarly, P is another important element for plant growth (Compton *et al*., 2000), and is mainly derived from soil parent material and fertilization (Wang *et al*., 1999). Consequently, P is considered as a limiting nutrient for plant growth at the geological time scale (Compton *et al*., 2000).

The cycles of C, N, and P in soils are closely corre-

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lated (Agren *et al*., 1991; Vitousek, 2004). Global warming resulting from an increase in atmospheric $CO_2$ alters the plant growth environment, and affects N and P turnover (Robinson *et al*., 1995). For example, rising temperature is expected to promote soil N mineralization and to enhance plant growth (Tong *et al*., 2005). Available P is influenced by the parent rock over a long time, but is mainly derived from the decomposition of litter and soil organic matter (SOM) over a short time (Kellogg and Bridgham, 2003). Climate warming impacts soil P availability by altering temperature and moisture, which control the decomposition of litter, SOM, and soil parent material (Robinson *et al*., 1995). Overall, the ecosystem C budget is restricted by soil N and P availability (Reich and Oleksyn, 2004), because they affect plant growth and control the accumulation and decomposition of SOM (Hobbie and Vitousek, 2000; Harrington *et al*., 2001). Furthermore, soil N and P availability may affect the N and P content of plants and thus plant photosynthesis (Cordell *et al*., 2001a; 2001b). Understanding the profile distributions of soil C, N, and P may therefore provide a solid foundation for exploring how these cycles are coupled.

Some studies have demonstrated that the vertical distribution of soil C, N, and P at specific sites or regions. Alvarez *et al*. (2011) studied the vertical distribution of C and N in the 0–30 cm soil layer under different management practices in Argentina. van der Wal *et al*. (2007) reported the P vertical distribution of 0–30 cm soil at an abandoned farmland in the Netherlands. Furthermore, Liu *et al*. (2012) reported the C vertical distribution of brown soil to a depth of 60 cm under different land use types in China. Qiu *et al*. (2012) investigated the profile distribution of P in red, alluvial, and purple soils in China. Wang *et al*. (2004) estimated the SOC vertical distribution and its relationship to climate and vegetation in Chinese terrestrial ecosystems based on soil geographic and vertical attribute data from the Chinese Second Soil Survey Database. However, it remains unclear whether the vertical distributions of soil C, N, and P can be fitted by mathematic functions, and whether the fitting functions remain consistent in different ecosystem types.

To date, the fitting functions of the vertical distributions of soil C, N, and P have not been reported at large scale. Possible reasons included the inconsistence of sampling and analytical methods in historical datasets, a deficiency of replicates, and a lack of data for deeper soil layers. Fortunately, the long-term monitoring program of the Chinese Ecosystem Research network (CERN) has overcome these limitations, through implementing consistent sampling designs and measurement methods over a long time period. In this study, a database of containing monitoring records at 74 long-term experimental plots in CERN were used to quantitatively assess the vertical distributions of C, N, and P in the 0–100 cm soil profile. The main objectives were to: 1) establish the fitting functions for the vertical distribution of soil C, N, and P in Chinese typical terrestrial ecosystems; 2) explore whether the fitting functions are consistent among different ecosystem types, and 3) provide scientific parameters for the accurate estimation of soil C and N storage at regional and national scales.

## 2 Materials and Methods

### 2.1 Study area and data processing

The study area covers most of the typical terrestrial ecosystems in China. In order to explore the fitting functions of soil C, N, and P profile distribution in typical terrestrial ecosystems in China, we used the data from the long-term monitoring experimental plots at field stations of CERN (www.cerndata.ac.cn) (Fu *et al*., 2010) (Fig. 1).

In the data processing, we only selected 33 field stations that have been regularly monitored for more than 10 years. At each station, more than 2 plots were selected. If a specific station contained different ecosystem types (agriculture, forest, grassland, and desert), we selected 2 plots for each ecosystem type. A total of 74 experimental plots were selected, and the description (e.g., ecosystem type, topography, soil type, and dominant species) for each plot was provided in Table 1.

### 2.2 Measurements of C, N, and P

A total of 21 354 records were available for soil C, N, and P in 0–100 cm soil depth from 2004 to 2013. The SOC content (g/kg) was measured using the modified Mebius method (Nelson and Sommers, 1982). Total N (TN) content (g/kg) was measured using the modified Kjeldahl wet digestion procedure (Gallaher *et al*., 1976). Total P (TP) content (g/kg) was determined by the ammonium molybdate method after persulfate oxidation (Kuo, 1996).

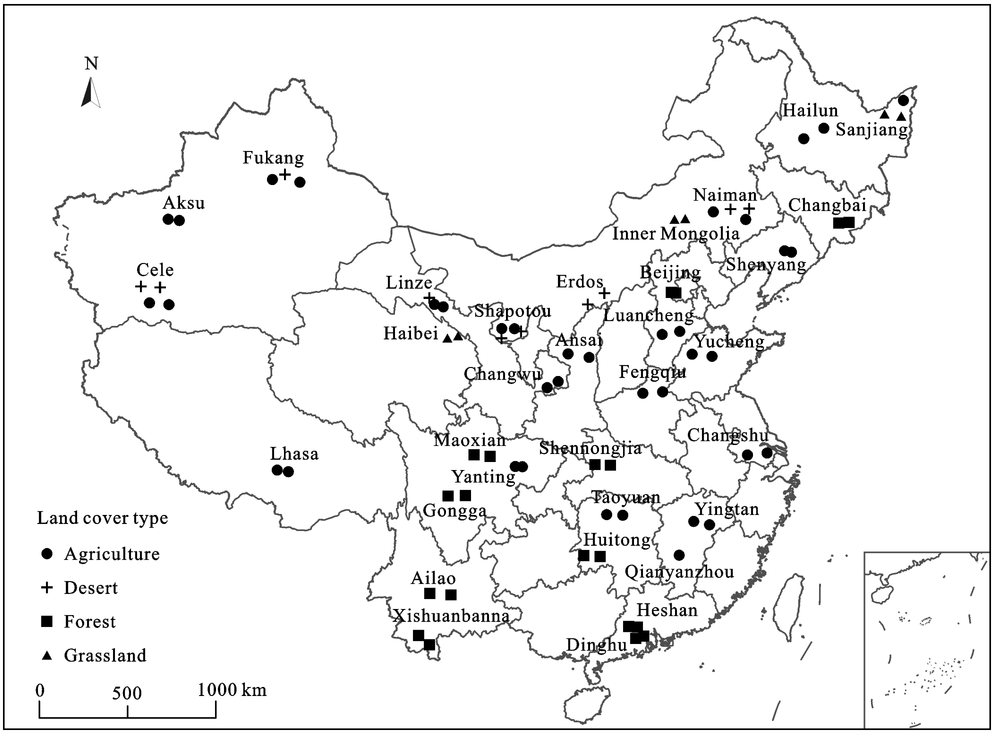


**Fig. 1** Long-term experimental plots of Chinese Ecosystem Research Network (CERN) used in this study. Different ecosystem types of experimental plots in each ecological station were represented as different shape in legend. Names were informal abbreviations for each station

**Table 1** Information of long-term monitoring plots of Chinese Ecosystem Research Network (CERN) in this study

| Ecological station type | Station | Ecosystem type | Plot No. | Topography | Soil type | Dominant species |
|---|---|---|---|---|---|---|
| | Aksu | Agriculture | A | Flat ground | Irrigation-farming soil | Cotton |
| | | | B | Flat ground | Irrigation-farming soil | Cotton |
| | Ansai | Agriculture | A | Terrace | Cultivated loessial soil | Spring maize, maize, soybean |
| | | | B | Terrace | Cultivated loessial soil | Spring maize, maize, soybean |
| | Changshu | Agriculture | A | Flat ground | Paddy soil | Wheat, rice |
| | | | B | Flat ground | Paddy soil | Wheat, rice |
| | Fengqiu | Agriculture | A | Flat ground | Fluvo-aquic soil | Maize, wheat |
| | | | B | Flat ground | Fluvo-aquic soil | Maize, wheat |
| | Hailun | Agriculture | A | Flat ground | Black soil | Maize, wheat, soybean |
| | | | B | Flat ground | Black soil | Maize, soybean |
| | Lhasa | Agriculture | A | Flat ground | Fluvo-aquic soil | Winter wheat, Spring barley |
| | | | B | Flat ground | Fluvo-aquic soil | Winter wheat, rape |
| Agriculture | Linze | Desert | A | Flat ground | Gray-brown desert soil | *Nitraria sphaerocarpa* |
| | | Agriculture | A | Flat ground | Aeolian sandy soil | Maize, wheat, spring wheat |
| | | | B | Flat ground | Aeolian sandy soil | Maize, wheat, alfalfa |
| | Luancheng | Agriculture | A | Flat ground | Meadow cinnamon soil | Wheat, maize |
| | | | B | Flat ground | Meadow cinnamon soil | Wheat, maize |
| | Qianyanzhou | Agriculture | A | Flat ground | Hydromorphic paddy soil | Rice |
| | Shenyang | Agriculture | A | Flat ground | Aquic brown soil | Maize, soybean |
| | | | B | Flat ground | Aquic brown soil | Maize, soybean |
| | Taoyuan | Agriculture | A | Flat ground | Paddy soil | Rice |
| | | | B | Flat ground | Paddy soil | Rice |
| | Yanting | Agriculture | A | Slop land | Calcareous purple soil | Maize, wheat |
| | | | B | Slop land | Calcareous purple soil | Maize, wheat, rape |
| | Yingtan | Agriculture | A | Gentle slope | Red soil | Peanut |

Continued table

| Ecological station type | Station | Ecosystem type | Plot No. | Topography | Soil type | Dominant species |
|---|---|---|---|---|---|---|
| Agriculture | | | B | Flat ground | Red soil | Peanut |
| | Yucheng | Agriculture | A | Flat ground | Saline flavo-aquic soil | Maize, wheat |
| | | | B | Flat ground | Saline flavo-aquic soil | Maize, wheat |
| | Changwu | Agriculture | A | Flat ground | Dark loessial soil | Wheat, maize |
| | | | B | Flat ground | Dark loessial soil | Wheat |
| Forest | Ailao | Forest | A | Slope land | Mountain yellow-brown soil | Evergreen broad-leaved forest |
| | | | B | Slope land | Brown soil | *Planus coppice* |
| | Xishuanbanna | Forest | A | Slope land | Humid-thermo ferralitic soil | Seasonal rainforest |
| | | | B | Slope land | Humid-thermo ferralitic soil | Secondary forest (valley) |
| | Heshan | Forest | A | Low hill | Lateritic red soil | Acacia mangium forest |
| | | | B | Low hill | Lateritic red soil | *Schima superba*, *Castanopsis hystrix* |
| | Beijing | Forest | A | Slope land | Mountain brown soil | Deciduous broadleaved mixed forest |
| | | | B | Slope land | Mountain brown soil | North China larch |
| | Dinghu | Forest | A | Slope land | Lateritic red soil | Subtropical evergreen broadleaved forest |
| | | | B | Slope land | Lateritic red soil | Masson pine forest |
| | Gongga | Forest | A | Slope land | Brown coniferous forest soil | *Abies fabri* |
| | | | B | Gentle slope | Skeleton soil | *A. fabri*, *Populus purdomii* |
| | Huitong | Forest | A | Slope land | Yellow soil | Coniferous forest |
| | | | B | Slope land | Yellow soil | Coniferous forest |
| | Maoxian | Forest | A | Slope land | Cinnamon soil | Coniferous and broadleaved mixed forest |
| | | | B | Slope land | Brown soil | Deciduous broad-leaved shrub |
| | Shennongjia | Forest | A | Slope land | Mountain yellow-brown soil | Evergreen broadleaf mixed forest |
| | | | B | Slope land | Mountain dark-brown soil | Coniferous forest |
| | Changbai | Forest | A | Flat ground | Dark-brown soil | Broad-leaved korean pine forest |
| | | | B | Flat ground | Dark-brown soil | Birch forest |
| Grassland | Inner Mongolia | Grassland | A | Flat ground | Dark chestnut soil | *Leymus chinensis* |
| | | | B | Flat ground | Chestnut soil | *Stipa grandis* |
| | Haibei | Grassland | A | Flat ground | Felty soil | Alpine *kobresia* meadow |
| | | | B | Flat ground | Dark felty soil | Alpine *kobresia* meadow |
| | Sanjiang | Grassland | A | Depression | Bog soil | Carex |
| | | | B | Flat ground | Bog soil | *Deyeuxia angustifolia* |
| | | Agriculture | A | Flat ground | Albic soil | Soybean, wheat, maize |
| Desert | Erdos | Desert | A | Gentie dune | Aeolian sandy soil | *Artemisia ordosica* |
| | | | B | Gentie dune | Aeolian sandy soil | *A. ordosica* |
| | Cele | Desert | A | Dune | Aeolian sandy soil | *Alhagi sparsifolia* |
| | | | B | Dune | Aeolian sandy soil | *A. sparsifolia* |
| | | Agriculture | A | Flat ground | Aeolian sandy soil | Cotton |
| | | | B | Flat ground | Aeolian sandy soil | Cotton |
| | Fukang | Desert | A | Flat ground | Aeolian sandy soil | *Haloxylon ammodendron* |
| | | Agriculture | A | Flat ground | Gray desert soil | Cotton, wheat, maize |
| | | | B | Flat ground | Gray desert soil | Wheat, winter wheat |
| | Naiman | Desert | A | Flat ground | Meadow aeolian sandy soil | *Artemisia annua* |
| | | | B | Gentle slope | Aeolian sandy soil | *Caragana microphylla* |
| | | Agriculture | A | Flat ground | Meadow aeolian sandy soil | Soybean, wheat, maize |
| | | | B | Flat ground | Meadow aeolian sandy soil | Maize |
| | Shapotou | Desert | A | Flat ground | Aeolian sandy soil | *Artemisia ordosica* |
| | | | B | Fat ground | Aeolian sandy soil | *Artemisia ordosica* |
| | | Agriculture | A | Flat ground | Cumulated irrigated soil | Maize, wheat |
| | | | B | Flat ground | Cumulated irrigated soil | Maize, wheat |

Note: A and B represent different experimental plots with different dominant species or ecosystem types in the same ecological station

### 2.3 Classification of ecosystem types and climate zones

All plots were divided into four ecosystem types (agriculture, forest, grassland, and desert) and six climatic zones (temperate, warm temperate, north subtropical, mid-subtropical, south subtropics, and Tibetan Plateau zones) (Zhang *et al.*, 2010) to explore the general trends.

### 2.4 Curve estimation

The soil C, N, and P content was first averaged at different depths for the 10-year monitoring period. The data were then analyzed by Curve Estimation of SPSS 13.0, which contain quadratic, compound, growth, logarithmic, S, exponential, inverse, and power functions.

When the coefficient ($R^2$) of the fitting functions was similar, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were used to determine the best fit function, from which functions with smaller AIC and BIC values were selected (Bozdogan, 1987; Aho *et al.*, 2014). In practice, AIC and BIC were calculated as follows:

$$AIC = n \times \ln(Rss/n) + 2(k+1) \quad (1)$$

$$BIC = n \times \ln(Rss/n) + 2(k+1) \times \ln(n) \quad (2)$$

where *RSS* is the residual sum of squares; *n* is the number of observations, and *k* is the number of estimated parameters.

## 3 Results

### 3.1 Vertical distribution of soil C, N, and P content

The profile distribution of soil C, N, and P content was higher in the upper soil layer compared to the deep soil layer, irrespective of vegetation types or climate zones. For example, Figs. 2–4 show that soil C, N, and P content significantly decreases with increasing soil depth in agriculture (Fengqiu-A), forest (Xishuangbanna-A), grassland (Inner Mongolia-A), and desert ecosystems (Shapotou-A). Similar trends were observed in other plots (data not shown).

### 3.2 Fitting functions for vertical distribution of soil C, N, and P

As shown in Table 2, the vertical distribution of soil C,

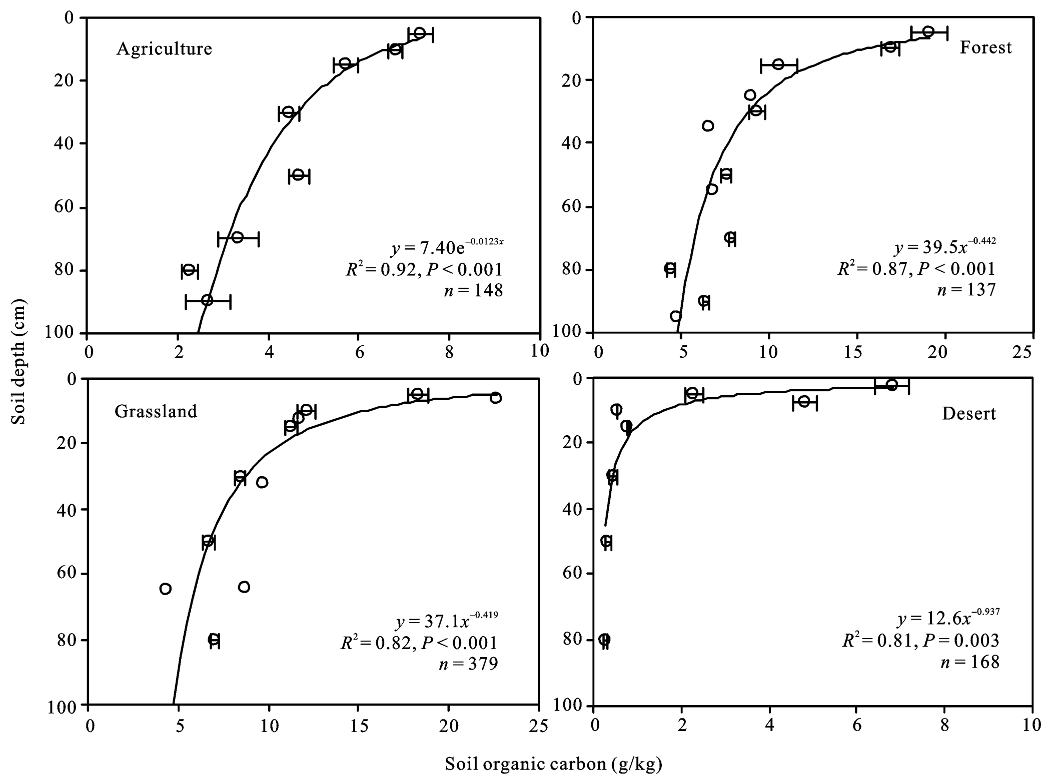


**Fig. 2** Vertical distribution of soil organic carbon of typical terrestrial ecosystems. Agriculture: Fengqiu-A; forest: Xishuangbanna-A; grassland: Inner Mongolia-A; desert: Shapotou-A. In the functions, *y* and *x* represent soil organic carbon (g/kg) and soil depth (cm), respectively

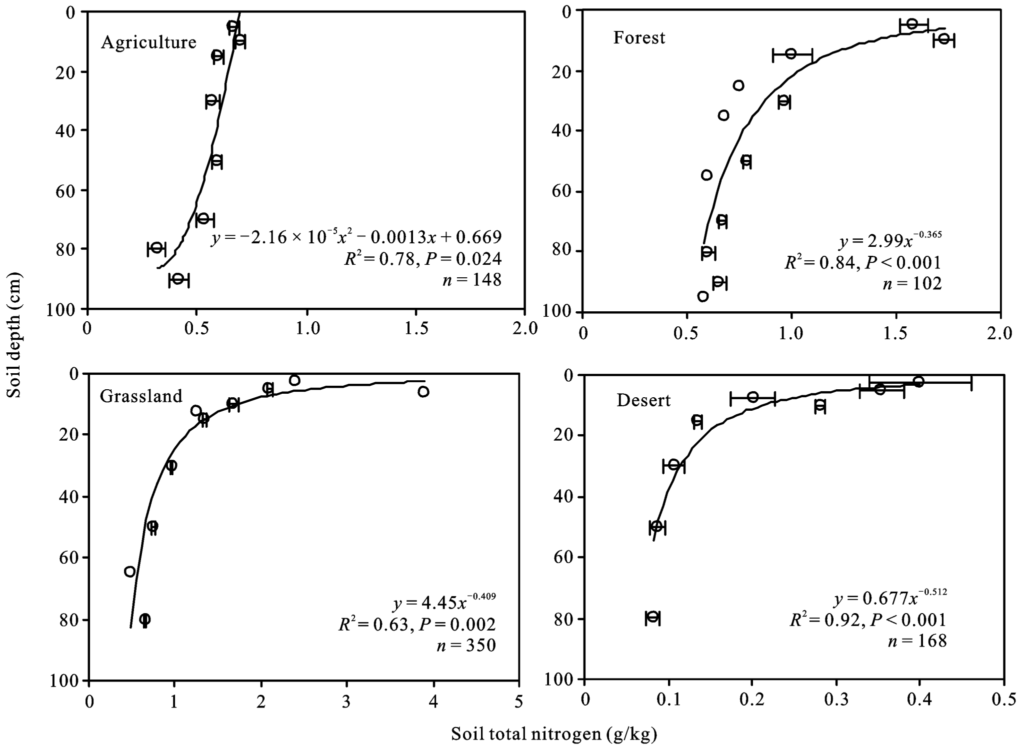


**Fig. 3** Vertical distribution of soil total nitrogen of typical terrestrial ecosystems. Agriculture: Fengqiu-A; forest: Xishuangbanna-A; grassland: Inner Mongolia-A; desert: Shapotou-A. In the functions, $y$ and $x$ represent soil total nitrogen (g/kg) and soil depth (cm)

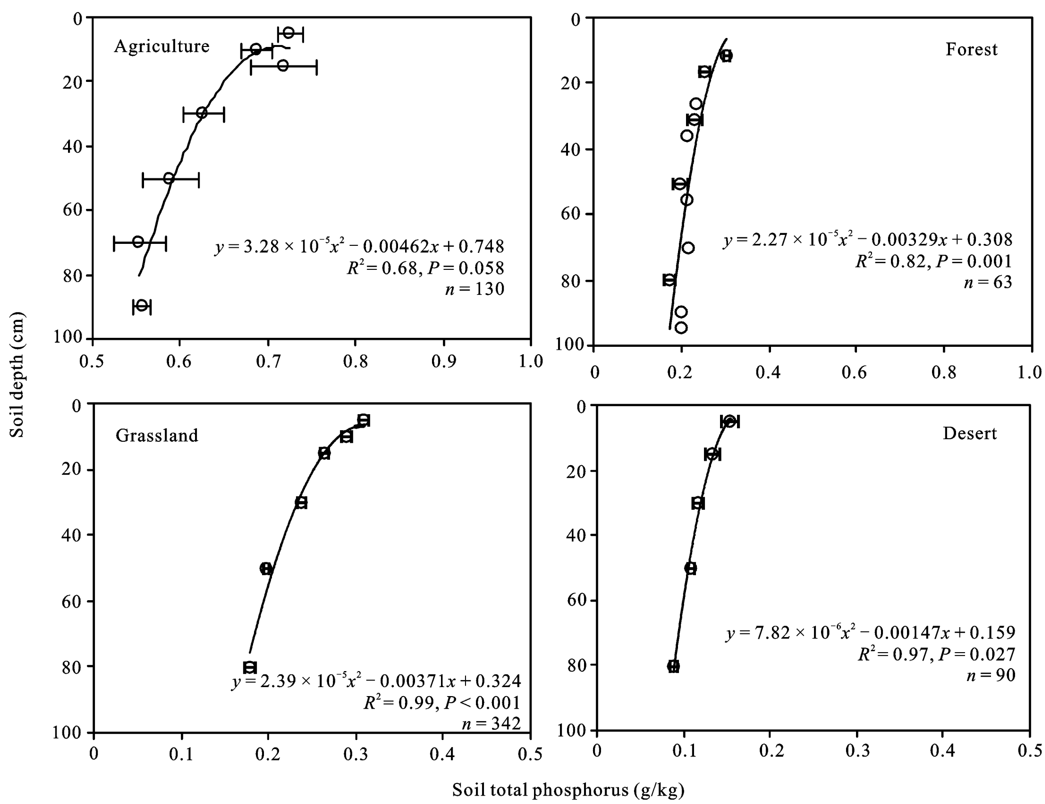


**Fig. 4** Vertical distribution of soil total phosphorus of typical terrestrial ecosystems. Agriculture: Fengqiu-A; forest: Xishuangbanna-A; grassland: Inner Mongolia-A; desert: Shapotou-A. In the functions, $y$ and $x$ represent soil total phosphorus (g/kg) and soil depth (cm)

**Table 2** Fitting functions of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) against soil depth in 0–100 cm soil profile of typical terrestrial ecosystems in China

| Ecosystem type | Station | Plot No. | SOC | | | TN | | | TP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Function | $R^2$ | $P$ | Function | $R^2$ | $P$ | Function | $R^2$ | $P$ |
| Agriculture | Aksu | A | $y=6.26e^{-0.0127x}$ | 0.94 | 0.006 | $y=7.41\times10^{-5}x^2-0.0124x+0.740$ | 0.92 | 0.085 | $y=8.07\times10^{-5}x^2-0.0111x+0.926$ | 0.85 | 0.150 |
| | | B | $y=4.15e^{-0.00855x}$ | 0.83 | 0.033 | $y=7.25\times10^{-5}x^2-0.0095x+0.514$ | 0.95 | 0.054 | $y=1.57\times10^{-5}x^2-0.0043x+0.818$ | 0.95 | 0.049 |
| | Ansai | A | $y=6.28e^{-0.0137x}$ | 0.96 | 0.004 | $y=5.04\times10^{-5}x^2-0.0095x+0.710$ | 0.99 | 0.005 | $y=2.93\times10^{-5}x^2-0.0046x+0.731$ | 0.99 | 0.006 |
| | | B | $y=4.91e^{-0.00768x}$ | 0.99 | 0.001 | $y=-1.07\times10^{-6}x^2-0.0021x+0.495$ | 0.99 | 0.008 | $y=8.57\times10^{-6}x^2-0.0022x+0.668$ | 0.89 | 0.113 |
| | Changshu | A | $y=26.8e^{-0.0361x}$ | 0.78 | <0.001 | $y=4.35\times10^{-4}x^2-0.0649x+2.78$ | 0.95 | <0.001 | $y=-3.66\times10^{-6}x^2-0.0025x+0.819$ | 0.47 | 0.057 |
| | | B | $y=22.7e^{-0.0213x}$ | 0.94 | <0.001 | $y=4.12\times10^{-4}x^2-0.0574x+2.51$ | 0.95 | <0.001 | $y=-9.48\times10^{-5}x^2-0.0022x+0.734$ | 0.91 | 0.002 |
| | Fengqiu | A | $y=7.40e^{-0.0123x}$ | 0.92 | <0.001 | $y=-2.16\times10^{-5}x^2-0.0013x+0.669$ | 0.78 | 0.024 | $y=3.28\times10^{-5}x^2-0.0046x+0.748$ | 0.68 | 0.058 |
| | | B | $y=6.40e^{-0.00942x}$ | 0.90 | <0.001 | $y=-2.10\times10^{-5}x^2-0.0013x+0.584$ | 0.78 | 0.024 | $y=3.10\times10^{-5}x^2-0.0040x+0.677$ | 0.89 | 0.004 |
| | Hailun | A | $y=29.7e^{-0.0151x}$ | 0.97 | <0.001 | $y=2.78e^{-0.0169x}$ | 0.94 | 0.001 | $y=1.22\times10^{-4}x^2-0.0153x+1.03$ | 0.89 | 0.036 |
| | | B | $y=29.8e^{-0.0155x}$ | 0.97 | <0.001 | $y=2.60e^{-0.0161x}$ | 0.96 | 0.001 | $y=4.30\times10^{-5}x^2-0.0085x+0.920$ | 0.94 | 0.015 |
| | Lhasa | A | $y=15.3e^{-0.0221x}$ | 0.98 | 0.001 | $y=1.61e^{-0.0185x}$ | 0.98 | 0.002 | $y=6.57\times10^{-5}x^2-0.0070x+0.858$ | 0.89 | 0.327 |
| | | B | $y=10.6e^{-0.0199x}$ | 0.99 | <0.001 | $y=1.17\times10^{-4}x^2-0.0174x+1.11$ | 0.97 | 0.032 | $y=-6.91\times10^{-6}x^2-0.0034x+0.782$ | 0.99 | 0.066 |
| | Linze | A | $y=28.9x^{-0.891}$ | 0.91 | 0.003 | $y=1.54\times10^{-4}x^2-0.0190x+0.643$ | 0.95 | 0.010 | $y=6.09\times10^{-5}x^2-0.0072x+0.445$ | 0.96 | 0.007 |
| | | B | $y=59.6x^{-1.06}$ | 0.93 | 0.002 | $y=2.41\times10^{-4}x^2-0.0297x+0.919$ | 0.98 | 0.004 | $y=7.87\times10^{-5}x^2-0.0099x+0.537$ | 0.95 | 0.012 |
| | Luancheng | A | $y=30.2x^{-0.538}$ | 0.92 | 0.003 | $y=2.77\times10^{-4}x^2-0.0342x+1.42$ | 0.98 | 0.003 | $y=-0.175\ln x+1.10$ | 0.86 | 0.008 |
| | | B | $y=20.1x^{-0.409}$ | 0.86 | 0.007 | $y=2.10\times10^{-4}x^2-0.0264x+1.19$ | 0.94 | 0.016 | $y=1.03\times10^{-4}x^2-0.0152x+0.883$ | 0.99 | 0.009 |
| | Qianyanzhou | A | $y=57.8x^{-0.780}$ | 0.91 | <0.001 | $y=4.23\times10^{-4}x^2-0.0482x+1.56$ | 0.92 | <0.001 | $y=4.84\times10^{-5}x^2-0.0058x+0.291$ | 0.94 | 0.003 |
| | Shenyang | A | $y=16.3x^{-0.243}$ | 0.90 | 0.001 | $y=-0.154\ln x+1.39$ | 0.83 | 0.004 | $y=6.37\times10^{-5}x^2-0.0058x+0.582$ | 0.87 | 0.047 |
| | | B | $y=17.2x^{-0.243}$ | 0.78 | 0.009 | $y=-0.130\ln x+1.31$ | 0.76 | 0.011 | $y=2.65\times10^{-6}x^2+0.0016x+0.477$ | 0.40 | 0.362 |
| | Taoyuan | A | $y=23.3x^{-0.311}$ | 0.82 | 0.005 | $y=1.35e^{-0.00916x}$ | 0.73 | 0.014 | $y=6.93\times10^{-5}x^2-0.0080x+0.611$ | 0.90 | 0.011 |
| | | B | $y=18.1e^{-0.0165x}$ | 0.97 | <0.001 | $y=2.17\times10^{-4}x^2-0.0339x+1.83$ | 0.95 | 0.013 | $y=3.22\times10^{-5}x^2-0.0036x+0.505$ | 0.99 | 0.001 |
| | Yanting | A | $y=11.9x^{-0.352}$ | 0.94 | 0.006 | $y=-0.172\ln x+1.12$ | 0.89 | 0.017 | $y=9.57\times10^{-5}x^2-0.0091x+0.750$ | 0.69 | 0.314 |
| | | B | $y=6.14e^{-0.0121x}$ | 0.57 | 0.049 | $y=-1.13\times10^{-4}x^2+6.41\times10^{-5}x+0.720$ | 0.07 | 0.867 | $y=-1.08\times10^{-4}x^2-0.0053x+0.670$ | 0.12 | 0.776 |
| | Yingtan | A | $y=6.50e^{-0.0193x}$ | 0.94 | <0.001 | $y=5.95\times10^{-5}x^2-0.0101x+0.726$ | 0.94 | 0.004 | $y=5.82\times10^{-5}x^2-0.0074x+0.492$ | 0.95 | 0.003 |
| | | B | $y=8.51e^{-0.0204x}$ | 0.98 | <0.001 | $y=1.21\times10^{-4}x^2-0.0171x+0.925$ | 0.97 | 0.001 | $y=1.56\times10^{-4}x^2-0.0179x+0.751$ | 0.98 | <0.001 |
| | Yucheng | A | $y=31.5x^{-0.609}$ | 0.91 | 0.003 | $y=1.92\times10^{-4}x^2-0.0263x+1.18$ | 0.93 | 0.017 | $y=9.45\times10^{-5}x^2-0.0127x+0.989$ | 0.89 | 0.038 |
| | | B | $y=5.85e^{-0.0127x}$ | 0.98 | <0.001 | $y=4.43\times10^{-5}x^2-0.0080x+0.693$ | 0.99 | 0.002 | $y=9.20\times10^{-6}x^2-0.0017x+0.661$ | 0.88 | 0.044 |
| | Changwu | A | $y=10.6x^{-0.139}$ | 0.79 | 0.001 | $y=4.36\times10^{-5}x^2-0.0075x+0.991$ | 0.87 | 0.001 | $y=6.12\times10^{-5}x^2-0.0083x+0.896$ | 0.85 | 0.001 |
| | | B | $y=10.4x^{-0.141}$ | 0.76 | 0.024 | $y=7.46\times10^{-5}x^2-0.0098x+0.943$ | 0.91 | 0.027 | $y=4.63\times10^{-5}x^2-0.0069x+0.848$ | 0.92 | 0.024 |
| | Cele | A | $y=2.90e^{-0.00537x}$ | 0.83 | 0.004 | $y=1.07\times10^{-5}x^2-0.0027x+0.429$ | 0.80 | 0.041 | $y=2.92\times10^{-5}x^2-0.0034x+0.641$ | 0.98 | 0.004 |
| | | B | $y=6.84x^{-0.292}$ | 0.73 | 0.015 | $y=5.48\times10^{-5}x^2-0.0081x+0.564$ | 0.86 | 0.018 | $y=5.60\times10^{-5}x^2-0.0073x+0.795$ | 0.86 | 0.052 |
| | Fukang | A | $y=7.24e^{-0.0188x}$ | 0.98 | <0.001 | $y=5.16\times10^{-5}x^2-0.0109x+0.742$ | 0.93 | 0.001 | $y=-2.21\times10^{-5}x^2+5.88\times10^{-4}x+0.538$ | 0.02 | 0.951 |
| | | B | $y=10.3x^{-0.273}$ | 0.78 | 0.020 | $y=1.48\times10^{-4}x^2-0.0127x+0.587$ | 0.87 | 0.045 | $y=-1.14\times10^{-4}x^2-0.0147x+0.510$ | 0.18 | 0.743 |
| | Naiman | A | $y=8.41x^{-0.192}$ | 0.42 | 0.002 | $y=1.47/x+0.443$ | 0.45 | 0.001 | $y=3.51\times10^{-5}x^2-0.0081x+0.741$ | 0.36 | 0.019 |
| | | B | $y=e^{3.59/x+0.873}$ | 0.85 | 0.009 | $y=1.04\times10^{-4}x^2-0.0109x+0.549$ | 0.93 | 0.019 | $y=1.73\times10^{-4}x^2-0.0189x+0.940$ | 0.42 | 0.438 |
| | Shapotou | A | $y=6.93e^{-0.0309x}$ | 0.89 | <0.001 | $y=2.08\times10^{-4}x^2-0.0255x+0.852$ | 0.97 | <0.001 | $y=1.22\times10^{-4}x^2-0.0158x+0.637$ | 0.87 | 0.001 |
| | | B | $y=40.6x^{-0.954}$ | 0.89 | <0.001 | $y=2.08\times10^{-4}x^2-0.0256x+0.832$ | 0.93 | 0.001 | $y=1.24\times10^{-4}x^2-0.0153x+0.553$ | 0.95 | 0.051 |
| | Sanjiang | A | $y=42.9x^{-0.376}$ | 0.64 | 0.001 | $y=6.49x^{-0.538}$ | 0.71 | <0.001 | $y=1.94\times10^{-5}x^2-0.0089x+0.969$ | 0.39 | 0.065 |

Continued table

| Ecosystem type | Station | Plot No. | SOC | | | TN | | | TP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Function | $R^2$ | $P$ | Function | $R^2$ | $P$ | Function | $R^2$ | $P$ |
| Forest | Ailao | A | $y=132e^{-0.0199x}$ | 0.99 | <0.001 | $y=8.90e^{-0.0186x}$ | 0.99 | <0.001 | $y=1.26e^{-0.00695x}$ | 0.96 | <0.001 |
| | | B | $y=119e^{-0.0279x}$ | 0.98 | <0.001 | $y=6.08e^{-0.0260x}$ | 0.99 | <0.001 | $y=8.96\times10^{-5}x^2-0.0122x+0.822$ | 0.50 | 0.355 |
| | Beijing | A | $y=21.0e^{-0.0299x}$ | 0.98 | <0.001 | $y=0.00109x^2-0.133x+4.41$ | 0.99 | <0.001 | $y=1.37\times10^{-4}x^2-0.0148x+0.575$ | 0.98 | 0.004 |
| | | B | $y=25.8x^{-0.0325}$ | 0.99 | <0.001 | $y=4.54e^{-0.0309x}$ | 0.99 | <0.001 | $y=5.63\times10^{-5}x^2-0.0084x+0.552$ | 0.99 | <0.001 |
| | Dinghu | A | $y=93.3x^{-0.653}$ | 0.87 | <0.001 | $y=3.68\times10^{-4}x^2-0.0426x+1.70$ | 0.53 | 0.033 | $y=0.676/x+0.174$ | 0.88 | 0.001 |
| | | B | $y=37.1x^{-0.611}$ | 0.77 | <0.001 | $y=2.35/x+0.248$ | 0.81 | <0.001 | $y=5.04\times10^{-5}x^2-0.0029x+0.225$ | 0.55 | 0.060 |
| | Gongga | A | $y=481x^{-0.919}$ | 0.62 | <0.001 | $y=23.5x^{-0.697}$ | 0.72 | 0.001 | $y=e^{-4.22/x+0.376}$ | 0.93 | <0.001 |
| | | B | $y=e^{11.6/x+1.59}$ | 0.98 | <0.001 | $y=58.1x^{-1.43}$ | 0.91 | <0.001 | $y=1.08/x+0.977$ | 0.42 | 0.240 |
| | Heshan | A | $y=66.6x^{-0.652}$ | 0.79 | 0.001 | $y=7.36/x+0.396$ | 0.91 | <0.001 | $y=3.76\times10^{-9}x^2+6.47\times10^{-4}x+0.212$ | 0.77 | 0.026 |
| | | B | $y=17.8e^{-0.0235x}$ | 0.84 | 0.001 | $y=-0.364\ln x+2.05$ | 0.98 | <0.001 | $y=1.56\times10^{-5}x^2+1.26\times10^{-4}x+0.284$ | 0.18 | 0.606 |
| | Huitong | A | $y=21.2e^{-0.0290x}$ | 0.92 | <0.001 | $y=2.47\times10^{-4}x^2-0.0324x+1.59$ | 0.93 | <0.001 | $y=4.76\times10^{-5}x^2-0.0046x+0.178$ | 0.40 | <0.001 |
| | | B | $y=155x^{-0.934}$ | 0.97 | <0.001 | $y=4.27x^{-0.425}$ | 0.97 | <0.001 | $y=0.216/x+0.176$ | 0.27 | 0.228 |
| | Miaoxian | A | $y=197x^{-0.905}$ | 0.96 | 0.001 | $y=11.3x^{-0.734}$ | 0.95 | 0.001 | $y=8.15\times10^{-5}x^2-0.0094x+0.409$ | 0.96 | 0.040 |
| | | B | $y=154x^{-0.884}$ | 0.94 | 0.001 | $y=13.4/x+0.187$ | 0.99 | <0.001 | $y=6.93\times10^{-5}x^2-0.0088x+0.371$ | 0.89 | 0.112 |
| | Shennongjia | A | $y=77.3x^{-0.503}$ | 0.89 | 0.004 | $y=4.09x^{-0.393}$ | 0.84 | 0.011 | $y=4.32x^{-0.0531}$ | 0.51 | 0.176 |
| | | B | $y=64.9e^{-0.0144x}$ | 0.84 | 0.010 | $y=4.69e^{-0.0126x}$ | 0.91 | 0.003 | $y=e^{-0.409/x+1.57}$ | 0.24 | 0.407 |
| | Xishuanbanna | A | $y=39.5x^{-0.442}$ | 0.87 | <0.001 | $y=2.99x^{-0.365}$ | 0.84 | <0.001 | $y=1.15/x+0.181$ | 0.90 | <0.001 |
| | | B | $y=47.4x^{-0.345}$ | 0.64 | 0.017 | $y=7.11x^{-0.520}$ | 0.88 | 0.001 | $y=9.13\times10^{-5}x^2-0.0117x+0.734$ | 0.89 | 0.004 |
| | Changbai | A | $y=1591x^{-1.53}$ | 0.77 | 0.004 | $y=77.4x^{-1.23}$ | 0.77 | 0.004 | $y=4.00\times10^{-4}x^2-0.0516x+1.81$ | 0.59 | 0.264 |
| | | B | $y=305x^{-1.13}$ | 0.92 | 0.001 | $y=13.8x^{-0.855}$ | 0.91 | 0.001 | $y=6.04/x+0.121$ | 0.85 | 0.026 |
| Grassland | Haibei | A | $y=70.9e^{-0.0348x}$ | 0.80 | 0.003 | $y=5.96e^{-0.0314x}$ | 0.91 | <0.001 | $y=-0.0536\ln x+0.996$ | 0.31 | 0.149 |
| | | B | $y=122x^{-0.364}$ | 0.80 | 0.003 | $y=11.1x^{-0.390}$ | 0.92 | <0.001 | $y=4.89\times10^{-6}x^2-0.0031x+1.03$ | 0.68 | 0.059 |
| | Inner Mongolia | A | $y=37.1x^{-0.419}$ | 0.82 | <0.001 | $y=4.45x^{-0.409}$ | 0.63 | 0.002 | $y=2.39\times10^{-5}x^2-0.0037x+0.324$ | 0.99 | 0.001 |
| | | B | $y=20.8e^{-0.0239x}$ | 0.99 | <0.001 | $y=-2.66\times10^{-4}x^2-0.0374x+1.81$ | 0.98 | 0.023 | $y=-6.06\times10^{-6}x^2-0.0012x+0.295$ | 0.98 | 0.017 |
| | Sanjiang | A | $y=789e^{-0.102x}$ | 0.77 | 0.002 | $y=33.2e^{-0.0723x}$ | 0.62 | 0.012 | $y=-3.82\times10^{-4}x^2+0.0036x+0.961$ | 0.64 | 0.048 |
| | | B | $y=183e^{-0.0879x}$ | 0.75 | 0.006 | $y=12.7e^{-0.0593x}$ | 0.77 | 0.004 | $y=6.19\times10^{-4}x^2-0.0451x+1.69$ | 0.59 | 0.111 |
| Desert | Cele | A | $y=1.34e^{0.00183x}$ | 0.66 | 0.049 | $y=4.24\times10^{-6}x^2+3.48\times10^{-4}x+0.183$ | 0.80 | 0.090 | $y=-1.42\times10^{-5}x^2+7.76\times10^{-4}x+0.563$ | 0.67 | 0.190 |
| | | B | $y=1.49e^{-0.00134x}$ | 0.37 | 0.199 | $y=-8.55\times10^{-6}x^2+8.18\times10^{-4}x+0.179$ | 0.22 | 0.691 | $y=-1.05\times10^{-5}x^2-0.0011x+0.561$ | 0.84 | 0.061 |
| | Erdos | A | $y=6.06/x+0.706$ | 0.99 | 0.001 | $y=0.293/x+0.122$ | 0.74 | 0.060 | $y=-6.96\times10^{-6}x^2-0.0011x+0.244$ | 0.95 | 0.048 |
| | | B | $y=-0.638\ln(x)+3.11$ | 0.94 | 0.006 | $y=-0.0693\ln x+0.354$ | 0.96 | 0.003 | $y=2.98\times10^{-5}x^2-0.0019x+0.245$ | 0.59 | 0.408 |
| | Fukang | A | $y=4.56x^{-0.427}$ | 0.94 | 0.007 | $y=2.03\times10^{-5}x^2-0.00297x+0.235$ | 0.90 | 0.098 | $y=6.56\times10^{-5}x^2-0.0080x+0.476$ | 0.95 | 0.046 |
| | Naiman | A | $y=e^{2.72/x+0.732}$ | 0.93 | 0.008 | $y=0.991/x+0.243$ | 0.96 | 0.004 | $y=6.20\times10^{-6}x^2+5.57\times10^{-4}x+0.260$ | 0.67 | 0.326 |
| | | B | $y=2.98/x+0.414$ | 0.96 | 0.003 | $y=-0.0235\ln x+0.176$ | 0.98 | 0.001 | $y=4.01\times10^{-5}x^2-0.0053x+0.249$ | 0.90 | 0.103 |
| | Shapotou | A | $y=12.6x^{-0.937}$ | 0.81 | 0.003 | $y=-0.0980\ln x+0.466$ | 0.86 | 0.001 | $y=7.82\times10^{-6}x^2-0.0015x+0.159$ | 0.97 | 0.027 |
| | | B | $y=4.23/x+0.240$ | 0.97 | <0.001 | $y=-0.0406\ln x+0.233$ | 0.90 | 0.001 | $y=0.200/x+0.104$ | 0.96 | 0.003 |
| | Linze | A | $y=5.64\times10^{-5}x^2-0.0113x+1.13$ | 0.92 | 0.082 | $y=-0.0241\ln x+0.219$ | 0.92 | 0.010 | $y=0.341/x+0.278$ | 0.99 | 0.001 |

Notes: A and B represent different plots with different dominant species or ecosystem types in the same ecological station; $y$ and $x$ represent the content of soil organic carbon (g/kg) and soil depth (cm), respectively

N, and P in all plots was well fitted by different curve functions, although the fitting functions differed among different plots. The SOC profile distribution was better fitted with exponential functions in the artificial agricultural ecosystems only excluding the plots of Changwu and Naiman stations from 38 plots. Among the type of the best fitting functions, there were 53% of the exponential function and 45% for the power function. Similarly, soil TN can be fitted by quadratic functions in all plots ($P < 0.05$ for all plots), with 76%, 11%, and 8% of the best fitting functions being respectively quadratic, exponential and logarithmic functions. In total, the power functions fitted the SOC profile distributions well in 36 natural ecosystems plots (desert, forest, and grassland) except for the plots of Cele station ($P < 0.05$ for all plots). The best fitting functions were about 44% for the power function, 36% for the exponential function, and 6% for the S function and 8% for inverse functions. Soil TN content was best fitted by power functions in the natural ecosystems, with the best fitting functions being 31%, 19%, and 19% for power, exponential, and quadratic functions, respectively.

Quadratic functions well depicted the profile distribution of TP in the 0–100 cm soil for all 74 plots (Table 2, Fig. 4). The best fitting functions for TP were the quadratic function (97%) followed by logarithmic functions in the artificial ecosystems, and the quadratic functions (67%) followed by the inverse (19%) and S (6%) functions in the natural ecosystems.

Overall, the best fit functions for soil C and N content clearly differed between artificial (agriculture) and natural (desert, forest, and grassland) ecosystems; however, the vertical distribution functions of soil P content were similar in both artificial and natural ecosystems.

### 3.3 Stoichiometric ratios of C, N, and P in soil

Stoichiometric ratios of C, N, and P of soils are ordered as follows: grassland > forest > agriculture > desert (Table 3). The similar vertical distributions of soil C, N, P, and their best fitting functions in both artificial and natural ecosystems indicated the close coupling relationships between soil C, N, and P at a large scale. The stoichiometric ratios of C, N, and P were also associated with climate to some extent. The ratios generally were lower in the warm temperate and north subtropical zones, higher in the temperate and south subtropical zone, and highest in the Tibetan Plateau (Table 3).

**Table 3** Stoichiometric ratios of soil C, N, and P in Chinese terrestrial ecosystems

| Classification | Type | C∶N | N∶P | C∶P |
|---|---|---|---|---|
| Ecosystem type | Agriculture | 9 | 1 | 13 |
| | Forest | 13 | 3 | 41 |
| | Grassland | 14 | 6 | 83 |
| | Desert | 8 | 1 | 5 |
| Climatic zone | Temperate | 13 | 3 | 40 |
| | Warm temperate | 8 | 1 | 10 |
| | North subtropical | 11 | 1 | 12 |
| | Mid-subtropical | 10 | 2 | 21 |
| | South subtropical | 14 | 3 | 42 |
| | Tibetan Plateau | 13 | 4 | 54 |

Note: Tibetan Plateau have been classified individually due to especial climate and altitude

## 4 Discussion

### 4.1 Fitting functions for profile distribution of soil C, N, and P

This study established a set of the fitting functions for the profile distribution of C, N, and P in the 0–100 cm soil layer in the Chinese terrestrial ecosystems. The exponential function, quadratic function, and quadratic function were found to be more suitable to characterize the vertical distribution of soil C, N, and P, even though the best fitting functions differed among different ecosystems. Many studies have demonstrated that the soil C, N, and P content decreases with increasing soil depth (Panda *et al.*, 1988; Bowman and Savory, 1992; Hobley *et al.*, 2013). Furthermore, Zinke (1978) developed the cumulative log-log models to describe SOC profiles. Jobbagy and Jackson (2000) used the logarithm functions to construct the relationships between SOC and soil depth using three global databases. Our study suggests that it should be cautious to use a general function to simulate the change of SOC content with increasing soil depth because the best fitting functions differed among ecosystems.

### 4.2 Differences between artificial and natural ecosystems

The fitting functions for the profile distribution of soil C, N, and P content in the 0–100 cm appeared to differ in artificial and natural ecosystems. The exponential and quadratic functions fitted the C, N, and P profile distribution well in agricultural soils. In contrast, the power and quadratic functions were the best fitting functions for natural soils (forest, grassland, and desert soils). Turner (1989) reported that the soil environment may alter as a result of changes in natural and ecological processes under different ecosystem types. In the artificial ecosystems, natural and human factors jointly influence the distribution of soil nutrients (Wang *et al.*, 1996), with fertilization and cultivation exerting stronger impacts on the upper soil (Coleman *et al.*, 1993; Drinkwater and Snapp, 2007). Furthermore, Crow *et al.* (2009) reported that the C and P content in the surface soil was directly related to the input of litter and mulch in farmlands. In the deep soil layer, soil genesis becomes more important. In natural ecosystems, soil forming factors, such as climate, topography, parent material, biology, and time are important for soil C, N, and P vertical distributions (Sinsabaugh *et al.*, 1993; Olander and Vitousek, 2000; Xia *et al.*, 2014). Furthermore, soil P content is regulated by various biological factors and disturbance in the short-term, while geochemical factors of the parent rock represent the main controlling factors in the long-term (Kellogg and Bridgham, 2003).

### 4.3 Coupling relationship of soil C, N, and P vertical distribution

The best fitting functions observed here imply the close coupling relationships among the C, N, and P storage in the 0–100 cm soil profile. Ecological stoichiometry (or soil C∶N∶P ratios) are expected to provide a new approach to analyze the coupling cycles of soil C, N, and P (Sterner and Elser, 2002). Our findings showed that the C∶N, N∶P and C∶P ratios ranked in order from grassland > forest > agriculture > desert. The observed differences were mainly due to differences in the element ratios of vegetation consumption and release from soil and atmosphere (Sterner and Elser, 2002).

Some studies have suggested that climate factors play an important role in the vertical distribution of soil C, N, and P by controlling soil development, biota, and their interactions (Chadwick *et al.*, 1999; Oleksyn *et al.*, 2003; Vitousek, 2004). The stoichiometric ratios of C, N, and P were associated with climate in this study. The general trends were lower in warm temperate and north subtropical zones, and higher in temperate (or Tibetan Plateau) and south subtropical zones. The tropical and subtropical ecosystems with high productivity do not maintain relatively high soil C content due to the stronger effects of temperature on SOM decomposition, but high temperatures and ample precipitation in these systems may result in high P leaching rates and P occlusion of highly weathered soils (Vitousek *et al.*, 1987; Neufeldt *et al.*, 2000; Zhang *et al.*, 2005), leading to the highest C∶P and N∶P ratios. In contrast, the dry and cool climate of temperate deserts results in low productivity, lower soil C and N content, and low P loss through leaching, along with higher soil P content. Consequently, temperate deserts have the lowest soil C∶P and N∶P ratios among all climatic zones (Tian *et al.*, 2010). In addition, Walker and Adams (1958) reported that C∶P ratios declined much faster than the C∶N ratios with increasing soil depth. One possible explanation for this phenomenon is that soil P mainly derives from soil weathering, in addition to soil available P migrating through plants and surface accumulation.

The delineation of fitting functions for the vertical distribution of soil C, N, and P in typical terrestrial ecosystems is of great significance. First, the functions provide a scientific basis and new approaches to accurately estimate the storage of soil C, N, and P at regional and national scales. These fitting functions are of significance for scientists to integrate sparse data from different sources with different soil depths to estimate C storage at large scale. Second, the coupling cycles of C, N, and P have been considered as one of the hot spots of global climate change study (Lal, 2004; Schipper *et al.*, 2004).

## 5 Conclusions

Regression functions were built for the profile distribution of soil C, N, and P content in the 0–100 cm depth in the Chinese terrestrial ecosystems. The best fitting functions with respect to soil C, N, and P content differed, to some extent, in different plots, especially between artificial and natural ecosystems. In both the artificial and natural ecosystems, the best fitting functions were exponential and power functions for C, quadratic and power functions for N, and quadratic functions for P. The best fitting functions for soil C, N, and P content indicated a close coupling relationship among the storage and turnover of soil C, N, and P. The stoichiometric ratios of soil C, N, and P content ranked as follows: grassland > forest > agriculture > desert, and are associated with climate. This study is the first to build the fitting functions of vertical profiles at the national scale. The study provides an important tool to accurately estimate soil C, N, and P storage at a large scale, and give new insights into the coupling cycles of soil C, N, and P.

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## References

Agren G I, Mcmurtrie R E, Parton W J *et al*., 1991. State-of-the-art of models of production decomposition linkages in conifer and grassland ecosystems. *Ecological Applications*, 1(2): 118–138. doi: 10.2307/1941806

Aho K, Derryberry D, Peterson T, 2014. Model selection for ecologists: the worldviews of AIC and BIC. *Ecology*, 95(3): 631–636. doi: 10.1890/13-1452.1

Alvarez C R, Costantini A O, Bono A *et al*., 2011. Distribution and vertical stratification of carbon and nitrogen in soil under different managements in the Pampean Region of Argentina. *Revista Brasileira De Ciencia Do Solo*, 35(6): 1985–1994. doi: org/10.1590/ S0100-06832011000600015

Andrews S S, Karlen D L, Cambardella C A, 2004. The soil management assessment framework: a quantitative soil quality evaluation method. *Soil Science Society of America Journal*, 68(6): 1945–1962. doi: 10.2136/sssaj2004.1945

Bowman R A, Savory D J, 1992. Phosphorus distribution in calcareous soil profiles of the central plains. *Soil Science Society of America Journal*, 56(2): 423–426. doi: 10.2136/ sssaj 1992.03615995005600020013x

Bozdogan H, 1987. Model selection and Akaike's information criterion (AIC): the general theory and its analytical extensions. *Psychometrika*, 52(3): 345–370. doi: 0033-3123/ 87/0900-SS03$00.75/0

Chadwick O A, Derry L A, Vitousek P M *et al*., 1999. Changing sources of nutrients during four million years of ecosystem development. *Nature*, 397(6719): 491–497. doi: 10.1038/ 17276

Coleman D C, Foissner W, Paoletti M G, 1993. *Soil Biota, Nutrient Cycling and Farming Systems*. Boca Raton: Lew Publishers.

Compton J S, Mallinson D J, Glenn C R *et al.*, 2000. Variations in the global phosphorus cycle. In: Glenn C R *et al*. (eds.). *Marine Authigenesis*: *From Global to Microbial*. Tulsa: Society of Economic Paleontologists and Mineralogist, 21–34.

Conant R T, Paustian K, Elliott E T, 2001. Grassland management and conversion into grassland: effects on soil carbon. *Ecological Applications*, 11(2): 343–355. doi: 10.1890/1051- 0761(2001)011[0343:Gmacig]2.0.Co;2

Cordell S, Goldstein G, Meinzer FC *et al.*, 2001a. Morphological and physiological adjustment to N and P fertilization in nutrient-limited Metrosideros polymorpha canopy trees in Hawaii. *Tree Physiology*, 21(1): 43–50. doi: 10.1093/treephys/ 21.1.43

Cordell S, Goldstein G, Meinzer F C *et al.*, 2001b. Regulation of leaf life-span and nutrient-use efficiency of metrosideros polymorpha trees at two extremes of a long chronosequence in Hawaii. *Oecologia*, 127(2): 198–206. doi: 10.1007/s0044200 00588

Crow S E, Lajtha K, Bowden R D *et al.*, 2009. Increased coniferous needle inputs accelerate decomposition of soil carbon in an old-growth forest. *Forest Ecology and Management*, 258(10): 2224–2232. doi: 10.1016/j.foreco.2009.01.014

Dewes T, 1999. Ammonia emissions during the initial phase of microbial degradation of solid and liquid cattle manure. *Bioresource Technology*, 70(3): 245–248. doi: 10.1016/S0960-8524(99)00046-2

Drinkwater L E, Snapp S S, 2007. Nutrients in agroecosystems: rethinking the management paradigm. *Advances in Agronomy*, 92: 163–186. doi: 10.1016/S0065-2113(04)92003-2

Fu B J, Li S G, Yu X B *et al.*, 2010. Chinese ecosystem research network: progress and perspectives. *Ecological Complexity*, 7(2): 225–233. doi: 10.1016/j.ecocom.2010.02.007

Gallaher R N, Weldon C O, Boswell F C, 1976. Semi-automated procedure for total nitrogen in plant and soil samples. *Soil Science Society of America Journal*, 40(6): 887–889. doi: A1976CU29900018

Harrington R A, Fownes J H, Vitousek P M, 2001. Production and resource use efficiencies in N- and P-limited tropical forests: a comparison of responses to long-term fertilization. *Ecosystems*, 4(7): 646–657. doi: 10.1007/s10021-001-0034-z

He N P, Yu Q, Wu L *et al.*, 2008. Carbon and nitrogen store and storage potential as affected by land-use in a *Leymus chinensis* grassland of northern China. *Soil Biology & Biochemistry*, 40(12): 2952–2959. doi: 10.1016/j.soilbio.2008.08.018

Hobbie S E, Vitousek P M, 2000. Nutrient limitation of decomposition in Hawaiian forests. *Ecology*, 81(7): 1867–1877. doi: 10.1890/0012-9658(2000)081[1867:Nlodih]2.0.Co; 2

Hobley E, Willgoose G R, Frisia S *et al.*, 2013. Environmental and site factors controlling the vertical distribution and radiocarbon ages of organic carbon in a sandy soil. *Biology and Fertility of Soils*, 49(8): 1015–1026. doi: 10.1007/ s00374- 013-0800-z

Jobbagy E G, Jackson R B, 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, 10(2): 423–436. doi: 10.2307/2641104

Kellogg L E, Bridgham S D, 2003. Phosphorus retention and movement across an ombrotrophic-minerotrophic peatland gradient. *Biogeochemistry*, 63(3): 299–315. doi: 10.1023/A: 1023387019765

Kuo S, 1996. Phosphorus. In: Sparks D L *et al.* (eds.). *Methods of Soil Analysis*. *Part 3*. *Chemical Methods*. Wisconsin: Soil Science Society of America and American Society of Agronomy, 869–919.

Lal R, 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677): 1623–1627. doi: 10.1126/science.1097396

Liu Jing, Yan Li, Wang Yurong *et al.*, 2012. Effect of different landuseonvertical distributionof soil organiccarboninbrown-soil. *Soil and Fertilizer Sciences in China*, 4(1): 18–21. (in Chinese)

Nelson D W, Sommers L E, 1982. Total carbon, organic carbon, and organic matter. In: Page A L *et al.* (eds.). *Methods of Soil Analysis*. Madison: American Society of Agronomy and Soil Science Society of American, 539–552.

Neufeldt H, Da Silva J E, Ayarza M A *et al.*, 2000. Land-use effects on phosphorus fractions in Cerrado oxisols. *Biology and Fertility of Soils*, 31(1): 30–37. doi: 10.1007/s003740050620

Olander L P, Vitousek P M, 2000. Regulation of soil phosphatase and chitinase activity by N and P availability. *Biogeochemistry*, 49(2): 175–190. doi: 10.1023/A:1006316117817

Oleksyn J, Reich P B, Zytkowiak R *et al.*, 2003. Nutrient conservation increases with latitude of origin in European Pinus sylvestris populations. *Oecologia*, 136(2): 220–235. doi: 10.1007/s00442-003-1265-9

Panda D, Sen H S, Patnaik S, 1988. Spatial and temporal distribution of nitrogen in a puddled rice soil following application of urea-based fertilizers by different methods. *Biology and Fertility of Soils*, 6(1): 89–92. doi: A1988M 400000017

Qiu Yaqun, Gan Guojuan, Liu Wei *et al.*, 2012. The study of distribution characteristics of phosphorus of typical soils in Hunan and its loss risk. *Chinese Agricultural Science Bulletin*, 28(8): 223–227. (in Chinese)

Reich P B, Oleksyn J, 2004. Global patterns of plant leaf N and P in relation to temperature and latitude. *Proceedings of the National Academy of Sciences of the United States of America*, 101(30): 11001–11006. doi: 10.1073/pnas.0403588101

Robinson C H, Wookey P A, Parsons A N *et al.*, 1995. Responses of plant litter decomposition and nitrogen mineralisation to simulated environmental change in a high arctic polar semi-desert and a subarctic dwarf shrub heath. *Oikos*, 74(3): 503–512. doi 10.2307/3545996

Schindler D W, 2006. Recent advances in the understanding and management of eutrophication. *Limnology and Oceanography*, 51(1): 356–363. doi: 000241296700002

Schipper L A, Percival H J, Sparling G P, 2004. An approach for estimating when soils will reach maximum nitrogen storage. *Soil Use and Management*, 20(3): 281–286. doi: 10.1079/ Sum2004255

Sinsabaugh R L, Antibus R K, Linkins A E *et al.*, 1993. Wood decomposition—nitrogen and phosphorus dynamics in relation to extracellular enzyme-activity. *Ecology*, 74(5): 1586–1593. doi: 10.2307/1940086

Sterner R W, Elser J J, 2002. *Ecological Stoichiometry*: *the Biology of Elements from Molecules to the Biosphere*. Princeton: Princeton University Press.

Tian H Q, Chen G S, Zhang C *et al.*, 2010. Pattern and variation of C:N:P ratios in China's soils: a synthesis of observational data. *Biogeochemistry*, 98(1–3): 139–151. doi: 10.1007/s10533-009-9382-0

Tong Xiaojuan, Tao Bo, Cao Mingkui, 2005. The responses of soil respiration and nitrogen mineralization to global warming in terrestrial ecosystems. *Progress in Geography*, 24(4): 84–96. (in Chinese)

Turner M G, 1989. Landscape ecology—the effect of pattern on process. *Annual Review of Ecology and Systematics*, 20(1): 171–197. doi: 10.1146/annurev.es.20.110189.001131

van der Wal A, De Boer W, Lubbers I M *et al.*, 2007. Concentration and vertical distribution of total soil phosphorus in relation to time of abandonment of arable fields. *Nutrient Cycling in Agroecosystems*, 79(1): 73–79. doi: 10.1007/ s10705-007-9097-3

Vitousek P M, 2004. *Nutrient Cycling and Limitation*: *Hawai'i as a Model System*. Princeton: Princeton University Press.

Vitousek P M, Walker L R, Whiteaker L D *et al.*, 1987. Biological invasion by myrica-faya alters ecosystem development in Hawaii. *Science*, 238(4842): 802–804. doi: 10.1007/s10705- 007-9097-3

Walker T, Adams A R, 1958. Studies on soil organic matter: I. influence of phosphorus content of parent materals on accumulations of carbon, nitrogen, sulfur, and organic phosphorus in grasslands soils. *Soil Science*, 85(6): 307–318.

Wang Jizhi, Ma Yulan, Jin Guozhu, 1996. *China Cumulated Irrigated Soils*. Beijing: Science Press. (in Chinese)

Wang Qingren, Li Jiyun, Li Zhensheng, 1999. Studies on plant nutrition of efficient utility for soil phosphorus. *Acta Ecologica Sinica*, 19(3): 129–133. (in Chinese)

Wang S Q, Huang M, Shao X M *et al.*, 2004. Vertical distribution of soil organic carbon in China. *Environmental Management*, 33: S200–209. doi: 10.1007/s00267-003-9130-5

Xia L Z, Liu G H, Ma L *et al.*, 2014. The effects of contour hedges and reduced tillage with ridge furrow cultivation on nitrogen and phosphorus losses from sloping arable land. *Journal of Soils and Sediments*, 14(3): 462–470. doi: 10.1007/ s11368-013-0824-x

Zhang C, Tian H Q, Liu J Y *et al.*, 2005. Pools and distributions of soil phosphorus in China. *Global Biogeochemical Cycles*, 19(1): 1–8. doi: 10.1029/2004gb002296

Zhang Jingyun, Yin Yunhe, Li Bingyuan, 2010. A new scheme for climate regionalization in China. *Acta Geographica Sinica*, 65(1): 3–12. (in Chinese)

Zinke P J, Sabhasri S, Kunstadter P, 1978. Soil fertility aspects of the Lua forest fallow system of shifting cultivation. In: Kundstadter P *et al.* (eds.). *Farmers in the Forest*. Hawaii: University Press, 134–159.